The Irish Bioeconomy
Definition, Structure, and Situational Analysis
The Irish Bioeconomy - Definition, Structure, and Situational Analysis

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This interim report of the BioÉire project represents a description of the current bioeconomy in Ireland and sets the scene for analysis of the opportunities to expand the Irish bioeconomy in line with the Europe 2020, Innovation Union, and Resource Efficient Europe initiatives outlined by the European Union.

A Bioeconomy for Ireland - the BioÉire project - is supported by the Department of Agriculture, Food and the Marine under the Competitive Research Call 2014
Foreword

In the last ten years Ireland has experienced both the exhilarating high of economic boom and the crushing low of recession. While the Celtic Tiger brought significant employment and production, a harsh lesson that was quickly learned was the vulnerability of the national economy. Although much of the Celtic Tiger boom was related to construction and thus much of the job losses associated with the recession was in this sector, the current recovery period offers an opportunity to find secure and sustainable ways to re-establish the Irish economy as a whole. A prime example of how this could be achieved is by increasing the use of indigenous organic materials, obtaining greater value from the by-products and side streams of current production processes, and exploring and developing new products and processing opportunities from underutilised resources.

Ireland’s biological sectors are responsible for significant employment, produce substantial volumes of outputs with formidable financial value, and play a role in feeding an ever-growing global population. The agri-food industry (incorporating fisheries and forestry) employs over 8% of the national workforce, is responsible for 7.6% of total gross value added, and produces exports worth more than €10 bn annually. A number of government strategies are in place to increase production levels and outputs of the agriculture, food, forestry, marine, and renewable energy industries. There is currently no specific strategy in place which views these industries as sub-sectors of the bioeconomy as a whole, however.

Adopting a mentality of supply web rather than supply chain illustrates the overlap between various sub-sectors of biological production and highlights the potential for one sub-sector to feed directly into another to create new or to develop immature processes or products. Expanding these crossovers will require assistance and support to take advantage of new value-added opportunities which will benefit the economy as a whole by reducing waste, creating employment, increasing production and exports, and enhancing production sustainability. Identifying the most appropriate opportunities to expand these sectors is essential to ensuring support mechanisms are targeted correctly and used efficiently.

Following a significant review and analysis of the current status of the Irish bioeconomy and all its sub-sectors, a number of interviews were performed with key players positioned within the Irish bioeconomy or an international bioeconomy. These interviews offered an opportunity to obtain informed opinions and views as to where the Irish bioeconomy has potential to be expanded and developed. Including international experts facilitated discussion
relating to both the possibilities and the problems encountered when developing a bioeconomy designed to take advantage of a country’s own specific resources. The primary outcome of these interviews was a longlist of generalised value chains which are considered to be underdeveloped or non-existent in an Irish context. Generalising the value chains allowed discussion relating to the possibility of the development of the value chain rather than the output of a specific product, i.e. the discussion was not focussed on the manufacture of product A from feedstock B but rather looked at all the possible uses of feedstock B as a source of materials, chemicals, food, etc such that each use of feedstock B could then be explored in detail.

Subsequent discussion of these value chains with an expert group allowed a shortlist of generalised value chains to be generated for discussion and evaluation later in the BioÉire project. The ultimate aim of the BioÉire project is to identify up to eight value chains which will be evaluated in terms of technical viability, economic viability, and sustainability thus informing development of integrated measures to overcome barriers and facilitate exploitation of commercial opportunities for the expansion of the Irish bioeconomy.
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1. Introduction
1.1. Definition of ‘Bioeconomy’ as a Concept

There are many definitions and descriptions of what constitutes a ‘bioeconomy’. These definitions range from what could be considered broad, non-specific, or generic - such as that adopted by the United States who describe a bioeconomy as being “based on the use of research and innovation in the biological sciences to create economic activity and public benefit” (White House, 2012) and that of McCormick and Kautto (2013) who describe an economy "where the basic building blocks for materials, chemicals and energy are derived from renewable biological sources” - to the more detailed such as that of the Organisation for Economic Co-operation and Development (OECD) who describe a bioeconomy as referring to “the set of economic activities relating to the invention, development, production and use of biological products and processes” (OECD, 2009) and the European Commission who describe a bioeconomy as involving “the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy” (European Commission, 2012).

One thing that is clear from these varying definitions is that a bioeconomy involves the use of organic materials as feedstocks to generate outputs. A bioeconomy is not just about using organic materials, however, but also includes rethinking the current uses of organic materials and looking for new ways to use these materials to obtain the greatest possible value from biological resources before they are ultimately considered to be waste. In this light, the bioeconomy represents a circular economy in that it can obtain feedstock for one process from the discards of another. Implementing a circular economy can present opportunities to reduce process costs by preventing waste and its associated handling and to increase the environmental efficiency associated with a process by obtaining value from substances which would otherwise be considered waste. Process efficiency can also be increased if parallel processors can streamline their activities into a mutually beneficial partnership. Each partnership, and the advantages which can be derived from such an arrangement, will depend on the parties involved and the specifics of their respective activities, however it is fair to say that any agreement which improves process efficiency and resource use and which decreases the environmental impact of modern day life will have significant sustainability benefits.

Recent interest in the concept of a circular economy as well as the ever-present threat of depleting finite resources, food shortages, and climate change has highlighted the importance of obtaining maximum value from organic resources. This importance has been recognised
across the world with the US and the EU pledging to increase the penetration of bio-based activities into their respective economies. In 2012 the American government published a blueprint for their national bioeconomy plan which they say offers the potential to “live longer, healthier lives, reduce our dependence on oil, address key environmental challenges, transform manufacturing processes, and increase the productivity and scope of the agricultural sector while growing new jobs and industries” (White House, 2012). The importance and value of a bioeconomy can easily be seen in this statement. The EU similarly released a policy document which is designed to introduce and support a European-wide bioeconomy as well as national bioeconomies within member states based on increasing research and innovation in bio-based industries “to improve the management of its renewable biological resources and to open new and diversified markets in food and bio-based products” (European Commission, 2012).

Despite the vast amounts of money and time spent on research, development, and innovation in bio-based industries in Ireland, there is currently no bioeconomy strategy in place to provide direction for the development of a national bioeconomy. The importance of environmental consciousness and the use of renewable resources are recognised, however, and have been highlighted in a number of recent government documents including environmental protection schemes, various waste management policies, and Food Harvest 2020 and FoodWise 2025, two of the most important agriculture and food industry development documents to be published in recent years. It is widely recognised that the gap between research and industrial implementation is an obstacle for the bioeconomy in Ireland (Feely, 2015). To this end it is imperative that a national strategy be introduced to fully support a bioeconomy in Ireland such that opportunities that offer the potential to increase process efficiency, reduce environmental impact, support rural development, reduce waste generation, etc can be implemented to Ireland’s net benefit. A bioeconomy strategy is not one-size-fits-all as each country, not just in Europe but across the world as a whole, has specific opportunities as well as obstacles which must be explored fully to obtain maximum value from their inherent resources. The first stage in introducing such a strategy for Ireland is to review the current status of each of the bioeconomy sectors and how this status was achieved so that an evaluation can be conducted of where our strengths and weaknesses lie. This will allow the preparation of a strategy which is tailored specifically to Ireland.

In light of the many, and widely varying, definitions of what is included in a bioeconomy it is appropriate when considering the current state and the potential of the bioeconomy in Ireland
to agree on definitive boundaries and parameters for what will be assessed within this project. As Ireland is directly and indirectly influenced by European policy and legislation which may therefore also affect an Irish bioeconomy it is considered most appropriate to adopt the definition of the European Commission. As such, the bioeconomy of Ireland will be evaluated according to the following definition:

*The bioeconomy is defined as encompassing the production of renewable biological resources and the conversion of these resources and waste streams into value added products such as food, feed, bio-based products and bioenergy.*

1.2. The Global Bioeconomy and Ireland’s Place in it

From a global perspective, the last five years have seen a flurry of policy development around the bioeconomy. At a European level *A Bioeconomy for Europe* aims to focus the EU’s common efforts in the right direction to “help Europe to live within its limits” and highlights how “sustainable production and exploitation of biological resources will allow the production of more from less, including from waste”. In addition to the overall EU strategy various national and regional strategies have also been produced to provide guidance across Europe, North America, and Asia, each with their own specific emphases, political motivations, and designated pathways for development. The strategies put forward by the USA and Canada, for example, seek to leverage their huge areas of forest, coastline, and arable land and increase the value of the agricultural and forestry sectors while promoting rural development. Existing agricultural strategies have been supplemented by research-focused strategies that target development of industrial biotechnology in the agriculture and health sectors in particular. Conversely, in countries with few natural resources but strong industrial structures such as Germany, Japan, France, and Italy national bioeconomy strategies emphasise the innovative potential offered by the bioeconomy and point to the potential of the bioeconomy to reinvigorate specific sectors. The UK bioeconomy strategy seeks to leverage its highly developed service sector and excellent bioscience research. The bioeconomy is seen as an opportunity to capitalise on these strengths to develop science-based, high-value industries.

Despite ambitions to introduce a bioeconomy strategy by the end of 2013 (Howell, 2013), there is currently no strategy or policy in place which directly supports or encourages a bioeconomy in Ireland. The aim of this report is to evaluate how bio-based industries in Ireland can be nurtured to increase the impact and contribution to the national economy with
the ambition of feeding into an Ireland-specific bioeconomy strategy along the lines of those presented in Table 1. Ireland has a number of self-specific attributes which could be enhanced to develop a strategy designed to increase the outputs, employment, and sustainability of our primary production sectors. Some of these attributes occur naturally while others have been introduced at various times through governmental intervention with the aim of supporting, expanding, or protecting various aspects of the primary production sectors. Some of the measures which have been implemented to the benefit of primary production are Growing for the Future (DAFF, 1996), Food Harvest 2020 (DAFF, 2010a), and Delivering Our Green Economy (Government of Ireland, 2012), each of which has played a part in achieving the current levels of bio-based output. One of the most significant naturally-occurring phenomena which influence the output capacity of Ireland’s primary production sectors is the inherent climate: cool summers and mild, damp winters facilitate the growth of grass and the various cereal crops which support the production of livestock (Holden and Brereton, 2003) and form the basis of the agriculture and food sectors.

Increasing the potential of the primary production sectors will require tailor-made policy measures which support and develop new, more efficient, and more sustainable production pathways which take advantage of this climate. Although Ireland is a member state of the European Union and will be affected by measures introduced at European level, it is important too that measures introduced at a national level take advantage of Irish uniqueness to promote Irish production.

Table 1: Selected recent international, national, and regional bioeconomy strategies

<table>
<thead>
<tr>
<th>Region</th>
<th>Strategy Document</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Commission</td>
<td>A Bioeconomy for Europe</td>
<td>2012</td>
</tr>
<tr>
<td>Germany</td>
<td>National Policy Strategy on the Bioeconomy</td>
<td>2013</td>
</tr>
<tr>
<td>Finland</td>
<td>Sustainable Growth for Bioeconomy</td>
<td>2014</td>
</tr>
<tr>
<td>USA</td>
<td>National Bioeconomy Blueprint</td>
<td>2012</td>
</tr>
<tr>
<td>Canada</td>
<td>Blueprint beyond Moose and Mountains</td>
<td>2011</td>
</tr>
<tr>
<td>Sweden</td>
<td>Research and Innovation Strategy for Bio-Based Economy</td>
<td>2011</td>
</tr>
<tr>
<td>UK</td>
<td>UK Bioenergy Strategy</td>
<td>2011</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Netherlands Bio-based Economy 2010-2015</td>
<td>2010</td>
</tr>
<tr>
<td>Denmark</td>
<td>Agreement on Green Growth</td>
<td>2009</td>
</tr>
<tr>
<td>Austria</td>
<td>Bioeconomy Background Paper</td>
<td>2013</td>
</tr>
<tr>
<td>Flanders, Belgium</td>
<td>Bioeconomy in Flanders</td>
<td>2014</td>
</tr>
</tbody>
</table>
The main sectors which contribute to the Irish bioeconomy in its current format are agriculture, food (and beverages), fisheries, and forestry. The food and beverage industry accounted for 70% of the total industry consumption of Irish raw materials in 2014 (DAFM, 2014a). A report issued in May 2015 noted that the food and beverages industry was responsible for 22% of total gross industry output and that the agriculture, food, fisheries, and forestry (including wood processing) sectors employed a combined total of 163,000 people in 2014 (DAFM, 2015a), just under 10% of the total workforce in Ireland. An important aspect of this employment is its decentralised nature: while much of the food processing activity occurs in urbanised centres agriculture, fisheries, and forestry occur predominantly in rural areas which are a priority for development under the EU bioeconomy strategy (European Commission, 2012). The contribution of the bioeconomy to the overall Irish economy is therefore significant; it has substantial responsibility for employment and value addition on a national scale.

1.3. Ireland’s Natural Value

This report endeavours to analyse and evaluate the Irish bioeconomy with the aim of determining how best to expand its employment and earning potential while promoting environmental consciousness and resource efficiency. There are a number of aspects of the various sub-sectors of the bioeconomy which cannot be included in this analysis, however. For example, healthy and productive soil is the basis for all aspects of the agriculture sector which is the anchor of primary production and which feeds logically into the food sector and has potential to feed into other bio-based sectors such as renewable energy. Soil also has environmental value which, although related to and significantly influential on primary production, can be considered to be distinct from its productivity value. Soil provides various ecosystem services including water filtration, nutrient cycling, and carbon storage much of which is a result of the activities of the micro- and macro biodiversity within the soil (Pascual et al., 2015). Soil is one of the most important global carbon sinks: McGrath and Zhang (2003) reported that the volume of organic carbon in soil globally is almost equivalent to the total carbon stored in the atmospheric and biotic pools due to interactions between parent materials, texture, pH, and land use activities. Carbon sequestration in soil has an important role in preventing the advance of climate change by removing carbon from the atmosphere via plant photosynthesis (Tomlinson, 2005); plant material has been described as a conduit through which carbon is removed from the atmosphere and stored in soil (Tomlinson, 2005). Although the carbon storage facility and the financial and environmental value of this activity
are an essential facet of the soil system, these services and values of soil are beyond the scope of this report.

Ireland has long been regarded as a “green” country and has a long history of agriculture and food production. The natural landscape which plays such an integral role in these sectors also plays an important part in other aspects of Irish life. Much of Ireland’s tourism industry is reliant on the natural environment, clean water networks, and mature forestry for example, and the importance of conserving biodiversity and environmental sustainability has long been recognised in agriculture policy such as the REPS scheme. This scheme was originally launched in 1994 and promotes ways of using agricultural land which are compatible with the protection and improvement of the environment, biodiversity, the landscape and its features, among others (DAF, 2007). There are various other socio-economic benefits associated with the natural environment which are advantageous to both the economy and the population as a whole and without which Ireland would be a very different place, but their inclusion is beyond the scope of this report due to the parameters outlined by the EU definition of a bioeconomy.

The current conditioning of a resource and its potential suitability for additional use is essential knowledge when considering the capacity to expand any process. Financial assistance may be in place for a farmer to diversify into the production of energy crops, for example, but if the land being considered for expansion is unsuitable due to drainage conditions or fertilisation requirements then growing this biomass is not necessarily environmentally sustainable or financially viable. Similarly, increasing fish catches will only be sustainable if prior knowledge exists of the stocks and natural replenishment rates and whether such an increase can be absorbed both by fish stocks and by processing facilities. It is essential that all of the necessary information is available and considered before any potential change is introduced, including the availability of non-organic resources such as labour force, equipment, and other relevant infrastructure. Ireland is in a fortunate position in that extensive mapping of our land base (Creamer et al., 2014) has previously been conducted which will facilitate obtaining the information necessary when evaluating an amendment to current practices. Although this information is essential for in-depth discussion of specific options to expand productivity and may be referred to later in the text, an in-depth discussion of this information is beyond the scope of this report.
1.4. Additional Contextual Information

Adopting the European Commission’s definition of a bioeconomy as one which encompasses the production of renewable biological resources and their conversion into value-added products requires a framework within which to analyse the production and conversion of bio-based products. To conduct this analysis, a bioeconomy framework described by Nita et al. (2013) has been adapted for an Irish setting and is provided in Figure 1. This ‘value web’ approach highlights the overlap between bioeconomy sub-sectors and between organic materials, and illustrates the potential for competition between sub-sectors for use of the same materials. It is within this framework that we have endeavoured to describe the current status of the Irish bioeconomy and to highlight areas where the outputs of the bioeconomy can be expanded or enhanced for financial and environmental benefit.

As a member of the European Union, Ireland is strongly influenced by legislation and reform introduced on a European level as well as that introduced on nationally. As such, changes introduced at European level will directly or indirectly influence the potential to expand the

![Figure 1: Value web used to analyse the Irish bioeconomy, adapted from Nita et al. (2013)](image-url)
Irish bioeconomy. Various legislative measures introduce limits on production capacity and restrict production quantities such as catch quotas are designed to maintain future fish stocks, or can impact the side effects of production such as the measures introduced to protect water quality. A number of measures will have cross-sectoral influence such as the reform to the Common Agricultural Policy which will influence both the agriculture and food sectors and the Nitrates Directive which will have an impact on both the agriculture and the bioenergy sectors; others are specific to one sector such as the Landfill Directive which will influence the uptake of waste treatment via anaerobic digestion and the capture of landfill gas. The overlapping nature of these European and national measures leads to a complex infrastructure within which to expand and enhance the Irish bioeconomy. A number of these measures and the overlap between legislation and sub-sectors are illustrated in Figure 2 to highlight this complexity.

Each of the “non-productive” alternative facets of the natural environment is relevant for the overall environmental credentials of a biological process and should be considered as such. The concept of a circular economy and of sustainable and efficient resource use underpins a

Figure 2: Selected European and national policy and legislative measures which will influence development and expansion of the Irish bioeconomy (this diagram does not presume to be exhaustive)
bioeconomy, but the environmental impact of a new process must also consider consequences on existing processes. A new production process may be resource efficient in that it can derive source materials from a waste material rather than requiring the use of new finite resources, but the introduction of this new process must first consider whether that feedstock is currently essential to another process and the impact that its diversion will have on the original process. For example, if wheat straw is diverted away from mushroom composting to instead produce bioethanol for use as a transport fuel, an alternative compost material must then be found. If the alternative material is only available abroad and must be imported, the carbon footprint and overall sustainability of straw use must be considered, including how much bioethanol must be produced to offset the now higher carbon footprint associated with mushroom production. This consequential lifecycle analysis - and indeed the impact on other environmental credentials such as the avoidance of greenhouse gas emissions, changes in water quality, etc - although having relevance to the bioeconomy as a whole, cannot be not included in this analysis. Consequential lifecycle analysis should be undertaken for each new or amended process which is being considered under the guise of the Irish bioeconomy, but such an endeavour is a significant undertaking of work in its own right and therefore lies beyond the parameters outlined by the definition of the bioeconomy adopted for this report.

1.4.1 Glossary and Abbreviations

Although boundaries have been put in place to differentiate between the various sub-sectors of the Irish bioeconomy it can be difficult to obtain information relating specifically to the sub-sector in question. Data relating to primary production are often presented for the agriculture and food sector, for the agri-food and fisheries sector, or for the Irish food and beverage sector, for example. A glossary has been compiled in an attempt to clarify for the reader what is included in each term used in the text so that any ambiguity or cross-over between terms is, where unavoidable, clearly defined and explained.
REPS: Rural Environmental Protection Scheme
SE(A)I: Sustainable Energy (Authority of) Ireland
SFE: Supercritical fluid extraction
SME: Small and medium-sized enterprise
SRC: Short rotation coppice
UNECE: United Nations Economic Commission for Europe
VFA: Volatile fatty acid
WBP: Wood Based Panels
2. Current Status of the Irish Bioeconomy
2.1. Primary Inputs into the Irish Bioeconomy

2.1.1 Agricultural Resources

2.1.1.1. The Importance and Relevance of the Agricultural Supply Chain in Ireland

The importance of the Irish agricultural sector cannot be underestimated, holding social, cultural, and economic relevance in the nation’s past, present, and future. Agriculture is the oldest and largest indigenous industry in the country, forming an intrinsic part of the Irish identity and connecting generations of families to the land and nature. Currently agriculture contributes significantly to employment rates and national gross domestic product (GDP), boasting the most substantial output multiplier effect compared to any other industry in Ireland (Phelan and O’Connell, 2011). Its economic impact at local scale is also increasingly recognised, supporting rural development and livelihoods within and beyond the farm-gate through its use of domestic inputs and the development of spin-off processing industries. The agricultural sector is paramount to Irish economic recovery with policy roadmaps in place to increase both the output quantities and value of this primary production sector. Already exporting produce to 175 countries worldwide (DAFM, 2015b), continued expansion of existing markets and potential development of new customer bases for Irish agricultural output represent distinct foci for future policy and infrastructural development nationally. Agriculture is also increasingly recognised as forming the basis for a future bio-based economy (DAFM, 2015b; FAO, 2013), a low carbon, sustainable alternative of economic growth predicated on the use of renewable biological resources. Agriculture not only holds intrinsic (social, cultural, political, economic) value as a standalone sector, it also supports a host of other bioeconomic activities from bioenergy production to bio-chemical creation. In essence, developments in agriculture hold the power to transform our everyday practices of production and consumption and have the potential to meet societal needs not only for food but also for fuel and fibre in increasingly different and sustainable ways.

Agriculture additionally contributes to society beyond an economic or market value. While the environmental impacts of modern agriculture need to be acknowledged and addressed, Irish farmers are also natural custodians of the landscape, delivering a variety of public goods and ecosystem services. This includes the management of natural resources (land, water, air, habitats, and species), the provision of recreational access, support for tourism, and the
foundation for Ireland’s clean, green food reputation (Teagasc, 2008). Nevertheless, the negative environmental impacts of poor agricultural practices, particularly with regard to greenhouse gas emissions, water pollution, biodiversity loss, and soil degradation need to be reduced. As a result, the sustainable development of Irish agriculture represents a principal ambition within the government’s latest strategy for the sector, Food Wise 2025, with the acknowledgement that future economic gains from agriculture cannot come at a cost to the environment (DAFM, 2015b). While more concrete plans for how this is to be achieved need to be developed with the advent of new farming technologies, growing environmental awareness, increasingly strict environmental regulations, and changing farmer practices, enhancing the environmental performance of Irish agriculture is critical to its future success.

### 2.1.1.2. Structural Features

According to the Department of Agriculture, Food, and the Marine (DAFM) total land area in Ireland equates to 6.9 million hectares of which 4.5 million or approximately 65% is used for agricultural purposes (DAFM, 2015b). This places Ireland as second in the list of EU countries with the highest percentage of land devoted to agriculture, behind the UK at 70.9% (FAO, 2014). Physical characteristics of the Irish landscape influence the percentage of land available for agriculture, influenced for example by soil types or the presence of lakes or mountains. Approximately 80% of agricultural land in Ireland is devoted to pasture, hay, and grass silage reflecting the dominance of livestock and dairy production in the Irish agricultural context and its unique comparative advantage for sustainable, grass-based production systems. A further 11% is dedicated to rough grazing while 9% is used for crop, fruit, and horticulture production (Teagasc, 2015a).

The Census of Agriculture (CSO, 2012a) recorded 139,860 family farms across the country in 2010. This compares with the 141,527 family farms recorded in 2000, a drop of 1.2% in national farm numbers over the decade. The Irish agricultural supply chain has witnessed a steady decline in farm numbers from 228,000 in 1975 (DAFM, 2014b). Some agricultural sub-sectors have been worse affected than others: the number of milk producers fell from 68,000 in 1984 to 17,000 in 2015 for example, a decrease of 75% over the period (ICOS, 2015; Prospectus, 2003). This highlights longer term trends of increased specialisation and consolidation across the Irish agricultural landscape. Small farm categories (less than 5 hectares) have witnessed the most dramatic reduction in numbers.
Specialist beef production continues to dominate Irish agriculture with over 55% of farms classified as such. More than 11% were classified as specialist dairy with a further 11% denoted as mixed grazing and livestock. Almost 13,600 farms (a little under 10%) were identified as specialist sheep farms (CSO, 2012a). Distinct geographic patterns emerge regarding the distribution of these farm holdings in Ireland: the vast majority of dairy farming takes place in the southwest while sheep farming dominates in upland areas of the west, and 78% of specialist tillage takes place in the southeast (CSO, 2012a). The average farm size in 2015 was 37 hectares (DAFM, 2015c) however Irish farms are typically fragmented with the average holding made up of 3.8 parcels (CSO, 2012a).

Approximately 54,000 farmers (41%) lease land from other land owners (DAFM, 2014b). Such leasing arrangements, which typically operate on an 11 month contract basis, have implications for the productivity of the agricultural supply chain. It influences farmers’ ability and desire to invest resources in the land, upgrade farm infrastructure such as fencing, and develop long term productivity strategies such as fertiliser use. Policy moves to extend 11 month contract arrangements have been mooted of late but progress is slow, representing a significant threat to the future viability and expansion of the agricultural supply chain. The price of Irish agricultural land features at the top of the global land price survey at €3,899 ha$^{-1}$ compared to €2,205 ha$^{-1}$ in the UK (Whelan, 2014). According to DAFM (2014b), less than 0.5% of the total land area in Ireland is sold each year. New agri-taxation measures are currently being introduced in an attempt to combat this static trend.

The Annual Review and Outlook for Agriculture published in 2015 revealed that the average farmer age in 2014 was 57 (DAFM, 2015c), however 25% of farm holders were over 65 years of age with only 6.2% under the age of 35. This comes in spite of governmental efforts to encourage more young people into farming. According to DAFM (2014b) the number of farmers aged less than 35 years has fallen by more than 50% between 2000 and 2010, with more than half of all farmers reported to be aged 55 or older. Such demographics are in keeping with wider European age profiles in farming which highlight that 30% of farmers are over 65 while only 10% are under 35 (DAFM, 2015c). These averages mask diversity between European countries, however: more than 14% of farmers in Poland are under the age of 35 for example, while more than 45% in Portugal are over 65 years of age (DAFM, 2015c). Plans remain in place in Ireland to continue the drive to recruit younger farmers, with a number of education programmes and tax incentives to be put in place to facilitate farm transfers to younger generations (DAFM, 2015b). From a gender perspective, only 12% of
farms in Ireland are owned by women in contrast to the 30% proportion of female farmers recorded across the EU (DAFM, 2015c).

There has been a slow but steady increase in the number of organic operators in Ireland, with 1,282 organic producers recorded at the end of 2014. The total area of land under organic production in Ireland has risen by almost 65% since 2002 to more than 55,000 hectares by the end of 2014 (DAFM, 2015c). This reflects wider global trends that have seen the land area under organic management increase from 11 million hectares in 1999 to 37.2 million hectares in 2011 (FAO, 2013). Despite these increases organic production equates to less than 1.2% of total utilisable agricultural land area in Ireland (DAFM, 2015c), compared to 20% of farmland farmed organically in Austria for example (FAO, 2014).

The future structure of Irish farming is open for interpretation and change as pushes to address challenges of fragmentation, achieve environmental sustainability, and harness economies of scale dominate national policy discussions. The potential exists for increased collaboration and partnership between farmers with aims of restructuring the Irish agricultural landscape, attracting younger farmers, and facilitating processes of succession and inheritance. Despite the national importance of agriculture in the country, however, Ireland is considered to be a small player in terms of global food production. For example, Leip et al. (2010) described Irish dairy farming as a low input, low output system. The average herd size in Ireland stands at approximately 60 cows, considerably lower than dairy competitors in New Zealand, Australia, and the USA (IFA, 2014). A reasonably static trend in recent years, herd size is expected to increase due the abolition of milk quotas (Clarke, 2014). Ireland produces 0.9% of the global milk supply, supplying just 5.5 billion litres of the 720 billion litres of milk produced annually (ICOS, 2015). Even with the abolition of milk quotas and the projected 50% increase in Irish milk output, Ireland will still only account for a little over 1% of the global milk supply. By comparison, Irish agriculture supplies approximately 10% of the infant milk powder used worldwide (Bord Bia, 2015a), highlighting the dominance of Irish ingredients in certain dairy sub-sectors. The importance of quota developments in a national context should not be underestimated given their direct and indirect economic benefits as well as wider environmental and social impacts (greenhouse gas emission production and increased labour demands on farm, for example). Reading of future agricultural opportunities should consider Ireland’s positioning within, and contribution to, global agriculture as a whole.
2.1.1.3. Economic Profile

2.1.1.3.1. Employment, Income, and Economic Sustainability

While difficult to disaggregate statistics for the agriculture sector specifically, according to DAFM (2015c) the agri-food sector accounted for 163,000 jobs in Ireland in 2014, 8.4% of total employment. Approximately 65% of these jobs (some 105,950) reside in the primary production sectors of agriculture, forestry, and fishing. Reflective of the significant multiplier effect inherent in the agri-food sector Enterprise Ireland (2009) further state that the sector accounts directly and indirectly for 1 in 8 jobs in the country, or 230,000 in total. This figure includes employment across farming, manufacturing, and distribution services making the agri-food sector the largest employer in Ireland.

The Teagasc National Farm Survey (n=80,000) reported an average family farm income of €26,974 in 2014 (Hennessy and Moran, 2014). Significant differences in income can be observed according to farm system, size, and employment status (full-time or part-time) across Ireland. Dairy farmer income, for example, has experienced substantial gains in recent years, increasing 31% in 2013 (DAFM, 2015c) and leading to the average dairy farmer in Ireland earning €68,887 (Hennessy and Moran, 2014). This compares to an average income of €14,551 on sheep farms and €10,271 on cattle rearing farms. The survey indicated that 40% of overall farms surveyed by Teagasc earned an income of less than €10,000 in 2014. This raises questions regarding the economic sustainability of some Irish farms, something that is mirrored in the fact that 51% of all farm households surveyed reported obtaining an off-farm income as an extra source of income. In addition, 30% of farmers also work off the farm. Due to the economic recession in Ireland, however, securing off-farm employment has become increasingly difficult for many farmers who typically seek jobs in construction-related industries. As such, off-farm employment rates have been in decline in recent years, dropping from 59% in 2006 to 49% in 2013. Longer term trends in farm income mapped by the Irish Farmers’ Association (IFA) Farm Income Review highlight the vulnerabilities of this income source to inflation: while national farm income appears to have remained relatively static at 97% of the rate recorded in 1994, in real terms with inflation taken into account 2014 figures are only 62% of the 1994 level (IFA, 2015). A lack of indexation consideration for inflation in the EU direct farm payments is largely responsible for this discrepancy and represents a threat to the future economic viability of Irish farms (IFA, 2015).
Additional concerns surrounding economic sustainability relate to the heavy reliance of Irish farming on subsidies from Europe and from other sources. This includes reliance on the Single Farm Payment (the largest component of farming subsidies in Ireland) as well as payments from the Disadvantaged Area Scheme, the Rural Environmental Protection Scheme, and the GLAS agri-environmental scheme which supports the provision of public goods by farmers. Although the average subsidy payment to farmers has been in slight decline since 2012, according to Hennessy and Moran (2014) the average direct payment per farm accounted for 70% of farm income in 2014, standing at €18,859. On some lesser earning cattle and sheep farms direct payments accounted for more than 100% of farm income. This contrasts with the dairy sector where subsidies represented just 25% of farm income (Hennessy and Moran, 2014). Unsurprisingly, differences in subsidy reliance are also reflected in the employment status of the farm, that is, whether it is a full-time or part-time engagement. In 2013 for example, of the 59% of farms surveyed that operated on a part-time basis, average direct payments accounted for 140% of the family farm income (DAFM, 2015c). This highlights the high reliance of these farms on external funding to cover production costs.

Such precarious economic conditions are further reflected in the fact that almost one third of farms in Ireland are considered economically vulnerable, with half of all farm households in the border region considered to be economically vulnerable (Hennessy and Moran, 2015). Nationally only 37% of Irish farms were classed as economically viable in 2014, meaning that the farm income was capable of remunerating family labour at the minimum agricultural wage as well as providing a 5% return on any capital invested in non-land assets. An additional 31% of farm households were considered to be economically sustainable but only as a result of the farmer or their spouse earning an off-farm income. The final 32% of farm households were classed as economically vulnerable, meaning that the farm business is not viable and no off-farm income exists. According to DAFM (2014b) about half of these economically vulnerable farm holders are aged 65 and over, perhaps transitioning from a period of active farming towards retirement and farm transfer. The number of vulnerable farms has not changed significantly over the last decade however, suggesting persisting challenges in the Irish agricultural sector. Such statistics highlight the intense vulnerability of those engaged in an agricultural career in Ireland, despite the importance and prestige awarded to agriculture in national policy and economic circles. As highlighted by Hennessy and Moran (2015) the picture is even more stark on consideration of the gaps that exist
between farming systems such that 80% of dairy farms are classed as viable compared to just 20% of cattle farms.

Assessing the market income of farms prior to subsidies, Hennessy and Moran (2014) revealed that cattle rearing, cattle finishing, and sheep systems had consistently negative market incomes between 2012 and 2014. There is a distinct geography to this economic sustainability also, with farms in the southeast considered to have the highest average income (approximately €40,000) and lowest reliance on subsidies. Farms in the border region are considered to be the most disadvantaged, with the lowest average income and highest reliance on subsidies (Hennessy and Moran, 2014). New agri-taxation review measures published in Budget 2015 nonetheless signal continued support for the Irish farming sector with aims to increase land mobility in the sector, aid farm succession, and complement wider agricultural policies relating to competitiveness and environmental sustainability. This includes twelve new taxation measures that provide income tax exemptions when leasing farm land, purchasing farm diesel, and investing in farm buildings for example, as well as a number of capital gains and stamp duty measures related to farm restructuring, retirement, and land transfers (DAFM, 2015c).

The maintenance of direct payments to farmers is considered vital by Phelan and O’Connell (2011) to safeguard the viability and growth of the agricultural sector in Ireland. They report that a drop of 20% in direct farm payments would result in a reduction in farm incomes of 9-39% depending on the farming system. It would also cause a fall in output in the cattle and sheep sector worth €450 million. This would result in an economy-wide loss of €780 million. While subsidies are secured for farmers up to 2020 under the latest wave of Common Agricultural Policy reforms, the Irish government is under pressure to state its position strongly in the next round of negotiations if the Irish farming sector is to achieve the growth targets set under Food Wise 2025 (DAFM, 2015b). Simply abolishing or even reducing payments is not an option if the desired growth in agricultural output and value is to be achieved, highlighting the dependence of both national and local livelihoods on international negotiations. If abolished, the vast majority of farms will cease to exist and farmers will have to seek out other sources of income and employment. The Agriculture and Food Development Authority, Teagasc, has been running an Options Programme since 2011, advising more than 500 family farms to date about their opportunities for off-farm employment and additional income generating activities. Such activities will also need to continue to secure future livelihoods in the agricultural sector.
2.1.1.3.2. National Contribution

The broader output multiplier effect of the agricultural sector must be acknowledged in terms of its contribution to the wider national economy. According to Phelan and O’Connell (2011) every €100 of agricultural output generates an additional €73 output in the wider Irish economy. This figure is 18% higher than the average economic impact of all other manufacturing sectors in Ireland. Agriculture also boasts a significant contribution to national income, generating €97 gross national product for every €100 of agricultural output. This can be partly attributed to the tendency of the agricultural sector to source most of its inputs domestically, reducing a dependence on imports. The import content of Irish agriculture is 24% lower than any other manufacturing sector in the Irish economy. Irish farmers spend approximately €4 billion annually on inputs with the vast majority of these purchased within 35 km of the farm gate (Phelan and O’Connell, 2011).

DAFM reports a public spend of €2.4 billion on the agri-food sector in 2014 including financing single farm payments, rural development schemes, and state bodies (DAFM, 2015b). Approximately €1.2 billion of this spend was obtained from EU sources. Private investment in agriculture is on the rise at farm level, with €867 million invested in the sector in 2014 across elements such as breeding stock, farm machinery, and farm buildings (DAFM, 2015c). This figure is up 99% on the total investment level recorded in 2010, bringing investment back to slightly higher than pre-recession levels recorded in 2006. Investment in agricultural machinery and equipment has been a significant driver behind these figures, up 149% from 2010 to 2015.

Finding new opportunities to add value in the agricultural sector will rely on appropriate innovation in the food supply chain, from increasing efficiencies on-farm to the development of novel foods and food ingredients (explored later in this report). Potential for further on-farm processing should also be explored to diversify farm activities and increase Irish farm income. Teagasc (2008) highlighted an example of a Canadian sunflower farm that produces insulin-bearing oils for use in injections for the management of diabetes, for example. The farm has its own processing plant and also provides products for the cosmetics industry. This type of multi-stream processing or bio-refining holds particular promise and potential for the development of the agricultural sector in Ireland’s future bioeconomy, developing multiple products and markets from every farm output. More traditional calls to increase support for artisan food and the direct selling of farm produce may also shape the future of Irish agriculture (Teagasc, 2012).
2.1.1.4. Inputs to the Agricultural Supply Chain

The cost of agricultural inputs has a significant effect on the overall viability of the Irish agricultural sector. In addition to impacting farm income it also affects the profitability of every agricultural output. Agricultural input costs (intermediate consumption) across the EU decreased by 3.6% in 2014 (DAFM, 2015c), primarily because of cost reductions in feed (down 8.1%), fertilisers (down 6.4%), and energy rates (down 3.9%). A knock-on effect was observed in Ireland with the overall cost of total inputs down 6.2% in 2014, largely driven by a reduction in animal feed prices (down 9.7%) and fertiliser costs (down 3.6%). This decrease follows a 2.7% rise in costs in 2012 which illustrates the fluctuating nature of the cost of farm inputs on an annual basis. Good weather conditions, for example, increase the volume of biomass and time available for grass grazing thus reducing feeding costs on livestock farms. Positive news regarding input costs in 2014 were slightly offset by a 2.6% drop in the value of gross output at farm level however, reducing the impact on farm profitability. Table 2 outlines the value of inputs and outputs at producer prices in Irish agriculture for 2014.

Key inputs in the Irish agricultural sector include animal feed, synthetic chemical fertilisers, and energy. Water and seeds are also crucial to everyday farm functioning. Overall trends

Table 2: Outputs and inputs of Irish agriculture 2014 (after DAFM (2015c))

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>% Change 2014 over 2013</th>
<th>Share of GO/inputs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross output at producer prices</td>
<td>7,057.1</td>
<td>-2.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Cattle and calves</td>
<td>2,010.6</td>
<td>-6.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Pigs</td>
<td>471.3</td>
<td>-0.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Sheep and Lambs</td>
<td>232.7</td>
<td>14.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Poultry</td>
<td>137.2</td>
<td>4.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Milk</td>
<td>2,088.9</td>
<td>0.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Cereals</td>
<td>233.8</td>
<td>-19.1</td>
<td>3.5</td>
</tr>
<tr>
<td>Potatoes</td>
<td>88.7</td>
<td>-46.1</td>
<td>-2.6</td>
</tr>
<tr>
<td>Fresh Vegetables and Fruit</td>
<td>262.4</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Forage Plants</td>
<td>1,127.9</td>
<td>-2.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Other</td>
<td>403.7</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Intermediate Consumption (Inputs)</td>
<td>5,358.1</td>
<td>-6.2</td>
<td>-2.6</td>
</tr>
<tr>
<td>Animal Feed</td>
<td>1,327.6</td>
<td>-17.6</td>
<td>-8.8</td>
</tr>
<tr>
<td>Fertilisers</td>
<td>565.6</td>
<td>-7.9</td>
<td>-5.4</td>
</tr>
<tr>
<td>Energy and Lubricants</td>
<td>495.9</td>
<td>-1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Maintenance and Repairs</td>
<td>496.6</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Forage Plants</td>
<td>1,109.8</td>
<td>-2.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Contract Work</td>
<td>406.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Others</td>
<td>982.8</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Gross value added at basic prices</td>
<td>2,073.6</td>
<td>9</td>
<td>25.4</td>
</tr>
</tbody>
</table>
related to these inputs are explored below drawing on past trends as well as the most recent available data for Irish agricultural practices.

2.1.1.4.1. Feed

“*Ireland’s extensive, low-input, grass-based production systems are the foundation of our green credentials*” (Government of Ireland, 2012)

Feeding stuffs constitute the largest proportion of input costs on Irish farms, accounting for over one quarter of intermediate consumption in the sector (DAFM, 2015c). The volume, cost, and composition of feed varies considerably according to animal type, farm system, time of year, and feed manufacturer (Garnett, 2007). The prevalence of low input, low cost, grass-based grazing systems represents a distinct advantage for Irish agriculture, reducing the cost of animal feeding compared to other European member states (Government of Ireland, 2012). In addition the volume of compound feeding stuffs used in Ireland is in decline in recent years, totalling 4.072 million tonnes in 2014. The cost of feeding stuffs aside from grass is highly volatile however, and influenced by a number of external factors. The volume required is highly weather dependent, given the reliance on grass-based systems particularly in the beef and dairy sectors. The ability of ruminants to consume low energy-value fibrous foods allows for a diet that largely consists of fresh grass and silage although this is sometimes supplemented with prepared animal feed. Based on UK statistics, Garnett (2007) noted differences between the feeding patterns of dairy cattle and cattle that is raised for beef: dairy cattle are estimated to consume 20-22 kg of dry matter every day with a slightly above-average yielding dairy cow consuming approximately 7.3 tonnes of dry matter a year. While grass represents the most economical way of supplying this feed, Garnett (2007) emphasised a need for more concentrated nutrition to fully satisfy the animal’s metabolic requirements, particularly in higher yielding cows (a category that is on the rise due to increased selective breeding in the Irish dairy herd for high genetic merit animals). In the UK approximately one sixth of a dairy cow’s diet is estimated to come from concentrates and compound feed with the remaining six tonnes deriving from fresh forage and silage. By comparison, cattle reared for beef consume a largely grass-based diet in their formative year with this diet supplemented with compound feeds in fattening and finishing stages; the absolute volumes utilised are influenced by the intensity of finisher practices (Garnett, 2007). In Ireland weather patterns exert significant influence on the volume of prepared feeding stuffs required on farm, impacting annual grass growth rates in particular. By contrast, pigs and poultry
demonstrate a high reliance on prepared animal feed that contains a large proportion of cereals, sometimes as much as 60% (Garnett, 2007). Wheat and barley typically make up a high proportion (approximately 37%) of the total weight of prepared animal feed, with oilseed cake often accounting for a further 24.5% (Garnett, 2007). This composition can vary considerably according to the time of year and feed manufacturer, however. In Ireland, pig and poultry feed is largely imported which exposes this agricultural input to international conditions and prices fluctuations. The cost of this feeding stuff is particularly vulnerable to fluctuations in global cereal markets.

As a result of these factors the cost of feeding stuffs in the Irish agricultural supply chain has been in a constant state of flux in recent years, influenced by rainfall patterns, overall weather conditions, and global cereal harvests. Donnellan et al. (2014) highlighted how cattle feed prices have been fluctuating since 2007 (Figure 3). Fluctuations can also occur in terms of the volume of feed utilised per farm per year, with particularly high volumes of feed necessary in 2012 and 2013 due to adverse weather conditions. This increases input costs for Irish farmers. Better weather conditions in 2014 led to an estimated drop in feed use in the dairy sector by 15%. Coupled with falling cattle feed prices, Donnellan et al. (2014) thus estimated that a 22% reduction in dairy feed expenditure occurred in 2014.

Pig feeding costs have been even more volatile in recent history given the heavy reliance on imported feed in the Irish pig sector (Figure 4). Prices spiked significantly in 2013 due to poor global wheat and maize harvests. Despite some decline in prices in 2014, current pig feed prices are still at one of the highest rates in over 20 years. Depending on international harvests and competing feed demand from other countries, Donnellan et al. (2014) expected a

![Figure 3: Cattle feed prices 2007-2015 (after Donnellan et al. (2014))](attachment:image.png)
further increase in pig feed cost of 3% in 2015. Given that feed represents the largest input cost in the pig sector, accounting for approximately 75% of input costs, such fluctuations and high prices have considerable impact on the profitability of this sub-sector of Irish agriculture.

Efforts to promote grass-based feeding in Ireland remain a focus throughout industry and policy circles to achieve more economically and environmentally sustainable agriculture in Ireland. The grass-based systems form the heart of Ireland’s clean, ‘green’ image and mooted reputation for sustainable food production. As such, its features and credentials are enthusiastically promoted in the most recently published strategy for agriculture, Food Wise 2025 (DAFM, 2015b). In addition, organisations such as Teagasc continue to focus a large proportion of their research on the development of more efficient grass-based farming systems, practices, and technologies. For example, Teagasc have proposed a two tonne challenge to farmers to increase the utilisation of grass in feeding by two tonnes per hectare. It is envisaged that such a strategy could help to meet the expanding feed needs of the dairy industry in a sustainable way following the abolition of milk quotas in 2015. From an economic perspective this would also increase farm profits with each additional tonne of grass utilised estimated to increase profit by €161 per hectare per year (Teagasc, 2015b).

Further processing of grass into hay and silage provides additional low-cost feedstock for Irish farmers, particularly in the winter months. Silage production involves the controlled fermentation of cut grass while hay making relies on processes of dehydration. The latter is thus more weather dependent, requiring long periods of dry, warm, and breezy weather for optimal hay production (Kilroy, 2014). This has led to an increased transition to the use of

![Figure 4: Pig feed prices 1992-2014 (after Donnellan et al. (2014))](image-url)
silage on Irish farms of late, particularly for cattle. Though more expensive to produce, silage has a higher nutritional value than hay, with grass for silage cut at times when the grass is at its most digestible as opposed to the more mature grass that is utilised for hay. Additives are commonly used to assist the fermentation process in silage production, including enzyme products and bacterial inoculants. The most common method of grass conservation, it is estimated that silage accounts for 83% of the forage conserved in Ireland as opposed to just 16% conserved as hay (Rath and Peel, 2005). This figure has increased from silage constituting approximately 45% of conserved grass in the 1970s.

Zero-grazing practices have yet to become commonplace on Irish farms, with preferences for open range grazing where animals obtain minerals and water in open fields throughout the day. This compares to zero-grazing practices in other European countries whereby the grass is cut by the farmer and brought inside to the animals as feed (O’Kiely, 2015). Purported benefits of zero-grazing include increased control over the nutritional value of feed, increased control over the quantities eaten by farm animals, and access to fresh grass during wet seasons or from far away fields (O’Kiely, 2015; Alltech, 2014). More recently, zero-grazing has been praised for increasing farmer capacity to meet environmental regulations such as the Nitrates Action Programme which limits the use of open pasture to prevent nitrate and phosphorus run-off from manure (Alltech, 2014), and enables a higher milk yield per cow as a result of increased control over nutrient intake. Potential utilisation of zero-grazing methods may prove increasingly popular on Irish farms in the future, for example to enable better management techniques for farmers to achieve the two tonne challenge proposed by Teagasc (2015b). It is nonetheless a higher cost feeding system compared to conventional grazing and also requires greater volumes of slurry to be spread, issues which may limit its potential in the future of Irish agriculture.

Additional future opportunities also exist in the feed sector to promote and develop trading relationships between tillage and livestock farmers in Ireland. Food Harvest 2020 specifically established aims to promote farm-to-farm sales of grain to simultaneously provide an alternative feed market for cereal growers and reduce costs for animal feeders (DAFF, 2010a). This is a keen focus and interest of the IFA with mutual benefit for all parties involved, in particular to reduce the costs of feed input in Irish agriculture.
2.1.1.4.2. Synthetic Chemicals

Soil fertility represents an important issue in Ireland, fostering the need for the thorough and targeted use of fertilisers and soil improvers in Irish agriculture. Of 36,000 soil samples analysed by Teagasc in 2014, 90% were classed as sub-optimal in performance regarding the level of soil pH, nitrogen (N), phosphorous (P), and potassium (K) content, essential minerals for fertile, productive soils (Teagasc, 2015b). Given that “soil fertility is a key determinant of productivity on our pastures, tillage, and horticulture crops” (O’Mara, 2015), a lack of these nutrients can lead to a loss of productivity as high as €30,000 on an average Irish dairy farm (Teagasc, 2015b). Efforts to increase the fertility of Irish soils thus predominate across agriculture sub-sectors in Ireland. While land management techniques are also necessary in this practice, such as introducing drainage solutions and managing livestock grazing patterns, the application of synthetic chemicals has become commonplace across the Irish agricultural sector to improve the quality of soil. Different types and volumes of synthetic chemicals are applied across different farming systems: beef farming is typically classed as an extensive low input system for example, compared to dairy farming that utilises more synthetic chemicals, particularly nitrogen to encourage grass growth as part of an intensive high input system (Lalor et al., 2010).

As a whole, the EU reduced the use of nitrogen and phosphate fertilisers from 116 to 109 kg ha\(^{-1}\) between 2002 and 2010 (FAO, 2014). At a national scale, Ireland was highlighted as exhibiting the heaviest fertiliser use in the EU while the EU as a region was highlighted as applying the highest volume of fertilisers in the world (FAO, 2014). Ireland is reported to have used 393 kg of nitrogen and phosphate per hectare in 2009 (FAO, 2014). An additional 82.6 kg of potash (potassium-based fertiliser) was also used on Irish soils in 2009 (FAO, 2014), reflecting the fact that 75% of Irish soils have a low potassium content (Gouldings, 2015). Such results are prevalent despite the national Irish image of abundant fertile soils and naturally productive lands (Government of Ireland, 2012) and overall declines in NPK fertiliser use in Ireland from 1995 onwards (Lalor, 2010). Lalor (2010) reported decreases in nitrogen use (-20%), phosphorous use (-40%), and potassium use (-37%) in Irish agriculture between 2003 and 2008, attributing this to improved slurry application, high fertiliser prices, low farm incomes, and the impact of environmental regulations. More recently, Donnellan et al. (2014) highlighted further changes in the volume of fertiliser purchased in Ireland, with sales of NPK fertilisers fluctuating in the period post 2008 (Figure 5). Particularly elevated levels are noted in 2013 due to the fodder crisis that resulted in increased fertiliser application.
by farmers in an effort to bolster grass supplies and rebuild silage stocks; improved weather conditions in 2014 led to a 14% decrease in fertiliser expenditure in the dairy sector. In monetary terms, DAFM (2015c) reports an overall spend of €565.6 million on fertilisers in 2014, with a decrease in consumption of NPK fertilisers of 5.8% in 2014. With rising prices of petroleum-based chemicals, however, fertiliser costs are expected to increase for Irish farmers by 7% in 2015 (Donnellan et al., 2015); this lends weight to the argument calling for the development of sustainable, bio-based alternatives to minimise input costs in the future of Irish agriculture.

The use of pesticides and veterinary medicines must also be considered synthetic chemical inputs in Irish agriculture, though the FAO (2014) noted that statistics relating to their use are often lacking or incomplete. An overall decrease in pesticide use has been observed throughout western Europe in the past decade (FAO, 2014). The heaviest highlighted user of pesticides is Israel at 16 kg ha\(^{-1}\); this compares with reported pesticide use in Ireland of approximately 2 kg ha\(^{-1}\) in the period 2005-2009, a figure that is more in line with European counterparts (for example, France (3.3 kg ha\(^{-1}\) in 2010) and the UK (2.8 kg ha\(^{-1}\) in 2010)). The use of antibiotics in agriculture has long been debated and often causes controversy in consumer, health, and environmental circles. This controversy particularly stems from the use of antibiotics as a preventative measure to reduce the risk of disease, even in healthy herds (Michail, 2015). A number of campaigns have emerged opposing the use of antibiotics as a routine, preventative input and instead propose better animal health be achieved by keeping them in less intensive conditions. Retailers have a part to play in implementing such measures by agreeing to pay higher prices to producers to maintain higher welfare standards.

Figure 5: Sale of NPK fertiliser in Ireland 2004-2014 (after Donnellan et al. (2014))
(Michail, 2015). Some countries are already voluntarily cutting their antibiotic use in farming, with Danish pig production curbing its use by 13% between 2009 and 2013, for example (Michail, 2015). In the UK however, an increase in the use of antibiotics from 384 tonnes in 2008 to 420 tonnes in 2013 has been reported (Michail, 2015). In Ireland, DAFM (2015c) highlights the important role played by veterinary medicines and vaccines in ensuring the health of Ireland’s farm animal population. The report also emphasises the importance of effective and up-to-date regulations in ensuring the sole use of authorised medicines in the country and in tracing the final concentrations of residues. The National Food Residue Database operated by Teagasc represents a distinct success in this regard, acting as an important tool which monitors and communicates about the safety of Irish food. Containing data derived from annual chemical residue monitoring programmes, the presence of veterinary drugs, pesticides, heavy metals, prohibited substances, nitrates, and other chemical contaminants is closely monitored. Results can be used to boost consumer and industry confidence in the safety of Irish food despite the use of synthetic chemicals in Irish agriculture (NFRD, 2015).

The use of synthetic chemicals has become and will continue to be part of the modern agricultural landscape. Their use is often cited as critical to increase yields, protect produce, and secure income for farmers (FAO, 2014). Excessive use poses risks to both human and environmental health however (FAO, 2014), with effective regulation of this agricultural input at local, national, and international scales crucial for their safe and sustainable use into the future. Agricultural practices are generally moving towards a reduction in the use of synthetic chemical inputs from health and environmental standpoints. From a policy stance, Food Harvest 2020 highlighted specific aims to increase the targeted use of slurry in Irish agriculture, noting both economic and environmental benefits in reducing overall fertiliser costs and impact, particularly when undertaken in collaboration with pig or poultry producers (DAFF, 2010a). Reporting progress on this target, farm survey data obtained by Teagasc indicated an increase in the percentage of slurry applied in spring from 34% in 2003 up to 52% in 2009 (DAFM, 2014c). Teagasc also actively encourages and advises farmers on the targeted use of fertilisers to ensure that every kilogram of fertiliser utilised delivers maximum return (Wall et al., 2015). The importance of taking soil samples and utilising results to develop targeted fertiliser and lime applications is particularly emphasised by the authority with significant potential in this area to boost productivity.
2.1.1.4.3. Water

At a global level, over two thirds of freshwater withdrawn for human use is utilised in agriculture (FAO, 2014). Ever-increasing demands are being placed on this natural resource as agriculture continues to intensify, globalise, and move into more arid regions which need artificial irrigation for production. Irrigated crops provide 40% of the total cereal harvest worldwide, with rapid expansion of agricultural irrigation in developing countries seen in the last decade in particular (FAO, 2014). These practices raise concerns for water scarcity, salinisation, and overall security. Agricultural practices can also have a negative impact on water supplies from a pollution perspective with the potential for contamination and eutrophication of freshwater due to agricultural run-off. A number of regulations have emerged in recent decades to manage this environmental impact at both an international and national level. The FAO additionally highlights the need for technology and tools to track the impact of agriculture on the environment as well as the necessity for research to develop more sustainable production systems that limit damage to the environment (FAO, 2014).

Ireland as a nation holds a comparative advantage regarding water availability with multiple reports alluding to the plentiful supply available here (Government of Ireland, 2012; Dowling et al., 2009). With an average rainfall of 1,936 mm year\(^{-1}\) between 2000 and 2010, the temperate Irish climate facilitates a rain-fed agricultural sector (DAFM, 2015d) with a limited need for irrigation beyond greenhouse production methods. Such a rain-fed system classifies the majority of water use in the Irish agricultural supply chain as a naturally available “green water”, defined as the “fraction of rainfall that infiltrates into the soil and is available to plants” (Ringersma et al., 2003). This is perceived to be more sustainable and efficient than “blue water” systems that rely on manually abstracting water that has reached river systems through deep drainage groundwater or directly as runoff (Ringersma et al., 2003). According to Ringersma et al. (2003), 16% of global rainwater is utilised via green water systems in the maintenance of grasslands with a further 7% used for crops. A study jointly undertaken by Bord Bia and Cranfield University highlighted that less than 2% of the total water consumed in Irish beef and dairy production is abstracted blue water (Hess et al., 2012). The Government of Ireland (2012) nonetheless point to the need to support wider water conservation in light of growing populations, water conflicts elsewhere in the world, the need to support an increasing number of industries, and attract foreign direct investment to Ireland.

Water use in the Irish dairy and beef sectors, the most dominant forms of agriculture in Ireland, was reported to be approximately 148 billion litres per year (DEHLG, 2004). Water
use in the dairy sector per head of cow is almost double that of the beef sector, averaging 92 litres per head per day for dairy cattle compared to 54 litres per head per day in the beef sector (DEHLG, 2004). Extrapolating these figures to 2014, when the Irish agricultural system supported a total of 6,926,000 cattle (CSO, 2014) of which 1,100,000 were dairy cattle (ICOS, 2015) it can be estimated that Irish beef production farms consumed over 314 million litres of water every day while the dairy sector consumed over 100 million litres each day. On an annual basis, this equates to over 151 billion litres consumed by Irish beef and dairy farms alone.

Beyond water availability and security, issues of water quality tend to dominate any discussion of water use in the Irish agricultural sector (Dowling et al., 2009) with agriculture responsible for much of the negative environmental impact evident in the national waterways. Wastewater management on-farm has become an increasingly important issue in recent years with a number of environmental policy measures introduced in an attempt to regulate this arena. The European-led Nitrates Directive (91/676/EEC) focuses on reducing water pollution caused by nitrate run-off from farms and led to the establishment of Ireland’s Nitrates Action Programme, for example. This programme promotes best practice amongst farmers concerning the application of phosphorus or nitrogen on-farm, the storage of manure, and minimum set-back distances from water sources. The Agricultural Catchments Programme, operated by Teagasc and funded by DAFM, works with 300 farmers across the country to provide a scientific assessment of the effectiveness of the National Action Programme as well as acting as a national focal point for technology transfer and education of farmers. In addition, DAFF (2009a) highlighted the potential for “green agriculture-based technology to improve water quality” in the country. This includes the implementation of low cost, low management remediation technologies such as permeable reactive barriers, buffer strips, or biological materials on farms to treat surfacewater and agricultural run-off (DAFF, 2009a).

2.1.1.4.4. Other Farm Inputs

According to Donnellan et al. (2014) seed costs remain a relatively small component of overall input costs on cereal farms in Ireland, accounting for just 5% of overall farm costs in 2013. A decrease in seed costs in 2014 of approximately 20% therefore had a limited impact on overall farm profitability. Developing a domestic supply of seeds both for use in Irish agriculture and for export to Europe formed a specific recommendation in Food Harvest 2020
Among other reasons, biosecurity issues related to the potential importing of diseases that could occur when importing foreign seeds represents one potential explanation for this strategy.

Similarly, the energy costs associated with Irish agriculture are deemed to be less influential in economic terms compared to feed and fertiliser input costs. Donnellan et al. (2014) reported that energy and fuel represent less than 10% of the total costs on Irish dairy farms, with electricity accounting for 30% of this figure and motor fuel the remaining 70%. Monforti-Ferrario et al. (2015) report that direct energy consumption in the EU agricultural sector represented just 2.2% of the EU’s final energy consumption in 2013, a particularly striking statistic compared to the 70% of global freshwater consumed by the agricultural sector. It was estimated that 23.9 Mtoe of energy were consumed for agricultural purposes with the vast majority of this energy deriving from non-renewable fossil fuel sources. While the use of renewable energy sources in agriculture has been steadily increasing since 1990, oil and gas still account for almost 70% of the direct energy mix in EU agriculture with renewables only constituting 8%. Drawing on EuroStat data, Monforti-Ferrario et al. (2015) report that agriculture in Ireland utilised less than 0.25 Mtoe of energy in 2013 with over 70% of the Irish agricultural energy mix deriving from oil.

As with other agricultural inputs, however, energy use varies according to farming system. More energy is generally consumed on Irish dairy farms compared to beef farms to power milking parlours. Evaluating an energy audit of three research farms over a 30 week period, Upton et al. (2010) estimated that electricity usage on Irish dairy farms contributes an average of 60c litre⁻¹ to milk production costs. Levels of electricity consumed per dairy cow meanwhile ranged from 4 kWh cow⁻¹ week⁻¹ to 7.3 kWh cow⁻¹ week⁻¹, the equivalent of €0.60 to €1.10 per cow per week. The majority of this electricity is consumed in milk cooling processes (approximately 37% of energy use on-farm) followed by water heating (approximately 31%), vacuum pumps (approximately 19%), and lighting (10%) (Upton et al., 2010). Suggestions for more efficient energy consumption include alterations to plate cooling infrastructure, eliminating hot water leaks, and using energy efficient lighting. By comparison, energy use on tillage farms primarily relates to the diesel utilised in machinery for ploughing, sowing, spraying, and harvesting activities which consume upwards of 8 litres ha⁻¹. This was estimated to cost an average €8 per hectare of tillage in Ireland in 2013 (Coughlan, 2013). Such diversity in energy usage in Irish farming has implications when considering the use of non-fossil energy sources in the future which will require different
infrastructural investment, ranging from solar panels on milking parlours to the use of biodiesel in tractors.

Direct energy consumption per cultivated hectare has been decreasing since 1990, suggesting an overall trend towards more efficient agricultural production in the EU (Monforti-Ferrario et al., 2015). These figures mask levels of indirect energy consumption in the sector, however. A UK study found that between 2003 and 2007 agricultural practices in the UK consumed almost three times more energy indirectly than directly (DEFRA, 2008), results that hold relevance in an Irish context. Energy used directly by the agricultural industry for heating, lighting, and power for example accounted for approximately 0.5% of overall UK energy consumption while energy used indirectly in the production of fertilisers, pesticides, animal feed, and machinery, for example, accounted for 1.4% (DEFRA, 2008). According to Monforti-Ferrario et al. (2015) however, no exhaustive study of direct and indirect energy use in agriculture is available at the European level. National-level studies have highlighted the significant contribution of indirect energy consumption in different types of farming. Levels of indirect energy consumption can thus be assumed to increase the overall figure for agricultural energy use in Ireland, perhaps more than doubling it as seen in the UK data.

Broadly speaking, an overall rise in the cost of agricultural inputs was noted by DAFM (2014c) when reporting progress on the Food Harvest 2020 milestones, with particular mention of sharp rises in energy prices since 2010: the report describes how energy costs increased by 34% for Irish farmers between 2010 and 2014. DAFM (2014b) praised the Irish agricultural sector for still meeting the growth objectives laid out in Food Harvest 2020 and increasing the value of primary production by 33% despite these cost increases. Analysis of the forestry sector by DAFM (2015d) similarly reports a stark increase in energy prices of late, a rise of approximately 50% between 2005 and 2012, highlighting the risk this poses to farm viability in Ireland. DAFM (2015c) reports that while the price of all energy products decreased by 2.7% in 2014 in the agricultural sector, including a fall of 4.7% in electricity prices, the cost of motor fuel increased by 3.6%. The variations in energy prices will therefore impact differently across the farming sector. It will be negated by further rises in energy costs as the era of cheap petroleum-based energy increasingly comes to an end. The need to find alternative and renewable resources is thus paramount for the future viability of all industrial sectors including agriculture, and represents a significant driver for the development of Ireland’s future bioeconomy.
2.1.2 Forestry Resources

2.1.2.1. The Importance and Relevance of the Forestry Sector in Ireland

Traditionally in Ireland forestry was regarded by farmers as a land use of last resort and other than in exceptional cases was reserved for land parcels that were regarded as being marginal for use for productive agriculture (Forestry Focus, 2015a). Currently just over 10% of the total land area of Ireland is devoted to forestry (Figure 6) with 731,650 ha divided between state (54%) and private ownership (DAFM, 2014d). Although forestry levels are at their highest in 350 years (DAFM, 2014d), the EU average is 38% (DAFM, 2015d) and annual afforestation in Ireland has decreased from over 14,000 ha in 2000 to just over 7,000 ha (DAFM, 2013a). Bacon (2003) observed that in order to reach a scale of timber production large enough to support a range of processing industries, the national forest estate would need to increase to 1.2 million ha (17% of total land area) by 2030 which would require afforestation on an annual basis in excess of 25,000 ha.

DAFM (2014d) reported that since 1980, 83% of forestry has been planted by farmers on privately-owned land due largely to the introduction of grant aid schemes to encourage

Figure 6: Ireland’s forest estate in 2014 (after DAFM (2014d))
Table 3: Potential profit achievable from beef, sheep, and forestry production in Ireland (after Teagasc Specialist Service (2015) and Hennessy and Moran (2014))

<table>
<thead>
<tr>
<th></th>
<th>Net profit excluding premiums</th>
<th>Annual forest premium</th>
<th>Single farm payment</th>
<th>Total premiums</th>
<th>Net profit including premiums</th>
<th>Retained premiums (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beef</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suckling to weanling/store</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top third</td>
<td>241</td>
<td>-</td>
<td>-</td>
<td>511</td>
<td>752</td>
<td>147</td>
</tr>
<tr>
<td>Average</td>
<td>-72</td>
<td>-</td>
<td>-</td>
<td>472</td>
<td>400</td>
<td>85</td>
</tr>
<tr>
<td><strong>Sheep</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-breeding farms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top third</td>
<td>463</td>
<td>-</td>
<td>-</td>
<td>607</td>
<td>1,070</td>
<td>176</td>
</tr>
<tr>
<td>Average</td>
<td>44</td>
<td>-</td>
<td>-</td>
<td>517</td>
<td>561</td>
<td>108</td>
</tr>
<tr>
<td>Lowland Sheep</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top third</td>
<td>335</td>
<td>-</td>
<td>-</td>
<td>479</td>
<td>814</td>
<td>170</td>
</tr>
<tr>
<td>Average</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>418</td>
<td>453</td>
<td>108</td>
</tr>
<tr>
<td><strong>Forestry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conifer</td>
<td>440</td>
<td>265*</td>
<td>-</td>
<td>705</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Broadleaf</td>
<td>575</td>
<td>265*</td>
<td>-</td>
<td>840</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

* average across the three farming systems as per the Teagasc National Farm Survey 2014

reforestation. Afforestation in Ireland is largely driven by the availability of grant and premium supports and their relativity to other farm schemes, to agricultural commodity prices, and expectations in relation to the evolution of the Common Agricultural Policy (CAP) (DAFM, 2013a). Diversifying into forestry provides great income potential compared with beef and sheep production according to reports by Teagasc (Teagasc Specialist Service, 2015; Hennessy and Moran, 2014) (Table 3). The new Forestry Programme introduces schemes supporting agro-forestry and forestry for fibre with single rate grants both for private and farmer investors.

It is to be expected that the introduction of a single rate premium will attract private sector interest and investment (DAFM, 2015e). The planting targets for these schemes are outlined in Table 4. Increasing forestry has a number of associated objectives including contributing to climate change mitigation, producing commercial timber, providing a sustainable source of roundwood for wood product manufacture, providing biomass for energy production, providing sustainable jobs in rural areas, and improving water quality and woodland biodiversity (DAFM, 2015d). The second National Forest Inventory reported that Irish forests contained over 380 million tonnes of carbon in 2012 (DAFM, 2013b), equivalent to 24 times the greenhouse emissions that occurred in the same year.
Table 4: Schedule of plantings to 2020 (after DAFM (2015e))

<table>
<thead>
<tr>
<th>Programme Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Afforestation</strong></td>
<td>5,440</td>
<td>5,990</td>
<td>6,165</td>
<td>6,215</td>
<td>6,615</td>
<td>6,790</td>
<td>37,215</td>
</tr>
<tr>
<td><strong>NeighbourWood Scheme Establishment</strong></td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>2,700</td>
</tr>
<tr>
<td><strong>Agro Forestry</strong></td>
<td>10</td>
<td>20</td>
<td>25</td>
<td>40</td>
<td>50</td>
<td>50</td>
<td>195</td>
</tr>
<tr>
<td><strong>Forestry for Fibre</strong></td>
<td>100</td>
<td>200</td>
<td>500</td>
<td>500</td>
<td>1,000</td>
<td>1,000</td>
<td>3,300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>43,410</td>
</tr>
</tbody>
</table>

Conifers make up the majority of standing stock with conifer forests accounting for almost 69%, broadleaves for 17.5%, and mixed forestry for 14% of the stocked forest area (DAFM, 2014d). Sitka spruce is the most common species in forests in Ireland, occupying over 52% of the forest area (Table 5). DAFM (2014d) described it as a “mainstay in roundwood processing” as it has proven itself to be one of the most productive conifers in Ireland.

A very valuable part of the forest resource is the native woodlands sector which currently stands at approximately 100,000 ha, amounting to approximately 14% of total forest cover (Bullock and Hawe, 2014). Funding has been set aside for between 300 and 360 ha of native woodland conservation per annum as part of the new Forestry Programme. This measure includes support for public and private landowners and also for emergent native woodlands. It is estimated that if Ireland were to expand native woodlands to 25%, 50%, and 100% of

Table 5: Tree species composition in Ireland (after DAFM (2014d))

<table>
<thead>
<tr>
<th>Species</th>
<th>Area (ha)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitka spruce</td>
<td>334,560</td>
<td>52.4</td>
</tr>
<tr>
<td>Norway spruce</td>
<td>26,340</td>
<td>4.1</td>
</tr>
<tr>
<td>Scots pine</td>
<td>8,010</td>
<td>1.3</td>
</tr>
<tr>
<td>Other pine spp.</td>
<td>61,950</td>
<td>9.7</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>10,380</td>
<td>1.6</td>
</tr>
<tr>
<td>Larch species</td>
<td>27,740</td>
<td>4.4</td>
</tr>
<tr>
<td>Other conifers</td>
<td>3,850</td>
<td>0.6</td>
</tr>
<tr>
<td>Pedunculate and sessile oak</td>
<td>16,840</td>
<td>2.6</td>
</tr>
<tr>
<td>Beech</td>
<td>9,500</td>
<td>1.5</td>
</tr>
<tr>
<td>Ash</td>
<td>20,610</td>
<td>3.2</td>
</tr>
<tr>
<td>Sycamore</td>
<td>9,250</td>
<td>1.5</td>
</tr>
<tr>
<td>Birch spp.</td>
<td>37,370</td>
<td>5.9</td>
</tr>
<tr>
<td>Alder spp.</td>
<td>15,080</td>
<td>2.4</td>
</tr>
<tr>
<td>Other short living broadleaves</td>
<td>46,220</td>
<td>7.3</td>
</tr>
<tr>
<td>Other long living broadleaves</td>
<td>9,440</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>637,140</td>
<td>100</td>
</tr>
</tbody>
</table>
current total forest cover then the expected yield could be €274m, €436m, and €650 million respectively. These values are based on the benefits from increases in tourism and health, water quality and biodiversity, carbon storage and sequestration, and in the provision of timber and wood fuel (Table 6) (Bullock and Hawe, 2014).
<table>
<thead>
<tr>
<th></th>
<th>Amenity</th>
<th>Tourism</th>
<th>Health</th>
<th>Biodiversity*</th>
<th>Water/flood</th>
<th>Carbon</th>
<th>Wood products</th>
<th>Wood fuel</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Woodland</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best estimate</td>
<td>€35m</td>
<td>€50m</td>
<td>€2m</td>
<td>€30m</td>
<td>Slight</td>
<td>€2m</td>
<td>€0.5m</td>
<td>€3m</td>
<td>€102m</td>
</tr>
<tr>
<td>Upper estimate</td>
<td>€35m</td>
<td>€50m</td>
<td>€3m+</td>
<td>€40m</td>
<td>Slight</td>
<td>€8m</td>
<td>€1.4m</td>
<td>€6m</td>
<td>€143m</td>
</tr>
<tr>
<td>Possible future area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Scenario A (160,000 ha)</td>
<td>€65m</td>
<td>€60m</td>
<td>€4m</td>
<td>€60m</td>
<td>€3m</td>
<td>€45m</td>
<td>€25m</td>
<td>€12m</td>
<td>€274m</td>
</tr>
<tr>
<td>Scenario B (325,000 ha)</td>
<td>€120m</td>
<td>€70m</td>
<td>€6m</td>
<td>€70m</td>
<td>€6m</td>
<td>€90m</td>
<td>€50m</td>
<td>£24m</td>
<td>€436m</td>
</tr>
<tr>
<td>Scenario C (650,000 ha)</td>
<td>€150m*</td>
<td>€80m</td>
<td>€7m</td>
<td>€80m</td>
<td>€10m</td>
<td>€178m**</td>
<td>€100m***</td>
<td>€46m</td>
<td>€650m</td>
</tr>
</tbody>
</table>

Scenario A: expanding native woodlands to 25% of current total forest cover
Scenario B: expanding native woodlands to 50% of current total forest cover
Scenario C: expanding native woodlands to 100% of current total forest cover

* valued as a cultural ecosystem service only
* based on total forest amenity value of €236m, or a net €48m addition after displacement from conifer plantations.
** representing an average of values while increased area is in growing phase and excluding carbon storage value.
*** minimum roadside value after approximately 100 years, assuming that half the area is unharvested or contains lower value species
2.1.2.1.1. Environmental and Social Benefits of Forestry in Ireland

Forestry contributes significantly to rural development in Ireland in terms of diversification of farm income but also by being a significant rurally-distributed employer generating indirect employment in transport and maintenance, for example (DAFM, 2013a). Forestry also plays a significant role in Ireland beyond providing a revenue stream. Forests also bring a host of quantifiable benefits to national and local communities including the provision of services for visitors availing of the amenity, the benefits derived from carbon sequestration, the protection and promotion of biodiversity, wildlife conservation, environmental protection, and public health and well-being, as well as facilitating a wide variety of sporting activities (DAFM, 2013a). The amenity value has been estimated at €97 million which in turn generates €268 million in economic activities for communities in rural areas (COFORD, 2009). Annual visitor numbers to Irish forests are estimated to be 18 million (Coillte, 2014); the social aspect of forestry and its associated revenue is often overlooked.

Ireland’s forest sector is perfectly placed to make substantial contributions to Ireland’s future development in environmental, biodiversity, water quality, landscape, climate change mitigation, and renewable energy areas. Forests’ contribution to climate change mitigation through carbon sequestration forms an important element of the national climate change strategy (DAFM, 2013a). It has been estimated that Irish Kyoto-eligible forests will sequester about 4.8 million tonnes of carbon dioxide (CO₂) in 2020, representing between 40 and 60% of the distance to target (DAFM, 2013a). As well as increasing supply for the wood processing sector and contributing to job creation, increasing afforestation will support Ireland’s efforts to reach the demanding greenhouse gas emission reduction targets (which are anticipated to rise to 80% of the 1990 level by 2050) and will reduce dependence on fossil fuels and support the transition to a low carbon economy (DAFM, 2013a).

Recognising the important role played by forestry in carbon sequestration, water quality, biodiversity conservation, etc, a number of schemes have been introduced to certify the sustainability of wood production and processing. Two internationally recognised voluntary schemes are currently in operation in Ireland, the Forest Stewardship Council (FSC) scheme and the Programme for the Endorsement of Forest Certification scheme (PEFC). These schemes are in operation at all levels of the supply chain with a view to fostering best practice throughout while guaranteeing that forest products are produced having regard to the highest sustainable standards (Forestry Focus, 2015b). The National Forestry Standard, an
Irish standard applied by the Forest Service, is a means of measuring Ireland’s progress in the implementation of sustainable forest management. This standard ensures that sustainable forest management is achieved through the implementation of a Code of Best Forest Practice (Forestry Focus, 2015b). The FSC and PEFC certification schemes recognise the requirements of the National Forestry Standard but go beyond these to achieve higher levels of care for the environment and the social aspects of forestry. The FSC and PEFC standards are based on the principle of sustainable forest management and attempt to balance the economic, environmental, and social aspects of forestry; all aspects of forest management are covered by these schemes (Forestry Focus, 2015b). Forests seeking to comply with the FSC and PEFC standards are audited by independent professional auditors every five years; all aspects of the forest enterprise are measured against the requirements of the standard. In addition, sample audits are undertaken on an annual basis (Forestry Focus, 2015b).

A chain of custody system is also in place to facilitate the tracing of certified material from the forest through to final stage product to ensure that the wood, wood fibre, or non-wood material contained in the product or product line can be sourced to certified forests (Forestry Focus, 2015b). This system works on a global basis and to date PEFC has certified Chain of custody for over 16,000 companies worldwide. Central to the process is the establishment of verifiable sustainability of products from sustainably managed forests. Chain of custody certification begins at the forest gate and tracks the products’ progress through the various stages of transport, processing, storage, distribution, and eventually sale to the end user (Forestry Focus, 2015b).

In addition to the voluntary certification and standards in place in Ireland, the forestry and forest products sector is also controlled by the EU Timber Regulations. These regulations came into force in 2013 and have been introduced to eliminate the sale of illegally harvested timber in Europe and to reinforce the sustainable production of forestry (Teagasc, 2015c). Responsibility falls on each player in the supply chain to ensure the wood-based material they handle has been sourced legally and sustainably.

### 2.1.2.2. Structural Features

Irish forest ownership breaks down to approximately 46% of forestry held in private hands by in excess of 15,000 owners with the remaining 54% in public ownership, primarily by Coillte (DAFM, 2013a). The proportion of forests in private ownership has increased in recent times from 43% in 2006 to its current level (DAFM, 2014d). Private non-farmer investment in
afforestation has fallen significantly in recent years due to the high cost and limited availability of land coupled with a significant funding gap whereby farmers now receive on average three times more premium funding than non-farmers (DAFM, 2015e).

Ireland’s farm forest sector is characterised by a large number of small fragmented units. Between 1997 and 2002 forests greater than 20 hectares accounted for up to 40% of total planting annually whereas in recent years this has fallen to 16% of total planting. The average size of forests planted in recent years has reduced further to 6.5 ha (DAFM, 2014d). The 2011 National Farm Survey indicated an average ownership of over 11 ha per forest owner (Hennessy and Moran, 2012), although lesser average forest areas of 8 ha and 9 ha were found in farm forestry studies carried out in Clare and Cork respectively (Purser Tarleton Russell Ltd., 2009; 2004). Bacon (2003) highlighted the historical situation where forestry in Ireland has tended to be rather dispersed both geographically and in terms of the supporting services; Bacon (2003) also described the forestry sector as being in need of co-ordinated marketing efforts and the development of efficient supply chains. In a submission to the Consultation Paper on Forestry 2014-2020, Teagasc recommended that investments be made in forest technology and in particular in smaller scale technologies which may be more appropriate to the forest profile owned by private landowners (Teagasc, 2014a). Such technologies have the capacity to address the scale issues faced by many forest owners (Teagasc, 2014a). Coillte, which used to be the mainstay of the state afforestation programme, is now largely focused on reforestation. This has arisen because forestry-type land has become more expensive and is going into mainstream agriculture use with the consequence that less is available for forestry (Coillte, 2015). In addition, as the volume of timber harvested in Coillte’s forests increases, more Coillte-owned land is becoming available for restocking.

In 2010 the value of output from the forestry growing sector was estimated to be €673 million (Casey, 2013). Casey (2013) reported that although the demand for higher value timber for construction in the domestic market has fallen, the demand for forest-based biomass and firewood remains significant. In 2014 3.04 M m$^3$ of woody material (including firewood) was harvested in the Republic of Ireland, 85% of which was harvested by Coillte with the rest harvested from private forest sector (DAFM, 2015c). The forest-based industries sector in Ireland comprises the woodworking industries, the furniture industry, the pulp and paper manufacturing and converting industries, and the printing industry. The wood processing sector of the forest industry includes primary (sawmilling), secondary (panels), tertiary
(furniture and wood craft) (DAFF, 1996), and, more recently, wood energy including bioenergy and the specialities sector (including the wood biorefinery concept).

2.1.2.3. Economic Profile

The combined agri-food, forestry, and fisheries sector is a very valuable indigenous industry which in 2014 reached a record export value of almost €10.5 billion (DAFM, 2015f). The output of the forestry and forest products sector was estimated to be €2.3 billion, contributing 1.3% to Ireland’s GDP (IFFPA, 2015). The wood processing sector contributes significantly to the national economy and was reported as adding €701 million to overall gross value added (GVA) in 2013 (DAFM, 2015c). The wood processing sector in Ireland is primarily export-led; Ireland became a net exporter of sawn timber in 2010 for the first time since such records began in 1961 and exports have grown continuously since 2010 (Knaggs and O'Driscoll, 2014). In 2013 exports of forest products from the Republic of Ireland amounted to €339 million, a significant 12% increase on 2012 figures (Knaggs and O'Driscoll, 2014). The production of wood-based panels has shown continued growth in recent years, with an increase of 11% in exports in 2013 compared to 2012. 90% of manufactured output is exported, adding €199 million to the national economy (Knaggs and O'Driscoll, 2014). Two products, oriented strand board (OSB) and medium density fibre board (MDF), are key export lines produced for our most important export markets in the UK and the Benelux countries (IFFPA, 2015). On a European scale, despite the relatively healthy state of the sector, Ireland is highlighted by the European Commission as being one of the least specialised member states in the wood and wood products manufacturing sector (European Commission, 2013). Ample scope therefore exists to develop new products and new markets through research, development, and innovation.

The Irish forestry and forest products sector employs approximately 12,000 people, primarily in rural areas (IFFPA, 2015). There is scope to increase the scale of employment in forestry: it has been reported that an annual afforestation programme of 15,000 ha would create an average of 490 direct jobs (IFFPA, 2015). Most of these jobs would be in forest establishment, forest management, and timber harvesting and would be based in rural communities. The Irish government has a target of 17% afforestation by 2030, an undertaking which would require afforestation at a rate of 25,000 ha per year (IFFPA, 2015); this gives scope to significantly increase forestry employment.
DAFM described the sawmilling sector in Ireland as encompassing a large number of relatively small sawmills and a small number of medium- to large-sized mills. It has been estimated that 75% of all roundwood is processed by the five largest sawmills (DAFM, 2013a). The principal output from the sector is timber for the construction industry, pallets, and fencing products. Sawn timber exports comprise mainly pallet and fencing products. The wood-based panel industry is a key player in adding value to Irish wood fibre and in driving Irish exports, as outlined above. The three wood-based panel plants in the country provide direct employment for approximately 500 skilled personnel and indirectly provide employment in harvesting, transport, and ancillary services (DAFM, 2013a). The furniture and joinery sub-sector consists of approximately 300 firms, the vast majority of which are relatively small and employ less than ten people; a few medium-sized enterprises are also in operation. The timber used by the furniture and joinery industry is mainly imported, especially hardwood species (DAFM, 2013a).

2.1.2.4. Inputs in Forestry

2.1.2.4.1. Seeds

Selecting the right seed source has implications for the early growth and survival of plantations and on productivity and wood quality in later years (Forestry Focus, 2015c). Considering that the cost of seeds is only a small portion of the total cost of the establishment of a forest plantation there is little is to be gained and much to be lost through not using the best available seeds (Savill, 2003). Coillte has produced a reference table of recommended seed origins for use in Irish forests based on results from field trials conducted with a number of species over 30 years (Coillte Research & Development, 1994). Seed inputs for the production of planting stock in Irish forests are acquired from three main sources: seed stands, seed orchards, and imports from the species natural range.

Seed Stands

By eliminating poor genotypes from the seed-producing population pool, seed stands produce seeds which are well adapted to the Irish environment (Coillte Research & Development, 1994). Collecting seeds from these superior stands ensures that the genetic quality of the next generation will be as good as if not better than the original stand. Seed stand trees are generally of known parental seed origin, are healthy, show good growth rate, and have straight stems free of defects (Coillte Research & Development, 1994). Many of the stands
have been grown for one or two generations in Ireland from seeds that were originally collected in the species natural range. The main criteria for seed stand selection and the marketing of this material are outlined in EU Council Directive 1999/105/EC.

Seed Orchards

Seed orchards focus on producing seeds of superior genetic quality derived from material which has been bred as part of a dedicated breeding programme, and have a very important role to play in the future development and competitiveness of the industry (Forestry Focus, 2015c). The long term economic and biotic benefits from the improvement of tree species facilitated by seed orchards are well understood. Diseases, for example, have both direct and indirect effects on timber supply and demand including the cost of eradication/containment, the opportunity cost associated with suspending or restricting the planting of tree species, and the price effect on a diminishing supply of a particular species (Teagasc, 2014a). Improving the disease resistance of a species will therefore avoid a significant amount of this cost. Sourcing from Irish seed orchards also benefits the national exchequer as a whole by using a domestic product rather than importing material. Seed orchards in Ireland have traditionally been field-based with very significant establishment costs and tie up land for between 30 and 60 years (Teagasc, 2014a).

Seed/Plant Imports

Establishing a sustainable and secure supply of improved seeds is an important national goal. In the past, Ireland has had to rely on the importation of seeds from abroad, particularly for non-native tree species. Relying on imported seeds exposes the sector to biotic risks which can have associated economic risks (DAFM, 2015d). When one considers the length of the forest rotation the long term economic consequences of being unable to source the very best seeds has a negative impact on the viability, productivity, and profitability of the plantation (DAFM, 2015d). Importing a genetically poor species also has consequences for the genetic purity of the national stock as these trees have the potential to hybridise with native trees and then disperse genetically undesirable seeds (Douglas and Thomasset, 2013).

The national importance of Ireland’s forest genetic resource is acknowledged in the Forest Genetic Resources Reproductive Material measure of the Forestry Programme 2014-2020 (DAFM, 2015e) which aims to support the conservation and development of the resource. These objectives will be achieved through the operation of the Seed Stand and Seed Orchard Scheme. The primary objectives of these schemes are to increase the resilience, productivity
and quality of Irish forests; increase self-sufficiency in tree seeds production; provide for in-situ and ex-situ conservation of forest genetic resources; and provide breeding populations of designated broadleaf species (e.g. birch, oak, and sycamore) (DAFM, 2015g). Only broadleaf seed stands registered on the National List of Basic Material will be funded under the Seed Stand and Seed Orchard Schemes while the establishment of new seed orchards may include both conifer and broadleaf species.

1.1.1.1.1. Chemicals in Forestry

Coillte (2016) describes how forests can survive the loss of a small number of trees to naturally-occurring diseases and pests. This natural resilience prevents the extensive use of chemical inputs in forestry, with the possible exception of pesticides used during establishment stages to prevent competition between young trees and weeds, though physical removal of competing plants is used as a primary mechanism of weed control. Where chemical pesticides are used, treatment is restricted to the area immediately surrounding the affected trees through the use of spot spraying (Coillte, 2016).

Generally speaking there is not much requirement for fertiliser in the forestry industry. Any requirement for fertiliser is best determined by undertaking an appropriate site assessment and soil analysis which takes into consideration site conditions and species selection (DAFM, 2000): broadleaf species tend to have higher nutrient requirements (Teagasc, 2015d). Teagasc have described how one or more applications of fertiliser will sometimes be required to stimulate growth and that all such applications should be done according to the Forestry and Water Quality Guidelines (DAFM, 2000) to ensure protection of waterways from fertiliser discharge (Teagasc, 2015d). The most important nutrient inputs in forestry are phosphorus, nitrogen, and potassium. Phosphorus is of critical importance from an early stage for good root development while nitrogen and potassium are important for photosynthesis. It is important to control competing weeds prior to the application of fertiliser to young trees to ensure that the trees rather than the weeds benefit from the nutrients (Teagasc, 2015d). Depending on the underlying conditions of the site, supplementary applications of fertiliser may be required to maintain growth (Teagasc, 2015d). The benefits of providing satisfactory nutrient levels are tangible and will help promote vigorous growth and a healthy crop, earlier establishment of the trees, a decrease in the period of risk from weed growth, frost, and vermin, and earlier canopy closure after which nutrient recycling can increase (Teagasc, 2015d).
2.1.1 Marine Resources

Taking the surrounding seabed territory into account Ireland is one of the largest EU states, with sovereign or exclusive rights to an area ten times greater than its land mass (Figure 7) (DAFM, 2012a). Ireland’s coastline, inshore, and offshore waters contain some of the largest and most valuable sea fisheries resources in Europe yet are often overlooked when considering domestic food production potential (DAFM, 2012a). Highlighting the importance of these resources, in 2012 the Department of Agriculture, Food and the Marine released a strategy document with the aim of taking account of all of the value held in Ireland’s ocean whether that be as a source of food, employment, renewable energy, etc. Harnessing Our Ocean Wealth represents an integrated marine co-ordination plan for Ireland to promote investment and enable growth and sets out a number of initiatives to expand and develop the potential held within marine resources. Included in this strategy document are new and innovative ways to obtain value from natural resources such as marine-derived functional foods and ingredients and bio-materials (DAFM, 2012a). Harnessing Our Ocean Wealth sets targets for Ireland to double the value of its ocean wealth to 2.4% of GDP by 2030 and to

Figure 7: Ireland's sea territory (after Marine Institute (2016))
increase the turnover from the ocean economy to greater than €6.4bn by 2020.

A number of government departments and state agencies have responsibility for Ireland’s marine territory given the wide range of functions and processes associated with this resource. Recognising the broad scope of the sector and the need for better coordination an Inter-Departmental Marine Coordination Group (MCG) was established in 2009. The MCG meets monthly to discuss matters which require inter-departmental activity and includes representatives from the Department of Agriculture, Food and the Marine, the Department of Transport, Tourism and Sport, and the Department of Defence among others (DAFM, 2012a).

2.1.1.1. Fisheries

The Irish fisheries industry consists generally of the primary production sectors of fish catching and aquaculture, the primary and secondary processing sectors, the marketing sectors and ancillary industries such as transport and maintenance. The fishing industry has three main elements: commercial sea fishing; aquaculture; and seafood processing. In 2013 the industry employed approximately 10,800 people; the industry is an important source of employment in rural areas (DAFM, 2014a). The total fleet in 2013 comprised 2,050 vessels with the vast majority of these considered multipurpose, targeting whitefish, pelagic species, and bivalve molluscs. Despite being targeted by just 1.5% of the fleet, pelagic species account for a significant portion of the total landings: over 215,000 tonnes of pelagic species were landed by Irish vessels compared with 34,000 tonnes of shellfish, the next highest landing (DAFM, 2014a).

Ireland has a number of significant fishing ports dispersed along the Atlantic seaboard and along the Irish Sea. Killybegs, in the north-west, is by far the largest fishing port in Ireland (SFPA, 2015) and is strongly dominated by the pelagic sector. The main pelagic species landed at Killybegs are mackerel, horse mackerel, blue whiting, boarfish, and herring.

2.1.1.2. Macro Algae

Seaweeds, also called macroalgae, are plant-like marine organisms that generally live attached to rock or other hard materials in coastal and maritime areas. In 2010 world seaweed production (almost exclusively from aquaculture) was 19.9 million tonnes of which Europe was only responsible for 0.4%; worldwide macroalgae production increases 5.7 % every year (Netalgae, 2016). Seaweed is considered to be one of Ireland’s most underutilised natural resources (O’Toole and Hynes, 2009). Ireland’s macroalgae industry is based primarily on the
Atlantic coast. Aquaculture of macroalgae is limited in Ireland with production in just two counties. Most recent information indicates that 70 tonnes were produced in 2015, approximately twice the output of the previous year (BIM, 2016).

Ireland’s marine biotechnology and bio-products sector including seaweed harvesting was reported to have an annual worth of €44.5 million in 2012 and according to FAO estimates, approximately 30,000 wet tonnes of seaweed were captured (Vega et al., 2015). *Ascophyllum nodosum* represents the most commercially important species at 25,000 tonnes (Walsh and Watson, 2011) with *Laminaria hyperborea* and miscellaneous red seaweeds also commercially important (Vega et al., 2015). The main markets for seaweed are food, industrial specialities, fertilisers, cosmetics, pharmaceuticals, and feed. *Ascophyllum*, for example, is used for the extraction of alginic acid, a polysaccharide used in foods and in biotechnology (Guiry, 2016a); alginate can also be extract from *Laminaria hyperborea* however this practice has ceased in Ireland in recent years (Guiry, 2016b).

The vast majority (80%) of enterprises involved in seaweed harvesting and processing are microenterprises with five or fewer employees. In 2012 it was estimated that the industry employed between 185 and 300 people and had a value of €18 million per annum (Walsh, 2012). Over 99% of raw material comes from the manual harvesting of natural seaweed resources, with most of the harvesting occurring along the coasts of Donegal, Sligo, Mayo, Galway, Kerry and Cork (BIM, 2011). *Ascophyllum nodosum*, the most important species in Ireland, is processed at two factories the west coast at Galway and Donegal (BIM, 2011). Currently the main outlets for macroalgal material in Ireland are agricultural and horticultural products; higher value-added products such as foodstuffs and cosmetics are produced at lower volumes (Walsh, 2012).

The Irish macroalgae industry is mainly focused on servicing the international agricultural, horticultural, and animal welfare markets with approximately 95% of production being directed into these markets; small quantities are processed for speciality products like cosmetics, pharmaceutical, nutraceutical, food and other applications. Ireland exports a significant quantity of domestic seaweed production either as raw material or as processed products (BIM, 2011). In their analysis of the Irish seaweed industry, O'Toole and Hynes (2009) identified a number of potential applications of seaweed across the full range of value addition including food, agricultural/horticultural, feeds (all considered low value), pharmaceutical, environmental, biomaterials/biopolymers and health and wellbeing (all considered to be higher value).
2.1.2 Energy Crops Resources

2.1.2.1 Purpose-Grown Energy Crops

Ireland’s agricultural land is primarily used for livestock production with just 8% of land used for crop, fruit, and horticulture production (DAFM, 2015a). This production extends to approximately 360,000 ha with most recent figures available from the Department of Agriculture, Food, and the Marine indicating that just over 3,300 ha are sown with crops grown specifically for the generation of renewable energy in Ireland (Alford, Y., pers. comm., June 2015). Crops such as Miscanthus and short rotation coppice (SRC) willow are largely used for the generation of heat and/or electricity. In Ireland the vast majority of the land sown with energy crops is used for Miscanthus production (2,414 ha) with willow accounting for the remaining area (939 ha) (Alford, Y., pers. comm., June 2015). Much of this planting has come about as a result of a series of grant aid schemes introduced to encourage energy crop production. The Bioenergy Scheme has been in existence since 2007 and has supported the successful establishment of 3,353 ha of energy crops to date by reimbursing a percentage of the establishment costs to the grower. The most recent iteration of the Bioenergy Scheme focuses on the cultivation of willow rather than Miscanthus, which is the more attractive energy crop for end users as willow has a lower chloride content than Miscanthus and its use during electricity generation therefore causes less corrosion on power plant hardware (Egan, 2015).

Miscanthus is grown on approximately 2,400 ha in Ireland; these plantations are located predominately in the east of the country with plantations in counties Kildare, Offaly, Westmeath, Laois, Wexford, and Kilkenny and a small number of plantings in counties Tipperary, Limerick, and Cork (SEAI, 2015a). Willow is grown much less extensively in Ireland with plantings focussed in counties Meath, Cavan, Wexford, and Kilkenny (SEAI, 2015a). The biomass material harvested from energy crop plantings in Ireland is primarily used for electricity or combined heat and electricity generation (Dineen et al., 2015). Using Miscanthus or willow for heat or electricity generation is relatively straightforward: once the crop has been harvested at the appropriate moisture content it can be pelletised, chipped, or baled depending on the end user’s requirements and the material is then combusted (Caslin et al., 2015a). Thermochemical conversion of biomass into heat can be used directly to heat water or air, or can be used to raise steam which is then used to drive a turbine to produce electricity (Caslin et al., 2015b).
Switchgrass and Reed Canary Grass can also be grown in Ireland for heat and/or electricity generation however levels of planting are very low. Although Reed Canary Grass is a native Irish grass species, most recent information available indicates that it is not grown in Ireland for energy usage (Finnan and Caslin, 2007a). Reed canary grass is currently grown on a small scale with holdings in counties Meath, Carlow, and Laois (SEAI, 2015a). Switchgrass is not native to Ireland, nor is it currently grown in Ireland for energy use, but research indicates that both it and Reed Canary Grass can be successfully grown in Ireland to produce pellets for heat generation (Finnan and Caslin, 2007a; b). Reed Canary Grass can be grown on marginal land and although yields may be lower than those associated with other energy crops (Finnan and Caslin, 2007a), its harvest can provide an additional source of income from otherwise unused land as it is very tolerant of flooding (Finnan and Caslin, 2007a). Lower yields are also reported with Switchgrass, however establishment costs are lower than for Miscanthus (Finnan and Caslin, 2007b) which supports the case for its growth as an energy crop in Ireland. There are a very small number of hectares of Switchgrass in Ireland, with plantings located in counties Offaly and Galway (SEAI, 2015a). Both Reed Canary Grass and Switchgrass are grown from seeds (Finnan and Caslin, 2007a; b), unlike Miscanthus and willow which are propagated from rhizomes and cuttings, respectively; this is another favourable attribute of these grasses over the more popular Miscanthus and willow. Currently there is no financial support scheme to grow these species for energy purposes, however, which may explain why Miscanthus and willow have become the dominant energy species grown in Ireland.

In 2011 the Sustainable Energy Authority of Ireland launched an online interactive Bioenergy Mapping System which provides information to users on the growth, supply, and demand of energy crop biomass in Ireland. In July 2015 this map indicated that there were 17 industrial users of biomass for heat or electricity generation in the Republic (SEAI, 2015a). Biomass for energy generation is used both at a ‘national supply’ scale and on a smaller ‘private supply’ scale. The SEAI Bioenergy Map indicates that Edenderry Power Station (Edenderry, Co. Offaly), Lough Ree Power Station (Lanesboro, Co. Longford), and West Offaly Power Station (Shannonbridge, Co. Offaly) all have a demand for energy crop biomass for heat and/or electricity generation. These power stations originally used locally-sourced peat for electricity generation, however as a result of recent legislative measures a combination of peat and renewable materials is co-fired. In 2013 239,000 tonnes of mixed biomass material was co-fired with peat at Edenderry Power Station (Bord na Móna, 2014); it has been
estimated that electricity production in 2015 will consume 300,000 tonnes of biomass (Egan, 2015).

Purpose-grown energy crops are also used by smaller-scale users in the commercial and private sectors for heat generation in biomass boilers. In 2013, 229 GWh of electricity were generated from solid biomass fuels and 202 Ktoe of heat were generated from solid biomass and renewable waste (Dineen et al., 2015). According to the SEAI Bioenergy Map, these users include five timber processing plants producing chipboard, medium density fibreboard, doors, and floors among other products and nine sawmills producing timber for the construction industry. The biomass consumed by these operations is used for heat generation to dry the timber products. A small number of district heating systems have also been established in Ireland whereby the heat produced is used for space and water heating of a number of nearby buildings. One such system, implemented in Gurteen Agricultural College in Co. Tipperary, uses willow grown on-site as feedstock and the heat produced is used to meet the heating demands of the college buildings as well as in the drying of chip for the boiler itself. Establishing a self-supply of fuel and converting to renewable energy has saved the college approximately €17,000 a year in heating costs and these savings have seen a payback period of just five years (Anon, 2015).

The EU Renewable Energy Directive (2009/28/EC) was introduced in 2009 and implemented in Ireland in 2011 (Dineen et al., 2015). The Renewable Energy Directive is the most recent of a number of measures introduced by the EU to encourage the use of renewable resources for the provision of energy. The Renewable Energy Directive legislates for the use of renewable sources in the generation of electrical, heat, and transport energy in Europe by setting inclusion targets for each member state. Under the obligations set out by the Renewable Energy Directive, renewable sources must provide at least 16% of the final energy demand in Ireland by 2020, a target which has further defined by the Irish Government into 40% of electrical energy demand, 12% of heat energy demand, and 10% of transport energy demand (Dineen et al., 2015). Energy from biomass has a key role to play in meeting the 2020 targets. The energy contained in biomass can be converted to either electrical or heat energy through thermochemical conversion, such as the co-firing of energy crops with peat for the provision of electricity, and the combustion of energy crops in combined heat and power generation from which both heat energy and electrical energy can be obtained.
Ireland has one major indigenous fossil fuel source: peat has been used for centralised electricity generation since the 1950s. There are three solid fuel power generation plants in Ireland which convert peat into electricity: Edenderry Power Station which is operated by Bord na Móna, Lough Ree Power Station which is operated by ESB, and West Offaly Power Station which is also operated by ESB. These power plants were originally sited according to the readily available supply of indigenous peat as a fuel source. Irish Government targets outlined in Delivering A Sustainable Energy Future for Ireland provide for the incorporation of renewable energy sources in electricity generation, and specifically for co-firing biomass with peat (DCMNR, 2007). To date, co-firing has been successfully implemented at Edenderry Power Station; some initial testing has been carried out at the other two plants but no co-firing has yet been implemented. This is one obvious avenue to expand the use of renewable energy in electricity generation as the Edenderry Power Station provides just 2.5% of the national electricity demand (Bord na Móna, 2015). In October 2015 Bord na Móna announced their intention to stop harvesting peat for energy generation by 2030 (Forde, 2015). This provides a significant incentive to increase the use of renewable sources of energy in electricity generation.

Currently Bord na Móna co-fires woody materials, agricultural residues (namely palm kernel shells and sunflower husks), and purpose-grown energy crops with peat and revealed that they will consume 300,000 energy tonnes of biomass (30% of the fuel mix) by the end of 2015 and have ambitions to replace as much as 50% of the fuel mix with biomass materials (Bord na Móna, 2015). As part of their plan is to diversify land use following the cessation of harvesting of energy peat, it is intended that energy biomass will be cultivated on land from which they originally sourced peat (Forde, 2015). Biomass yields associated with peatlands are much lower than on “good cereal land” (Egan, 2015), however, which may create a challenge in securing a sufficient quantity of indigenous renewable solid fuel to replace indigenous fossil solid fuel.

The SEAI Bioenergy Map illustrates that significant areas of the Irish land base are suitable for the growth of Miscanthus, willow, oilseed rape, and Reed Canary Grass (SEAI, 2015a). Much of this land is currently in use for tillage or livestock production so is not readily available for expansion of energy crop holdings, nor is it probable that this land will be diverted away from its current use unless the price offered for energy biomass competes with the price offered for cereals or livestock. The most likely reason for a competitive price to be offered for energy crop biomass is if demand for energy crop biomass increases significantly.
There is significant scope to increase the amount of land used to grow dedicated energy crops; currently only 3,500 ha of land are used to grow energy crops for heat and/or power generation. The terms and conditions of the Bioenergy (Willow) Scheme 2015 state that farmers/land owners can grow up to 10 ha of willow under the Scheme while remaining eligible for REPS 4 payments (DAFM, 2015h), and short rotation coppice is specifically mentioned as being eligible for EU Basic Farm Payments (DAFM, 2014e). This should be highlighted so as to build confidence in land owners to expand into energy crops.

In May 2015 Mayo Renewable Power announced their intention to begin construction on a high efficiency combined heat and power plant in County Mayo which will generate sufficient electricity to power 42,000 homes (O'Halloran, 2015). The biomass which will be used to generate this power will initially be imported from Northern America but it is the company’s intention to use a combination of indigenous and imported biomass to meet this demand (O'Halloran, 2015). This represents another obvious avenue for the expansion of energy crop production in Ireland as Mayo Renewable Power represents a significant end user of the biomass.

There are two main factors holding back the expansion of energy crop plantations in Ireland at present: the current lack of a defined and mature market for biomass harvested from energy crops; and the negative financial implications associated with growing energy crops (Teagasc Tillage Sectoral Energy Crop Development Group, 2014). Although the Bioenergy (Willow) Scheme 2015 is in place which offsets some of the planting costs, energy crops are expensive to establish compared to conventional crops as specialised handling equipment and, in some cases, experienced operators may be required for successful establishment. Furthermore, investing time and money in establishing a crop which is not expected to provide revenue until at least year two and is then expected to provide revenue for up to 25 years has significant associated uncertainty without having a defined long-term market. Formalising and defining the market demand for indigenous energy crops is essential to strengthen the domestic energy crop sector and assuage concerns of landowners associated with the perceived risks of establishing long life cycle crops.

2.1.2.1.1. Employment

It is difficult to quantify the employment numbers currently associated with the growth of energy crops as most of the growers are farmers or land owners who have other agricultural holdings in addition to the energy crops, and as such are not solely associated with the energy
crop industry. For example, the 2010 census of Irish agriculture showed that 281 farms reported renewable energy production as a “gainful non-agricultural activity” (CSO, 2012a) however it is not specified what proportion of the farm labour was associated solely with the production of renewable energy. The same can be said for the contractors who harvest the energy crop biomass and for the operatives who are involved in the co-firing of energy crop biomass at the solid fuel power stations in Ireland as their responsibilities include more than the processing of energy crops. A report published in 2012 on the development of the Irish bioenergy industry indicates that permanent employment could grow to 3,600 jobs by 2020 with jobs in the energy conversion facilities, in supply industries, and in the wider economy (IrBEA/SEAI, 2012). This therefore suggests that the current level of employment directly associated with the bioenergy industry is below this figure. Projects such as the Mayo Renewable Power biomass plant offer great potential to expand employment associated with the cultivation of energy crops.

2.1.2.2. Other Resources

Some crops which are (or have previously been) grown in Ireland for feed or food purposes also have merit as energy crops. Arable land predominates in the south and east of Ireland (Clancy et al., 2012) and it is in these locations that most of the conventional crops which have potential as energy crops are grown. Wheat, oilseed rape, and sugar beet for example, have significant contents of starch, oil, and sugar respectively which can undergo transformational processes to produce liquid biofuels for transport use (Clancy et al., 2012). As they are conventional crops, their growth for bioenergy use would use existing farming knowledge and equipment readily available on Irish farms. Wheat is grown primarily in counties Louth, Meath, Kildare, and north county Dublin with smaller plantations in counties Offaly, Wicklow, Cork, Westmeath, and Waterford (SEAI, 2015a). Oilseed rape is grown predominately in counties Meath, Kildare, and Wexford with a smaller number of plantations in Offaly, Wicklow, Cork, and Westmeath (SEAI, 2015a).

Wheat was grown on 71,600 ha in Ireland in 2014. The trend for wheat production in Ireland has been mixed in recent years: 2014 showed an increase on 2013 production levels but is lower than the levels grown in the years 2008-2012. In Ireland wheat is predominantly grown as a winter crop, with less than 10% of the 2014 harvest grown as a spring crop (CSO, 2015d). The wheat grown in Ireland is destined for two main markets: animal feed and milling for flour production (DAFM, 2014f). Although over 700,000 tonnes of wheat were
produced in Ireland in 2014 (CSO, 2015a), Ireland is a net importer of wheat to fulfil its current needs (DAFF, 2010b).

Although oilseed rape is considered an excellent break crop and has been shown to increase subsequent wheat yields (Teagasc, 2009), it is recommended that oilseed rape be grown as part of a one-in-five rotation on tillage land, limiting the potential annual yield of this crop. The national oilseed rape holdings in Ireland have fallen from a recent peak of 17,500 ha in 2012 to its current level of 9,400 ha (CSO, 2015a). The intended end use of oilseed rape determines the variety which is sown. The uses can be broadly categorised as for animal feed, for biofuel production, or for human consumption (Teagasc, 2015e). The vast majority of the oilseed rape grown in Ireland is exported for processing in the UK where the seeds are crushed to extract the oil and the remaining protein cake is used for animal feed (DAFM, 2014f). The oil can then be used either for biofuel production or as a food ingredient.

Sugar beet, a potential feedstock for bioethanol, was a significant crop in Ireland until 2006 when the European Union restructured the sugar industry (Council of the European Union, 2006). Irish sugar beet production was significantly reduced by this move with just 10,300 ha of fodder beet grown in Ireland in 2014, down from a previous level of 31,000 ha of sugar beet and 4,000 ha of fodder beet grown in 2005 (CSO, 2015b). Beet is now grown in Ireland for animal feed uses. The majority of the material is consumed on-farm with approximately 25% sold for use elsewhere (DAFM, 2014f). As Ireland is a net importer of cereals, particularly of wheat, it would seem clear that the potential exists to produce additional volumes of indigenous cereals to offset these imports. These cereals are currently imported for use in defined and established markets of the animal feed and food industries therefore it is unlikely that any increase in indigenous cereal production would be earmarked for biofuel production, however. The food vs fuel debate has raged in many countries where cereals for fuel production are displacing cereals for food production, driving up food prices and potentially increasing global levels of food shortage.

Looking at agricultural output as a whole, the volume of production of grass far exceeds the production of all other crops in Ireland: 81% of the agricultural land in Ireland, equal to 3.6 million ha, is used for animal grazing through pasture, hay, and grass silage (DAFM, 2015a). Such is the volume of biomass produced that McEniry et al. (2013) reported that approximately 1.7 million tonnes of dry matter in excess of livestock requirements is collected annually. As well as its role in livestock production, grass can also be used as a feedstock in anaerobic digestion to capture methane for electricity or heat generation. With
such large quantities of biomass estimated to be surplus to requirements, this material could be diverted into renewable energy use without significantly interfering with existing supply chains. Perennial ryegrass is the dominant species of grass grown in Ireland, as in much of Europe, however the specific methane yields of a number of common grass species show little difference (McEniry et al., 2013); this result suggests that diverting additional grass biomass into AD would not require extensive reseeding to optimise methane yields. Grass can be digested fresh or after ensiling to facilitate storage; Pakarinen et al. (2008) reported that storage decreased methane yield, the extent of which being dependent on the length of storage. Such a loss may be unavoidable however, as storage will be essential to ensure a continuous supply of feedstock is available for a digester. Grass is usually co-digested with animal manure to optimise the nature of the feedstock which, given that more than 37 million tonnes of manure is collected annually in Ireland (Hyde and Carton (2005) reported the production of 37 million tonnes of cattle manure during the housing period based on a national herd of 6.3 million; the national herd now stands at 6.9 million head (DAFM, 2015a)), could provide a management option for vast quantities of organic material with the advantage of contributing to renewable energy targets.

2.2. Secondary Inputs into the Irish Bioeconomy

2.2.1 Organic By-Products Derived from Municipal Waste Collection and Treatment

2.2.1.1 Municipal waste

The definition of municipal waste in Ireland is broad and includes wastes from households and cleaning activities (street and parks cleaning) as well as non-hazardous waste from the commercial and services sector (shops, offices etc) and non-process industrial wastes. It does not include municipal wastewater treatment sludges (Watson, 2013). The definition used by the European Union and set out in the Landfill Directive states that “‘municipal waste’ means waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households” (Council of the European Union, 1999). The majority of municipal solid waste (MSW) generated in Ireland ultimately ends up in landfill, however the share of MSW sent to landfill has reduced significantly during the first decade of the millennium falling from 77% in 2001 to 53% in 2010 (Watson, 2013). The economic downturn has had an impact on the generation of certain waste streams, however forecasts
predict the total volume of municipal waste to increase over the next fifteen years once economic recovery takes hold (EPA, 2015a).

2.2.1.1.1. Biodegradable Municipal Waste

Within the MSW stream, there is a component known as biodegradable municipal waste (BMW). BMW is made up of the elements of household, commercial, and cleansing waste streams that will rot or degrade (EPA, 2016a). The main constituents of the biodegradable portion of municipal waste are typically parks and garden waste, food waste, timber, paper, card and textiles. The BMW fraction of MSW will be of most interest and importance to the Irish bioeconomy. In the past it was considered a problem to be disposed of; into the future it is arguably a potential zero-cost resource for use and value extraction in the bioeconomy.

In 2012 BMW accounted for 54% of all MSW accepted at landfills, equal to 589,259 tonnes of organic material (McCoole et al., 2014). As set out in the EU Landfill Directive Ireland can only landfill a maximum of 35% of the BMW generated in 1995 (427,000 tonnes) by July 2016; most recent information indicates that Ireland is on track to meet this EU requirement (EPA, 2016a).

Recent legislative measures have and will continue to have a significant impact on the volume and accessibility of organic material from municipal collections. Source separation of BMW has been introduced in both the commercial and domestic sectors, driven by obligations to comply with the EU Landfill Directive. Of particular interest for the development and expansion of the Irish bioeconomy is the separate kerbside collection of household food and garden waste (in a 3-bin system) which has shown annual increases in recent years.; 63,837 tonnes of BMW were collected in 2010, increasing to 77,494 tonnes in 2011, and 80,046 tonnes collected in 2012 (McCoole et al., 2014; McCoole et al., 2013).

According to an EPA report of the types of materials accepted for composting and anaerobic digestion at licensed facilities in Ireland in 2015, a total of 300,000 tonnes of organic wastes were accepted, consisting primarily (64%) of municipal wastes; there were also increases recorded in the volumes of garden and park wastes and wastes arising from the production of beverages (EPA, 2016b). It is arguable that these will be consistent, sustainable sources of materials potentially available for processing and value extraction in the context of the Irish bioeconomy.
2.2.1.1.2. Paper and Board Waste

In Ireland in 2012, 358,923 tonnes of paper and board (including composites i.e. beverage cartons) in the form of packaging waste was generated (McCoole et al., 2014) 30,726 tonnes was landfilled, 30,158 tonnes was recovered for energy, and 298,039 tonnes went into material recycling and other recycling. In total 328,197 tonnes were recovered with an overall recovery rate of 91% (McCoole et al., 2014). The vast majority of dry recyclables in Ireland are exported for recovery due to a lack of recycling facilities (Watson, 2013). Conversely, a relatively small amount of packing waste is imported into Ireland for recovery. In 2012 recovery operators reported treating 71,835 tonnes of packaging waste generated abroad (McCoole et al., 2014). Trade statistics show a net trade in the region of 445,000 tonnes per annum (Pöyry Management Consulting (London) Ltd, 2011).

Current uses for recovered paper in Ireland are very small: Erin Pulp Limited produces moulded fibre products and Ecocel produces cellulose insulation products in Ireland (Pöyry Management Consulting (London) Ltd, 2011). In addition, there is the low-value added recovery of shredded recovered paper for animal bedding in multiple locations. One estimate of prices paid for Irish recovered paper is in the range of €18-€105 for lower grade paper and €24-€110 for higher grade paper (Duffy, 2014). These figures are in stark contrast to the €450 per tonne paid to subsequently import paper (Bonsall, 2015a), suggesting a highly lucrative opportunity for value addition in the Irish bioeconomy.

2.2.2 Municipal and Industrial Wastewaters

Currently there is an obligation to report wastewater sludge data to the Environmental Protection Agency annually. In 2014 it was reported that 53,543 tonnes of sewage sludge were produced, of which almost 80% was used in agriculture, 17% was composted, and less than 1% was consigned landfill (EPA, 2015b). Historically sludge was disposed of via disposal at sea and through land-spreading however international legislation has ended these practices for the most part. Increasingly, environmental regulations are precluding land-spreading of untreated wastewater sludge based on fears over bio-contamination and slightly higher metal concentrations in the sludge wastes.

The composition of municipal wastewater includes organic load constituents such as carbohydrates, proteins, fats, oils and grease (FOGs), and inorganic load constituents such as nitrogen and phosphorus (EPA, 1997). Where treated sludge is used in agriculture or other land-use there are benefits from provision of nutrient content in terms of nitrogen,
phosphorus, potassium, sulphur, magnesium, and micronutrients which are present in the sludge (Usman et al., 2012). In addition, the organic content of the sludge can improve soil quality by increasing water absorbency and tilth and may reduce the possibility of soil erosion (Meyer et al., 2001). Wastewaters from agri-food processing have a reasonably high proportion of salts, nitrogen compounds, ammonium, and dissolved phosphates. The sludges from agri-food wastewater processing are generally considered ABPs as they originate from agri-products (European Parliament and Council of the European Union, 2009); depending on their ABP categorisation these sludges can be land-spread. Similar to municipal wastewater treatment sludges, they are high in proteins and carbohydrates.

Two components in sewage sludge that are technically and economically feasible to recycle are nitrogen and phosphorus. Technologies are currently in development to extract these essential nutrients from sludge, with phosphorus seen as the most significant nutrient due to depleting resources (Healy et al., 2015). Healy et al. suggest that the application of nutrients to agriculture via land spreading of treated sewage sludges recycling may be “essential for future sustainable development, as it is estimated that there are only reserves of 50-100 years of P”. Provided that it is treated to the approved standards, treated sewage sludge may offer an excellent source of nutrients and metals required for plant and crop growth (Healy et al., 2015).

Wastewater sludge can also be considered to be a valuable resource due to its energy content (Healy et al., 2015). Anaerobic digestion offers an attractive solution to deal with both an increase in demand for energy efficiency and an increase in national sludge volume (Fitzsimons et al., 2016). Anaerobic digestion of wastewater sludge produces methane gas which through conversion to electricity can meet a significant portion of the process energy demand of the treatment plant (O'Sullivan, 2015).

2.2.3 Agri Food Processing Residues

Environmental sustainability criteria are becoming ever more important to both the quality assurance and marketability of Irish food and beverages products. The bioeconomy offers opportunities for greater resource recovery from the agri-food processing sector and to underpin both the economic and environmental sustainability of production, through valorising waste streams. Ireland’s food and beverage industry processes significant amounts of agricultural commodities into finished food and beverage products that are exported globally. The residues which arise from such processing include spent grains from the
brewing and distilling industry, whey residues from cheese or casein production, dairy fat from milk processing, spent mushroom compost and stalk cut-offs from mushroom production, various sludges from wastewater treatment, and food crop residues from apple, potato, and other food processing (Brunton et al., 2014; Jaiswal and Abu-Ghannam, 2014; Teagasc Mushroom Stakeholder Consultative Group, 2013; Zall, 1992). For example, 55,000 tonnes of mushrooms are produced annually in Ireland with an associated waste generation of between 5% and 20% of production volume (Jaiswal and Abu-Ghannam, 2014). Approximately 160,000 tonnes of brewers’ spent grain are produced annually in Ireland, and the industrial processing of potatoes generates large quantities of peel that create disposal, sanitation, and environmental problems (Jaiswal and Abu-Ghannam, 2014). Other processing residues arising from the Irish bioeconomy include used cooking oil (10,000 tonnes generated annually) and tallow from rendering in the meat processing sector: Murphy et al. (2014) estimated that the total available tallow in Ireland (from all categories) in 2011 was 87,100 tonnes.

Currently some of these materials are used as animal feed (e.g. spent brewers grain and some whey residues) attracting values reportedly ranging from €35 up to €80 per dry metric tonne (Jaiswal and Abu-Ghannam, 2014; Murray, 2014; Higgins, 2014), however most are not transferred to another value-extraction process. Instead they are considered to be wastes and are land-spread for disposal, ultimately returning nutrients to the land. These materials could be considered a potential supply of feedstock for value addition and, could be processed to generate bio-materials or bioenergy, for example. There are a number of possibilities to extract value from these materials. High-value components such as enzymes (amylase, protease etc.), nutraceuticals, functional foods, food preservatives (polyphenols), organic acids (lactic acids etc), food additives and pharmaceutical products could be extracted enzymatically from food wastes such as those generated by Irish food processing (Jaiswal and Abu-Ghannam, 2014). Research in Ireland has looked at potato peels as a rich source of pharmaceuticals and bioactives (Teagasc, 2014b), and while the waste resulting from mushroom production is generally composted, research indicates that more valuable products such as chitin and beta glucan could be recovered from it (Jaiswal and Abu-Ghannam, 2014; Teagasc Mushroom Stakeholder Consultative Group, 2013; Wu et al., 2004).

Ireland has a cattle herd of 6.4 million including dairy and beef cattle; in 2014 1,019,000 tonnes of meat were generated from slaughterings including pig, sheep, and poultry meat (CSO, 2015c). This represents an increase of 9.4% on the 2013 slaughterings. Given the size
of the herd and the tonnage of meat slaughtered annually it is reasonable to assume that Ireland generates a relatively large amount of animal by-products from this agri-food processing. Animal by-products (ABPs) are defined as the entire bodies or parts of bodies of animals or products of animal origin not intended for human consumption including ova, embryos, and sperm (Regulation (EC) No. 1774/2002, since updated by Regulation (EC) No 1069/2009). They are sub-divided into three risk categories with Category 1 ABPs ranked as the highest risk. Category 1 is very high risk material which, amongst other items, includes specified risk material described as the carcasses of animals suspected or confirmed of being infected with transmissible spongiform encephalopathies; catering waste from international transport is also included in this category. The treatment options for this material are largely limited to burial in an approved landfill, incineration as a waste or combustion as a fuel though some Category 1 material may be used in the manufacture of derived products (European Parliament and Council of the European Union, 2009). Category 2 ABPs include manures and digestive tract content, the processing and value extraction of which is authorised in the Regulation (subject to the conditions outlined in the Regulation). The options available for value extraction include the manufacture of derived products, conversion into biogas or fuel, and the manufacture of soil improvers (European Parliament and Council of the European Union, 2009).

Most recent figures from the Department of Agriculture, Food and the Marine indicate that approximately 500,000 tonnes of raw ABPs are produced each year and are mainly rendered to produce meat and bone meal and tallow (DAFM, 2015i). A significant portion of the tallow produced is used within rendering plants to produce heat for the rendering process (Murphy et al., 2014). Alternatively, and depending on the risk category of the tallow produced, it can be used in animal feed, oleo-chemicals, and soap manufacture (Murphy et al., 2014). The cement production industry in Ireland uses meat and bone meal to fire the kilns; Lagan Cement, for example, source it from the local rendering industry in a ready-to-combust form and use it to partially replace fossil fuels such as coal and gas (Lagan Cement, 2012).

In addition to the significant volumes of material which arise from animal production and processing, smaller side streams also generate organic material which has potential for value addition. The dairy sector generates large volumes of residues and by-products that could be recovered for value-added processing rather than land-spreading for low-grade nutrient recovery, for example. Whey, a by-product of cheese production, is an example of value
addition from agri-food residues, with 124,700 tonnes of whey products processed from over five million litres of milk in 2009 (Geraghty, 2011). The dairy industry is in a current state of flux due to the restructuring of milk quotas: recently published data show that milk intake by Irish dairy processing plants increased by 28.3% between March 2015 and March 2016 (CSO, 2016). It is therefore plausible that levels of agri-food processing residues from the dairy industry have increased in tandem with the increase in the volume of milk being processed.

Although it does not represent a significant value-addition opportunity, agri-food processing residues can be harnessed for on-site bioenergy, contributing to the overall sustainability of the processing industry. Dairygold, one of the largest dairy processing companies in Ireland, has installed an anaerobic digester fed with dairy wastewater to generate biogas, saving more than 1,900 tonnes of carbon dioxide emissions in 2013 (Kelly, 2015a).

Despite being more associated with wet summers rather than consecutive weeks of harvest sunshine, Ireland does have a sizeable apple-growing sector. The total tonnage of culinary, dessert, and cider apples harvested in 2011 was 17,650 tonnes (DAFM, 2012b). Culinary apples sales were reported to be 9,425 tonnes in 2011, representing 53% of total sales tonnage; of this, 3,541 tonnes were sold into the cider market (DAFM, 2012b). It can be extrapolated that the processing of Ireland’s own cider apples generates in the region of 900 tonnes of apple pomace, a major by-product of the apple industry which represents twenty-five percent of the fruit weight (approximately seventy-five percent of the fruit weight is extracted as juice (Shalini and Gupta, 2010)). The largest producer of apple pomace by-product in the Irish cider industry generates 5,000 tonnes annually, with smaller and artisan producers generating an estimated 250 tonnes (C&C Group plc, pers. comm., November 2015; Traas, C., pers. comm., April 2016). Although this volume of residues is relatively small compared to other sectors, this material represents a higher energy value residue with sugars that could be used in higher-value added processes. Sugar-rich media can be important for biochemical production. Apple pomace is also a good source of phytochemicals primarily phenolic acids and flavonoids (Reis et al., 2014). Current common applications of apple pomace are the direct disposal to soil in a landfill and for the recovery of pectins (gelling agent, stabiliser, and source of dietary fibre) (Reis et al., 2014).

The sea fisheries industry is considered to be a good source of feedstock for value-addition in context of the Irish bioeconomy. Filleting of some fish species results in a significant percentage of each fish being leftover when the “meat” is cut away, with between 30% and
35% waste estimated (Faulkner, 2015). The material left behind remains rich in proteins and oils. Prior to the new Common Fisheries Policy there was also a significant amount of non-quota fish that fishing crews were required by European Union legislation to discard. During 2012 the Harbour Authority at Killybegs fishing port commissioned a survey to determine the amount of discards in the immediate vicinity of the harbour. Survey results indicated approximately 1,200 tonnes of fish were discarded in various states of decay (Faulkner, 2015). This material presents additional opportunities for post-processing value addition.

Fish waste, comprising of heads, tails, carcasses and offal from filleting, is currently used as ingredients for fish meal production used in the aquaculture industry; ingredients for pet food; and bait for crab and lobster fishing. Fish waste can be used as fish silage, fish meal, and fish sauce as well as in the production of various value-added products such as proteins, oils, amino acids, minerals, enzymes, bioactive peptides, collagen, and gelatin (Ghaly et al., 2013). Fish proteins are found in all parts of the fish and can be extracted by chemical and enzymatic processes (Ghaly et al., 2013). Sludge from fish processors and shellfish processing waste is used mainly for composting (Faulkner, 2015). Errigal Seafood Limited, a member of the Origin Green campaign, has been researching methods of additional meat recovery and the use of shells for organic fertiliser and road grit (Faulkner, 2015).

2.2.4 Current Technologies Associated with the Bioeconomy

2.2.4.1 Agriculture

A host of technologies are employed on-farm to assist in the transformation of agricultural inputs such as seeds, feed, energy, and labour into viable agricultural outputs including milk, beef, and cereals. This includes a range of animal breeding technologies and crop management practices as well as mechanisation advances. O’Riordan and Milbourne (2008) describe technological developments over recent decades at the farm level in Ireland as impressive, discussing the development of modern milking parlours and dairy units that automate feeding and milk practices on the farm and reduce the manual labour input required. They also commend developments in harvesting technologies that have resulted in combine harvesters being equipped with sophisticated computer interfaces and GPS systems for more effective and efficient harvesting capabilities, for example.

From an animal breeding perspective, much attention has been given of late to the concept of animal genomics to increase animal productivity and herd sustainability. The aim is to gain
mastery over exhibited DNA and animal traits through mapping, sequencing, and analysing the genomes of animals to allow for improved animal health and/or increased livestock productivity (Fadiel et al., 2005). Under recommendations of Food Harvest 2020, specific programmes of research have been launched including the Gene Ireland beef programme in 2012 which aims to double the rate of genetic gain in beef by 2020. The Next Generation Dairy Herd established at Teagasc focuses on accurate data collection and future-proofing the economic breeding index (DAFM, 2014c). Similar advances in breeding have increased the productivity of a variety of crops and cereals in Ireland. O'Riordan and Milbourne (2008) refer to the development of dwarf cereal varieties that have enabled a threefold increase in wheat yields in the space of thirty years, for example. Advances in fertiliser technologies as well as increasing awareness of soil nutrient management have further facilitated increases in cereal and horticulture yields in recent decades in Ireland.

Looking to 2030, O'Riordan and Milbourne (2008) foresee a continued and escalating contribution of technology to agriculture. Particular growth and opportunity is suggested in the arena of Omics technologies which explore the roles, relationships, and actions of the molecules that make up cells whereby scientific ability to tailor plant and animal species to exhibit certain traits could become commonplace. In this sense, new value-added products can be developed for the food industry and beyond into the pharmaceutical and cosmeceutical industries. At the same time, such techniques could help to minimise the risks of natural resource fluctuations such as soil fertility or rainfall patterns. Further developments in bioengineering technologies are also predicted to impact agricultural practices up to 2030, including the recently developed use of imaging technologies to replace manual grading in livestock production practices, for example (O'Riordan and Milbourne, 2008).

Advances in information communication tools have also benefitted farming both globally and at a national scale. A number of smartphone applications and technologies have emerged in Ireland in recent years to assist farmers in everything from reducing their carbon footprint (e.g. FarmCarbon Navigator), trading animals (e.g. Livestock.ie), managing animal health (e.g. Boviminder.com), to making informed grazing decisions (e.g. Grassometer.com) (DAFM, 2014b). PastureBase Ireland, for example, is a grassland management decision support tool developed by Teagasc that is capable of quantifying seasonal grass dry matter production across multiple enterprises, grassland management systems, and soil types. Use of remote sensed grass growth maps could also help to increase levels of grass production and
consumption on-farm, working towards the two tonne challenge proposed by Teagasc (2015b).

Processes of knowledge exchange with farmers will also be essential in the future technological development of the agriculture sector, alongside programmes to develop complementary farmer skillsets to utilise any new technology on-farm. This is a key aim of Food Wise 2025: to continue and progress farmer adoption of new and relevant technologies so that end goals of increasing output, enhancing environmental performance, achieving productivity gains, improving farm incomes, and meeting market demands may be achieved (DAFM, 2015b). Technology adoption at the farm level is key to improving Ireland’s competitiveness and sustainability for years to come (DAFM, 2015b). Addressing challenges of uptake will be essential to ensuring sufficient and appropriate adoption of technology in the Irish agricultural sector, including consideration of the age profile of farmers, levels of part-time farming, and the challenges associated with leasing rather than owning land. All of these factors impact the ability and desire of farmers to invest in technology and engage in skills development. Institutions such as Teagasc will continue to play an essential role in this knowledge and technology transfer through its dedicated farm advisory services and model demonstration farms.

2.2.4.2. Forestry

A number of technologies are currently in use in the forestry industry, ranging from nutrient application and biomass monitoring techniques to those used in the processing of forest-based products after harvesting. Technology in forestry is a developing concept and will play a major role in the future of the forestry industry in Ireland, particularly in the area of post-harvest processing for value addition.

LIDAR Terrestrial and Airborne Technologies

Light detection and ranging (LIDAR) remote sensing is a breakthrough technology for forestry applications which is easily integrated into GIS platforms (Turner, 2007). LIDAR instruments have demonstrated the capability to accurately estimate important forest structural characteristics such as canopy heights, stand volume, basal area, and aboveground biomass (Lefsky et al., 2002). LIDAR has an advantage over traditional systems particularly where terrain and drainage are not well understood (for harvesting and road construction planning) and where forest inventory costs are high. The quality of the data being captured is vastly superior and technical issues around the processing and handling of large volumes of
data have successfully been overcome. LIDAR is now firmly incorporated into the forest inventory and management systems of numerous forestry companies. LIDAR data can be used by foresters to measure the maturity and density of a stand and to reliably count trees, making it possible to predict key stand metrics and plan supply chain logistics accurately without being on-site. LIDAR has also been used to record individual tree metrics and maps showing spatial variation in tree stocking, allowing forest managers to accurately predict stocking and tree dimensions (Turner, 2007). TreeMetrics Ltd. are an Irish company to the forefront in this area of automated forest mapping and analysis (TreeMetrics Ltd., 2015).

Significant advances have also have been made in the development of photogrammetric software. New generations of satellite imagery such as NASA’s GEDI space-borne LIDAR satellite, ESA’s Sentinel satellites, cloud processing and Google Earth Engine are also being evaluated by forestry companies (Forest Industry Engineering Association, 2014).

Unmanned Aerial Vehicles

Both multi-rotor and fixed wing unmanned aerial vehicles (UAVs) are currently being trialled and used operationally for a number of applications for forest management in Australia and New Zealand. High-resolution monitoring for tree counting, survival assessments, weed and area mapping post establishment, wind row mapping, and monitoring change (harvesting, thinning, wind damage, fire, disease/drought) are some of the possible uses of this technology (Forest Industry Engineering Association, 2014). Research is also ongoing into the development of planting technologies that can be integrated with UAVs which will dramatically scale up forest establishment rates by using geospatial information in forest planning and management as well as site-specific silvicultural operations (Jozuka, 2015). The theory behind BioCarbon Engineering’s idea is that mapping UAVs will record detailed terrain data and generate high quality 3D maps of the area to be reforested, allowing researchers to outline landscape design and appropriate planting patterns. After consultation with ecologists to determine the most appropriate species, the UAVs will then be used to plant biodegradable, nutrient-rich seed pods containing germinated seeds (Jozuka, 2015).

2.2.4.2.1. Applications in Forestry

Biotechnology can be used in the forestry industry to improve fibre production and to protect trees, as well as in the pulp and paper industry. There is a belief that fibre production can be improved by inoculating seedlings with more efficient mycorrhizal fungi: mycorrhizal fungi
can enhance plant growth by improving mineral and water absorption, protecting against pathogens, and secreting growth enhancing hormones (Woldaardt, 2002).

*Treatment of Timber*

After felling, logs can be treated with fungi to improve debarking or to provide protection against staining and decay. For example, softwood logs inoculated with the white-rot fungus *Phlebiopsis gigantea* quickly become colonised; the fungus can loosen bark, reduce pitch, and protect the wood against sap staining by consuming the sugars in the wood and outcompeting sap-staining organisms (Woldaardt, 2002).

*Bio-pulping*

Woldaardt (2002) described bio-pulping as a solid-substrate fermentation process whereby lignocellulosic materials are treated with fungi prior to pulping; this reduces either the energy demand associated with mechanical pulping or the chemical demand associated with chemical pulping processes. The beneficial effects of fungal treatment on mechanical pulping are attributed to a reduction in the binding capacity of fibres and improved fibrillation. During bio-chemical pulping, the lignin content of the pulp or pulping time can be reduced (Woldaardt, 2002). Wood chips have also been treated successfully with fungal enzymes to improve the penetration of pulping liquor.

*Bio-bleaching*

Using enzymes using as xylanase as a pre-treatment step degrades lignin but causes limited degradation of hemicellulose, exposing lignin to further attack by subsequent bleaching chemicals (Woldaardt, 2002). Bio-bleaching reduces the volume of chemicals used in the bleaching process and therefore has environmental and economic benefits over traditional bleaching methods.

*Enzymatic De-inking*

Using commercially available cellulases, enzymatic de-inking can remove laser and xerographic inks from waste paper by hydrolysing fines to release ink particles (Woldaardt, 2002). The ink can then be removed by chemical or air flotation. The stripping of fines from fibres also results in improved drainage without a reduction in strength properties (Woldaardt, 2002).

*Control of Microbial Fouling*
Microorganisms in mill water systems cause slime or biofilm build-up, odour, and corrosion which can lead to increased maintenance costs. Biocides are often used to control microbial build-up, and deposits are removed using sodium hydroxide or dispersants. Inoculation of water systems with competing microorganisms or bacteriophages has been proposed to prevent the biofilm build-ups from occurring, but the most feasible biotechnological approach appears to be the use of enzymes to prevent aggregation of the microorganisms (Woldaardt, 2002).

**Effluent Treatment**

The oldest application of biotechnology in the pulp and paper industry is probably the treatment of wastewater (Woldaardt, 2002). Biological processes are usually used in secondary or polishing treatments that follow sedimentation or other primary treatment. Biological treatment processes include aerated stabilisation basins, activated sludge, oxygen-activated sludge, trickling filters, rotating biological contactors, anaerobic lagoons, upflow anaerobic sludge blankets, anaerobic filters, and anaerobic fluidised beds. Each of these systems has an associated microbial community that is responsible for the improvement of water quality (Woldaardt, 2002).

**2.3. Secondary Transformation Processes Associated with the Bioeconomy**

**2.3.1 Food Processing Technologies**

Commercial food processing is carried out across Ireland and includes primary activities such as the harvesting, sorting, slaughtering, cutting, cleaning, packaging, and refrigeration of raw agricultural product which is often followed by secondary processing activities such as blending, cooking, preserving, and packing of processed food and drink products. Outputs from both primary and secondary processing activities are then marketed and transported across Ireland as well as internationally, aided by a growing reputation and demand for Irish food abroad (DAFM, 2014c). Choosing the correct transformation technology is thus paramount within the food processing industry with direct implications for the physicochemical properties of the food or beverage output including its taste, texture, odour, aesthetics, and nutritional quality (Tiwari et al., 2013). Food processing has also become increasingly essential from a food safety and stability perspective, minimising the risk from pathogenic organisms and increasing shelf life. Pasteurisation (heating items to at least 72 °C for 15 seconds then quickly cooling to 5 °C), sterilisation (heating items to at least 120 °C for
several seconds before rapidly cooling), and freezing (maintaining food at controlled, low temperatures) have become commonplace to control, minimise, and eradicate food-borne pathogens, for example (EIC, 2015). Broadly speaking there are four main categories of food processing technologies: thermal, non-thermal, biochemical, and biophysical.

Thermal food processing typically concerns the method by which food is heated and can involve a range of methods from boiling, frying, grilling, and steam heating to batch roasting, smoking, and sous vide cooking (EIC, 2015). More recently, applications employing microwave and infrared techniques have emerged, changing the way in which food is cooked commercially. More novel techniques such as radio frequency heating (particularly for post-baking drying and quick defrosting purposes) and ohmic heating (uniformly heating the entire mass of the product using electric currents) are also gaining traction in research and development spheres but have yet to be fully commercialised in the Irish context.

Non-thermal processing has emerged particularly in the fields of pasteurisation and sterilisation where applying heat negatively impacts the sensory and nutritional attributes of the final product (Ojha et al., 2015; Ortega-Rivas and Salmerón-Ochoa, 2014). Non-thermal techniques are used instead to prevent microbial spoilage and pathogenic risks; such techniques are also considered to be more energy efficient and better able to preserve product quality than many thermal processes (Morris et al., 2007). Examples of non-thermal processing include the application of irradiation, pulsed electric fields, ultrasound, cold plasma treatment, and high hydrostatic pressure techniques. High pressure processing, for example, is a method of preservation in which a product is processed under hydrostatic pressure, inactivating undesirable microorganisms and enzymes in the final product.

Biochemical techniques applied in the food and drink industry include processes of pickling (for taste and preservation purposes), a range of brewing technologies, and fermentation techniques. Fermentation involves adding microorganisms to a product with the aim of producing an alcohol or acid to act as key preserving agents (EIC, 2015). It is utilised in the beer, wine, yoghurt, cheese, and dairy drink categories among others. The addition of preservatives and additives to foods is also included in the biochemical processing category. The addition of anti-oxidants to a product can prevent fats and oils from becoming rancid while emulsifiers and stabilisers can help to produce a more stable mixture of ingredients in items that might otherwise separate, for example.
Biophysical food processing incorporates some of the most basic techniques applied to agricultural outputs such as dicing, slicing, mincing, rendering, and macerating. Processes of liquefaction and emulsification also fall within this category as can techniques of drying or dehydration that transform agricultural outputs. Drying reduces the water content of a product, depriving microorganisms of a suitable environment for reproduction. More stabilised products across a range of categories such as powdered milks and soups, pasta, cereals, fish, and meat are produced in this way. Each of these food processing activities is carried out in Ireland, though some techniques are more widespread than others. The tendency for industry to adopt new and novel food processing technologies is influenced by a number of factors including technological capabilities, skillset, size, and market share of the individual company as well the costs, risks, consumer acceptance, and relative advantage of commercialising the technology.

An important aspect in the food processing industry which is crucial to product stabilisation, safety, quality, and shelf life, involves the packaging techniques applied to the final product before distribution. Packaging protects and preserves the food or beverage throughout the transportation and storage phases by providing a physical structure around the product that acts as a barrier against air, water vapour, external odours, and microorganisms as well as against physical damage (EIC, 2015). Packaging also maintains product quality and safety by retaining desirable internal levels of moisture and gases. Finally, packaging carries important information for transporters, further processors, retailers, and consumers through labelling and barcodes, including the product brand, ingredients, storage and cooking requirements, use-by dates, and processing batch details.

Food and beverage packaging techniques can take a variety of formats including modified atmosphere packaging, canning, and vacuum packing. More recently, techniques of low carbon packaging have also emerged alongside a range of biodegradable and compostable packaging options. O'Connor (2015) for example, highlights the range of sustainable polymers that can be utilised to create more environmentally-friendly and renewable packaging options. Although not all bio-based packaging is strictly biodegradable or compostable, O'Connor (2015) describes the range of opportunities that are emerging to replace fossil fuel-based packaging and ensure more sustainable inputs, production processes, and end of life management. Global food and beverage brands are beginning to expand into these areas: in 2015 for example, Coca-Cola unveiled plans to switch their entire production lines to bio-based bottles made from patented technology that converts natural sugars from sugarcane into the world’s “first fully recyclable PET plastic bottle” (Coca-Cola, 2015).
Other innovative ideas to emerge in the sustainable packaging arena include the development of clean food labels from fruit and vegetable waste (Crawford, 2015) and agricultural produce packaging derived from agricultural waste sources using upcycled wheat straw, tomato plant waste, or olive tree residues for example (Phillipson, 2015).

Smarter packaging options have also gained traction in recent years: Beresford et al. (2007), for example, highlighted the possibilities for nano-coating platforms on food products that have the capacity to display images, advertisements, and nutritional information in the future. A dedicated research group in University College Cork focuses on food packaging thematic research areas including the application of gas detecting sensors to monitor oxygen levels and detect faulty packaging materials in food packs (Hempel et al., 2013) and the development of edible and biodegradable films to maximise shelf life stability (Molinaro et al., 2013). With the consumption of bio-plastics increasing from 15,000 to 225,000 tonnes between 1996 and 2008 (Molinaro et al., 2013) the development of similar novel packaging techniques will continue as the global bioeconomy develops and society is increasingly compelled to transition away from fossil fuel-based materials.

The replacement of petrochemicals by bio-based materials across industries in Ireland is deemed particularly positive by Teagasc (2008) in the overall context of bioeconomy development, with such trends predicted to “radically affect farming, linking it to other industrial sectors and further integrating the rural economy with...new [bio-based] industries”. Connections between supply chains are paramount when considering future bioeconomy development with the potential for the food processing industry to act as a central crux absorbing inputs of agriculture, marine, chemical, and energy sectors to produce sustainable outputs for consumers for generations to come.

2.3.2 Bio-refining Platforms

2.3.2.1 Starch and Sugar Platform

The starch and sugar platform, which includes lignocellulosic and forestry/fibre platforms, centres on the valorisation of natural sugar sources. A number of processing technologies can convert these natural sugar sources into intermediates and end products. Although conceptually similar, each platform has its own unique complexities, opportunities, and challenges; a simplified overview of these platforms is provided in Figure 8.
2.3.2.1.1. Starch Platform

Starch is a polymer of glucose monomers linked together by glycosidic bonds (Bai et al., 2008). These polymers undergo pre-treatment to convert starch to monosaccharide glucose, and the resulting six-carbon (C6) sugars can be readily fermented by microorganisms to alcohols or organic acids. The starch bio-refinery platform utilises cereal grain feedstocks from a range of sources which can contain as much as 72% starch; wheat, barley, and maize are common examples (Corn Refiners Association, 2006). The actual starch-to-sugar conversion technology used varies somewhat depending on the type of feedstock being processed. Barley is malted to germinate the seeds which activates inherent enzymes which contribute to the starch-to-sugar conversion whereas wheat and maize are predominantly treated in a dry milling process where the grain is milled to fine granules to expose the starch in the grain. Adding water creates a slurry which is heated prior to the addition of enzymes that convert the starch to sugars. Maize can also be processed via a complicated and costly wet mill process which involves steeping in mildly acidic conditions to extract starch (Corn Refiners Association, 2006). Starches can be hydrolysed by the use of inexpensive enzymes such as α-amylase and glucoamylase (Klyosov, 1995).

Fermentation of the C6 sugars is often the preferred route as the technology is well established. Batch or continuous fermentation takes place in large, temperature-controlled tanks in which the sugars form a fermentation broth with water. Temperature, sugar

Figure 8: Overview of starch and sugar platform including lignocellulose and fibre platforms
concentration, and nutrients (nitrogen, in particular) within the broth are adjusted to meet the needs of the microorganisms (Wisconsin Biorefining Development Initiative, 2004). Fermentation begins as the growing population of microorganisms produce enzymes to break two-molecule sugars into single molecule sugars and then convert the single molecule sugars into commercial chemicals and by-products. Many starch platform bio-refineries are centred on the production of ethanol as a biofuel product, for example, with *Saccharomyces cerevisiae* the most popular microorganism involved. It has been claimed that *Zymomonas mobilis*, which has also been intensively studied over the past three decades, has the capacity to replace *S. cerevisiae* in ethanol production (Bai *et al.*, 2008). Reported ethanol yields, which depend on the cereal feedstock in question, include 400 l t\(^{-1}\) for corn, 380 l t\(^{-1}\) for barley (hull-less), and 392 l t\(^{-1}\) for winter wheat (El Bassam, 2010).

Organic acids such as lactic acid, citric acid, and succinic acid have been considered as a potential value-added fermentation route for starch using microorganisms like *Lactobacillus casei* (Afolabi *et al.*, 2012). During organic acid fermentation the pH of the broth decreases as the acid concentration increases and a neutraliser such as sodium hydroxide or calcium carbonate is used to stabilise pH, reduce inhibition, and increase productivity (Yang *et al.*, 2015). Products can be recovered as salts of calcium or sodium following concentration of the salt and conversion back into the acid. Traditional techniques use caustic chemicals to precipitate fermentation products which result in large volumes of waste salt materials such as gypsum (Wisconsin Biorefining Development Initiative, 2004). Membrane separation technology applies to the use of an engineered barrier with special properties which restricts the transport of various chemicals. Transport through the barrier by selected chemicals may be driven by convection, diffusion, electric charge (electrodialysis), or pressure, temperature, or concentration differences (Wisconsin Biorefining Development Initiative, 2004).

The maize grain ethanol production process generates a number of by-products, notably dried distillers grain (DDGS) and wet distillers grain both of which can be used as animal feed, usually for cattle (Williams *et al.*, 2015). DDGS is also the primary co-product when other cereals, such as wheat or barley, are used (Noblet *et al.*, 2012). The co-products of the maize wet milling process include corn steep liquor (a high-energy liquid feed ingredient), corn germ meal (a valuable addition to poultry and swine diets due to its amino acid balance), corn gluten feed (primary used in dairy and beef cattle rations), and corn gluten meal (an attractive ingredient in poultry diets due to its high content of xanthophylls) (US Grains Council, 2012). Additional by-products can include bran from the corn, rice, and wheat milling processes and
grain hulls (outer covering of the grain seed) commonly originating from oat and rice milling; each of these by-products can be valorised into a range of products (Mussatto and Teixeira, 2014; Saini et al., 2014; ElMekawy et al., 2013).

2.3.2.1.2. Sugar Platform

The starch platform described above illustrates the importance of sugars in bio-refinery valorisation. As most of the sugar in the world comes from two sources, namely sugar cane and sugar beet, and can be easily extracted it is no surprise that sugar is itself considered a bio-refinery platform. Sugar beet could be considered the most appropriate feedstock to develop a sugar bio-refinery industry in Ireland given that an industry existed here until 2006: production of sugar beet in Ireland historically averaged 50 tonnes per hectare (Travers, 2006).

The pre-treatment steps for the extraction of sugar from both beet and cane are similar: the cane or beet is sliced and juice is extracted either by crushing (cane) or via a counter-flow of hot water into an aqueous solution at pH 5.6-5.8 (beet) (Ortner et al., 2013). This results in the production of a raw juice and a wet pulp (95% moisture) which can be pressed using a screw press to recover additional sucrose. Impurities in the raw juice are removed by carbonisation with lime milk at 60-70 °C and pH 10.8-11.9 for 20 minutes followed by 30 minutes at 80-85 °C. Multiple-effect evaporation converts the raw juice into a thick syrup. The temperature is then reduced to stimulate crystallisation and the crystals are removed by centrifugation (Ortner et al., 2013). Unlike starch and cellulose there is no necessity to apply any additional technological operations such as chemical or enzymatic hydrolysis, which are expensive and energy consuming.

From this point the sugar platform resembles the starch platform, and fermentation is often the favoured route to fuels, bio-chemicals, etc. Brazil, second only to the US in terms of ethanol production output, uses sugar cane as a carbon source for Saccharomyces cerevisiae. The main feedstocks for the production of bioethanol in Europe are starch crops (such as common wheat) and sugar beet. Sugar beet crops are grown in most of the EU25 member states and yield substantially more ethanol per hectare than wheat (Demirbas, 2009). As with the starch and lignocellulose platforms, fermentation can be optimised for the production of higher value chemicals and organic acids which have potential as valuable intermediates.

Fermentation of sugar cane (133 g total sugar l\(^{-1}\)) and sugar beet (105 g total sugar l\(^{-1}\)) with Lactobacillus delbrueckii in batch fermentation resulted in the production of lactic acid of
120 g lactic acid l⁻¹ and 84 g lactic acid l⁻¹ respectively, for example. The optical purities of D-lactic acid from the feedstocks ranged from 97.2 to 98.3% (Calabia and Tokiwa, 2007).

Lactic acid can be produced as a bulk chemical with many potential applications. When produced in high optical purity, however, it can be used as a precursor for bio-polymer polylactic acid. There are two major routes to produce polylactic acid from the fermented lactic acid monomer: direct condensation polymerisation of lactic acid and ring-opening polymerisation through the lactide intermediate. The first route involves the removal of water by condensation and the use of solvent under high vacuum and temperature resulting in a relatively low- to intermediate molecular weight polymer due to the presence of water and impurities (Vink et al., 2003). Ring-opening polymerisation involves the removal of water to produce a low molecular weight pre-polymer which is then catalytically depolymerised to form a cyclic intermediate dimer, referred to as lactide, which is then purified to polymer grade using distillation. This purified lactide is polymerised in a solvent-free ring-opening polymerisation and processed into polylactide pellets. By controlling the purity of the lactide it is possible to produce a wide range of molecular weights (Vink et al., 2003). Wageningen University have been investigating the use of sugar beet for bio-polymer production and expect that sugar beet has the potential to be a suitable replacement for crude oil and natural gas as a raw material for plastics. Preliminary studies have shown beet to be resistant to high temperatures and to be more water-resistant than the current bio-polymers available (Wageningen UR, 2016).

In addition to the juice a number of residues are also available for further processing and valorisation including bagasse (in the case of sugarcane), beet pulp (sugar beet), molasses, and beet tails and green biomass (leaves, petioles, rootlets, etc). Beet pulp consists mainly of cellulose, hemicellulose, and pectin. Its composition is suitable for biological degradation: Hutnan et al. (2000) investigated a laboratory-scale model for sugar beet pulp anaerobic biodegradation and observed very good pulp digestion characteristics for methane production. In an alternative approach, a number of studies have examined the extraction of pectin from beet pulp to act as an effective emulsifier in oil-in-water emulsions. Pectin yields of 16.2% were achieved from dried beet pulp treated in an aqueous acid; the residual pulp can then be fermented to ethanol (Yapo et al., 2007).

Molasses can be used in a variety of applications including as an animal feed additive and in yeast production. In addition to the production of lactic acid and ethanol, molasses can be fermented to platform chemicals like succinic acid and citric acid. High yields (70% of
available sugar) of citric acid were produced from ferrocyanide-treated beet molasses in fermentation using *Aspergillus niger* (Clark and Lentz, 1963); *Actinobacillus succinogenes* has also been investigated for the production of succinic acid from cane molasses (Liu *et al*., 2008). Molasses also shows potential as a feedstock for the production of bio-plastic precursor polyhydroxyalkanoates (PHAs) by the soil bacterium *Pseudomonas aeruginosa* (Tripathi *et al*., 2011).

### 2.3.2.1.3. Lignocellulosic Platform

Lignocellulosic biomass is extremely abundant in nature and can come in the form of forestry, agricultural, and agro-industrial wastes (Mussatto and Teixeira, 2014). This can include the residues of the food-based crops described in the previous platforms. Lignocellulosic biomass is predominantly composed of cellulose, hemicellulose, and lignin along with some minor constituents. The respective content of the constituents varies among plant species and sources of biomass, with cellulose tending to be the largest component followed by hemicellulose and lignin. Typical biomass contains between 40 and 60% cellulose, 20 and 40% hemicellulose, and 10 and 25% lignin (Mussatto and Teixeira, 2014).

Like sugar and starch crops, lignocellulosic biomass is rich in sugars due to its high cellulose and hemicellulose contents which are rich in C6 and C5 sugars. Unlike the previous platforms however, these sugars are not easily accessible due to the complex nature of the lignocellulosic matrix. Over time plants have evolved resistance to degradation: the cellulose and hemicellulose components are surrounded by a tough lignin seal which provides rigidity. Pre-treatment is therefore an essential part of the lignocellulosic platform (Mussatto and Teixeira, 2014). This begins the process of breaking down the more easily hydrolysable (mainly hemicellulose) sugars and opens up the lignocellulose structure to make cellulose more accessible. Pre-treatment should also limit the formation of degradation products and preserve sugars (Shonnard *et al*., 2012). Physical pre-treatments are usually used to reduce particle size and facilitate handling. This includes chipping, milling, and grinding. This can also reduce the crystallinity of the cellulose. The particle size of the materials is usually 10-30 mm after chipping and 0.2-2 mm after milling or grinding (Kumar *et al*., 2009). Pyrolysis (rapid heating to temperatures of greater than 300 °C) has also been used as a physical pre-treatment of lignocellulose biomass, resulting in 80-85% conversion of cellulose to reducing sugars with more than 50% glucose (Kumar *et al*., 2009).
A physicochemical or chemical treatment step then takes place. The main purpose of this step is to separate the resistant lignin seal from the hemicellulose and cellulose with the aim of making sugars more accessible for hydrolysis. Significant improvements in hydrolysis sugar yields resulting from pre-treatment have been reported for many sources including poplar chips (90% glucose yield after enzymatic hydrolysis compared to 15% for untreated biomass), herbaceous residues such as corn stover (73% theoretical sugar yield with dilute sulphuric acid addition), wheat straw (80% theoretical conversion yield to ethanol with 0.9% H₂SO₄ addition), and agricultural residues such as *Brassica carinata* straw (70-99% enzymatic hydrolysis yield) (El-Zawawy et al., 2011). Steam explosion is a popular pre-treatment for lignocellulosic biomass whereby biomass is treated with high-pressure saturated steam (160-260 °C and 0.69-4.83 MPa) and then the pressure is suddenly reduced, causing the materials to undergo explosive decompression (Kumar et al., 2009). Steam explosion can be uncatalysed or catalysed through the addition of dilute acid or enzyme catalysts. Ammonia fibre explosion pre-treatment is similar to steam explosion: lignocellulosic biomass is exposed to liquid ammonia at high temperature and pressure for a period of time, and then the pressure is suddenly reduced (Kumar et al., 2009).

Hydrolysis follows the pre-treatments, performed to convert cellulose and additional hemicellulose to monomeric sugars for fermentation. Cellulose can be broken down into glucose either enzymatically by cellulases (a complex of endoglucanases, beta-glucosidases, and exocellulases) or chemically by acids. Dilute sulphuric acid is the most studied acid for acid hydrolysis and gives high hydrolysis yields. It can be applied at 180 °C for a short period of time or at 120 °C for 30-90 minutes in different types of reactors such as plug flow, batch, shrinking bed, and counter-current (Harun et al., 2011).

In addition to having to perform additional pre-treatment for the extraction of sugars, lignocellulosic biomass offers an additional challenge in that the monomeric C6 sugars are often more readily fermentable than the C5 sugars. In the production of ethanol for example, C6 sugars like glucose, galactose, and mannose are readily fermented to ethanol by many naturally-occurring organisms but the C5 xylose and arabinose sugars are fermented to ethanol by few native strains, and usually at relatively low yields. Advancements in genetic modification of bacteria and yeast have produced strains capable of co-fermenting both pentoses and hexoses to ethanol and other value-added products at high yields. The use of metabolic engineering for microorganisms such as *Saccharomyces cerevisiae*, which has had difficulty in metabolising xylose and other C5 sugars, has shown promise. By engineering
genes from *Pichia stipitis* into *S. cerevisiae* Jun and Jiayi (2012) significantly increased the microbial biomass (8.1 vs 3.4 g l\(^{-1}\)), xylose consumption rate (0.15 vs 0.02 g hr\(^{-1}\)), and ethanol yield (6.8 vs 3.5 g l\(^{-1}\)) after 72 hours fermentation using a xylose-based medium. Significant improvements have also been noted for *Zymomonas mobilis* among others (Agrawal, 2012).

On a commercial scale DONG Energy and DSM, a Dutch life sciences and materials company, have tested mixed C6 and C5 fermentation using DSM’s advanced yeast resulting in yields of 40% more ethanol per tonne of straw than achieved by traditional C6 fermentation (DONG Energy, 2013). Advances have also been made in the production of bio-butanol: it was recently reported that *Clostridium* sp. strain BOH3 is capable of fermenting 60 g l\(^{-1}\) of xylose to 14.9 g l\(^{-1}\) butanol, a similar conversion rate as the 14.5 g l\(^{-1}\) butanol produced from 60 g l\(^{-1}\) of glucose (Xin *et al.*, 2014). Importantly, strain BOH3 has been shown to consume glucose and xylose simultaneously, evident from its capability to generate 11.7 g l\(^{-1}\) butanol from a horticultural waste cellulosic hydrolysate containing 39.8 g l\(^{-1}\) glucose and 20.5 g l\(^{-1}\) xylose (Xin *et al.*, 2014).

Most research into the production of lactic acid has focused on production from either hexose or pentose sugars. Lactic acid bacterial strains have been isolated which metabolised both the hexoses and pentoses found in lignocellulosic hydrolysate (Eiteman and Ramalingam, 2015). The *Biofine* process involves the production of levulinic acid as a platform chemical from lignocellulosic biomass using two distinct acid-catalysed reactions, one fast using a plug-flow reactor and one slow using a back mix reactor (Hayes *et al.*, 2005). Levulinic acid is a valuable platform chemical due to its chemistry: it has two highly reactive functional groups that allow a great number of synthetic transformations. Levulinic acid can react as both a carboxylic acid and a ketone (Hayes *et al.*, 2005).

Residual lignin remaining from the pre-treatment hydrolysis phase can be used to produce steam or electricity which can be used within the process. Increasingly, the complex chemical nature of lignin is seen as having the potential to add greater value to the process. Phenols for example, which are currently produced using fossil oils, can act as platform chemicals from which a variety of new substances can be synthesised and then used in a wide range of products such as in the automotive and textile industries. Phenols are especially interesting as this platform makes use of the natural aromatic structure of lignin (LigniMatch, 2010). Various methods for the production of phenols from lignocellulose, especially from lignin, have been reported such as solvolysis including hydrolysis, hydrocracking (hydrogenolysis), pyrolysis, and alkaline oxidation (Yoshikawa *et al.*, 2013).
Lignocellulose bio-refineries can be a platform for the production a range of bio-chemicals and biofuels. As with the sugar and starch platforms fermentation is often the preferred route in lignocellulose bio-refinery scenarios. Fermentation and hydrolysis can occur in separate vessels each performed at optimum conditions, or simultaneously whereby both steps are performed in the same vessel. Alternatively, consolidate bio-processing simultaneously combines biomass hydrolysis, utilisation of liberated sugars, and fermentation in one reactor (Xu et al., 2010). While this would help to reduce processing costs, it is difficult to find suitable organisms to make this an efficient process (Harun et al., 2011).

2.3.2.1.4. Fibre Materials Platform

Ireland exports almost 500,000 tonnes of recovered paper per annum (Pöyry Management Consulting (London) Ltd, 2011) while at the same time importing most of its paper supplies (Initiative Economic Development et al., 2006). This exported material, combined with a projected doubling of forestry in Ireland over the coming years, holds potential as a feedstock for a fibre materials bio-refinery platform in Ireland which could be integrated into the existing pulp and paper industry (Phillips, 2011).

The pulping process isolates the cellulose fraction from forestry pulpwood or energy crop biomass; this cellulose fraction forms the primary raw material used for paper production. The pulp production process involves screening cellulose sources to remove metal followed by de-barking to remove grit and dirt as well as the bark which has very little cellulose fibre and is dark in colour; this material can be used as an energy source for the plant or alternatively as a feedstock for bio-refining as a source of bio-chemical extractives (Feng et al., 2013). Recovered paper is processed into pulp using a variety of commercially available, proven technologies; pulpers use either batch processing in a vessel with a high shear rotor or continuous processing using a long perforated drum. The pulper chops the paper into smaller pieces to which water and chemicals are added to form a slurry which goes through a screening stage before a centrifuge separates the pulp fibres from denser materials (Vamsi Kiran and Ram Babu, 2015). A de-inking stage is then undertaken to remove printing ink, adhesives, and other contaminants. Froth flotation is most commonly used in Europe and separates hydrophobic contaminants such as ink from the hydrophilic composition. Particle removal by flotation involves blowing air bubbles into the pulp slurry; the bubbles attach themselves to the ink particles and carry them to the surface where they can be removed as a foam (Fricker et al., 2007). A chemical surfactant is used to persuade the hydrophobic ink
particles to attach themselves to the bubbles. Ink particles between 50 and 150 µm in size can be removed by flotation bubbles; the size of the air bubbles introduced into the slurry determines the efficiency of particle removal (Fricker et al., 2007). Alternatively, wash de-inking consists of a washing stage whereby dispersants are added to wash out the printing inks. Washing does not remove larger particles but is a very efficient technique for removing particles in the size range of 10 µm and smaller (Fricker et al., 2007). Paper fibres can be recycled between four and six times, but get shorter and weaker with each recycling and are eventually strained out (Parliamentary Office of Science and Technology, 2005). When the pulp slurry is dewatered (thickened) the medium to fine particles are washed out.

The pulping process itself can be undertaken either via a mechanical process for woody biomass or a chemical process for any type of cellulose-rich biomass. Mechanical pulping, which produces approximately one third of the pulp in the EU, involves separating the fibres primarily through mechanical treatment in refiners. Most of the material therefore becomes pulp, including the lignin (Bajpai, 2014). Chemical pulping, which accounts for approximately two thirds of EU pulp production, separates the fibres through chemical treatment in either acidic or caustic solutions. These processes aim to separate lignin from the cellulose fibres. The dominant process for chemical pulping, used in approximately 90% of processes, is the kraft process (IEA Bioenergy, 2007) which involves the cooking of biomass chips and chemicals in aqueous solution in a pressure vessel to chemically dissolve the lignin and hemicellulose, thereby enabling the cellulose fibres to be separated relatively undamaged. Chemical processing can range from use of caustic soda and sodium sulphates to sulphurous acids and related base chemicals. In all plant designs digester chemicals are recovered and re-used in a closed loop cycle. Black liquor is produced as a by-product of the kraft pulping process and includes lignin, hemicelluloses, and other inorganic chemicals used in the process (Cushion et al., 2010). Once recovered the black liquor is transferred to a recovery unit where it passes first through a set of multiple-effect evaporators in which it is concentrated from 15% to about 70-75% solids (Cardoso et al., 2009). Black liquor is the most important source of energy from biomass in countries with large pulp and paper industry such as Sweden and Finland where it represents a potential energy source of 250-500 MW per mill (IEA Bioenergy, 2007).

A significant amount of research has been undertaken which focusses on the various products that could be incorporated into the pulp and paper process to create a fibre-based platform, i.e. a paper product with additional co-products. Such a platform would incorporate research
and emerging technologies into existing processes. The development of a bio-refinery platform from the existing pulping process will involve isolation of the lignin and hemicellulose components. Two technologies currently exist which can isolate these components: lignin removal from black liquor and hemicellulose extraction prior to pulping. A number of methods have been proposed for aqueous phase extraction of hemicelluloses in combination with pulp production: acidic pre-hydrolysis processes involve the hydrolysis of hemicelluloses to oligomeric and monomeric sugars which are dissolved in the hydrolysate either in a dilute solution of a mineral acid which catalyses the hydrolysis, or auto-catalytically (auto-hydrolysis) (Hamaguchi et al., 2012). Hemicellulose extraction is also carried out with green liquor in a near-neutral process, with strong alkaline solutions at low temperatures, or with white liquor (Hamaguchi et al., 2012). The resulting hemicellulose sugars can be fermented into ethanol or an array of marketable chemicals.

The most common lignin separation process is lignin precipitation by acidification, which can be done by using mineral acid and CO$_2$ (Hamaguchi et al., 2012). The black liquor from the evaporator moves into the acidification phase at a dry solids content of 30-45%. Carbon dioxide is mixed into the liquor to reduce the pH, resulting in the precipitation of lignin. The lignin is then dewatered using a press filter and dissolved again with wash water. The slurried lignin is then filtered again and the filtrate is returned to the evaporation plant (Hamaguchi et al., 2012). The isolated lignin can be used for bioenergy production however upgrading the bio-polymer can produce a range of value-added products. Upgrading may involve either degradation to generate products with low molecular mass such as phenols or other aromatics, or cross-linking or grafting which yields products with higher molecular mass such as adhesives or carbon fibres (Brodin et al., 2008).

### 2.3.2.2. Volatile Fatty Acids Platform

As will be discussed later, the biogas platform is a common route for valorisation of by-products and residues through the anaerobic digestion process. A less common approach to add value, but one with significant potential due to more recent advances in anaerobic digestion, is the fatty acid platform. Briefly, anaerobic digestion consists of four phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis which ultimately produce biogas. Fatty acids, organic acids with one or more carboxylic acid groups, are produced during the acidogenesis phase (Adekunle and Okolie, 2015). Although traditionally the production of biogas has been the focus of anaerobic digestion, in recent years it has been recognised that
targeting the production of organic acids instead of biogas may result in the production of more valuable end products (Kleerebezem et al., 2015).

Due to their influence on the process pH, VFAs can have an inhibitory effect on the digestion process which makes their recovery essential if the process is to continue at optimal conditions (Tuğtaş, 2011). Accumulation of certain VFAs may alter the anaerobic digestion process, causing reactions to become thermodynamically unfavourable which may result in changes in the pathways of certain reactions (Tuğtaş, 2011). Various techniques have been applied for the recovery of organic acids from aqueous solutions including electrodialysis, ion-exchange resin, adsorption, liquid-liquid extraction, and pervaporation (Choudhari et al., 2015).

In addition to the extraction of VFAs for the dual purpose of adding value and optimisation of the anaerobic digestion process, research has also focused on efforts to target anaerobic digestion for increased VFA production. It has been shown that varying the conditions of the reactor can enrich for particular fatty acids, for example acidic incubation conditions enriched for butyric acid production while neutral pH conditions resulted in acetic and butyric acid production in equal proportion (Cerrone et al., 2014). Rahim et al. (2014) found that the production of volatile fatty acids from biomass through anaerobic digestion was optimised by varying the cycle period of the digestion process with the concentration of mixed liquor suspended solids maintained at 8,000 mg l\(^{-1}\) for each cycle. Zeng et al. (2006) also found that an increase in solids concentration enhanced total VFA production, reporting increased propionic acid production.

The fermentation rate in anaerobic digestion reactors is influenced by the type, availability, and complexity of a feedstock. Neves et al. (2004) reported that excess lipids can lead to the reduction of the rate of hydrolysis since lipids and long chain fatty acids may be absorbed onto solid surfaces therefore reducing the accessibility of enzyme attack on other compounds. Hydrolysis, the first stage of anaerobic digestion, has been reported to be the rate-limiting step during digestion of many feedstocks (Ngas, 2012; Xie, 2012; Arsova, 2010). At low hydrolysis rates the accumulation of soluble precursors for fermentation will be reduced, thereby influencing the yield of VFAs and other fermentative products. To overcome low rates of hydrolysis various physical, chemical, and enzymatic interventions have been applied to increase feedstock solubility and to accelerate their biodegradation rate (Montgomery and Bochmann, 2014). Mata-Alvarez et al. (2000), for example, proposed that the use of a two-phase digestion process could facilitate much higher loads in the digester by separating...
hydrolysis and acidogenesis into one reactor while methanogenesis occurs in a separate reactor. Not only is the inhibition of the methanogens by VFAs thus avoided, different operating conditions can also be applied in order to maximise the yield of each stage depending on the desired end product. Two-stage anaerobic digestion systems open up the possibility of mixed community fermentation with recovery of high value VFAs in the first stage which can act as a platform for the production of a range of biofuels, bio-chemicals, polymers etc, and biogas production in the second from the remaining substrates. A simplified overview of a VFA platform bio-refinery is provided in Figure 9.

The organic acids produced and extracted from anaerobic digestion have a variety of applications. For example, acetic acid can be used as a chemical reagent in vinyl acetate production, propionic acid is used as a food preservative, butyric acid is used in food flavouring, and valeric acid is commonly used in the perfume and cosmetics industry (Du et al., 2014; Patočka and Jakl, 2010; Kumar and Babu, 2008; Commission of the European Communities, 1992). An alternative approach gaining considerable attention is the use of VFAs for the production of PHAs, a family of biodegradable polymers with properties similar to polypropylene. Ivanov et al. (2015) investigated the production of VFAs and hydrogen through acidogenic fermentation as a first step for PHA production and reported that the organic fraction of municipal solid waste can be converted to PHAs using a two-stage system that includes the production of organic acids through the acidogenic fermentation of

![Figure 9: Simplified VFA platform bio-refinery](image_url)
carbohydrates and the biosynthesis of PHAs from these organic acids.

In addition to the subsequent production of biogas during the methanogenesis phase, a VFA bio-refinery platform also allows for the production of biofuels. While VFAs themselves are unsuitable for fuel application due to the small carbon chain and the high oxygen to carbon ratio, there are two enzymatic reactions that increase the energy density of VFA without carbon loss: (1) bio-hydrogenation to an alcohol; and (2) chain elongation to a longer chain fatty acid (Steinbusch, 2010). Hydrogenation or elongation of acetate increases the energy density in the final products to ethanol or n-butyrate or even longer to caproate or caprylate. After these conversions, products have a higher energy density than the VFA or the starting biomass material, but have still a lower energy density than gasoline or diesel. Ethanol and butanol can be blended directly with gasoline whereas caproic and caprylic acids can be further processed to diesel or kerosene-like components (Steinbusch, 2010).

2.3.2.3. Lipid Platform

Lipids are molecules of biological origin that are insoluble in water and soluble in non-polar solvents. Examples include fatty acids, waxes, triglycerides, and phospholipids. Lipid bio-refineries are based on renewable oil which can be sourced from triglycerides contained in any kind of plant or animal and includes edible and non-edible varieties as well as virgin and used oils (Chou, 2012). World meat production reached 237.7 million tonnes in 2010 with large volumes of residues generated by animal processing plants in countries with intensive livestock production (Feddern et al., 2011). In addition, the world production of oilseeds was estimated to be 418 million tonnes in 2008/09 (United Oilseeds, 2009) resulting in the production of 133 million tonnes of virgin vegetable oil (Statista, 2016). A significant amount of this vegetable oil could be recovered for reuse. In 2003 a study in Ireland suggested the recovery rate for collection was 50% of total supply, and it was felt that 73% would be a realistically collectable volume (Bruton et al., 2009).

Lipids are essential in the production of biodiesel. For more than a decade, esterification and transesterification have been used to produce biodiesel from plant or animal-derived lipids (Feddern et al., 2011). Currently more than 95% of the world’s biodiesel is produced from edible oils such as rapeseed (84%), sunflower (13%), palm (1%), soybean, and others (2%) (Atabani et al., 2012). Expanding biodiesel production operations under a lipid platform bio-refinery offers the possibility of increasing the economic and environmental sustainability of biodiesel production through the utilisation of waste and the generation of a range of value-
added products. A summary of an oil and lipid bio-refinery platform is described in Figure 10.

Regardless of whether oilseeds or animal fats are the feedstock for the lipid platform bio-refinery, some pre-treatment will be necessary. In the case of oilseeds pre-treatment can be mechanical, chemical or both to initially clean, screen, and in some cases de-hull, hammer and/or pulverise the seeds. The seeds then undergo mechanical and/or chemical pre-treatment to separate the oil from the seeds. The quantity of oil extracted on a per acre basis depends on seed yield per acre, the efficiency of the extraction method, and the oil content of the seeds (Bart et al., 2010). Oil content varies from plant to plant. Oilseed rape grown in Ireland, for example, typically has an oil content of 43-44% (Teagasc, 2015e) whereas soybean has about 20% (Berk, 1992).

Mechanical separation of oil involves a screw press consisting of a vertical feeder and a horizontal screw with increasing body diameter to exert pressure on the oilseed as it advances along the length of the press. The barrel surrounding the screw has slots along its length, allowing the increasing internal pressure to first expel air and then drain the oil through the barrel. Oil is collected in a trough under the screw and the de-oiled cake is discharged at the

![Figure 10: Summarised oil and lipid bio-refinery](image-url)
end of the screw (Dunford, 2016). Extraction based solely on mechanical means will not remove all the oil as some oil residue will be left in the press cake. In rapeseed for example, high-powered mechanical pressing may result in a press cake with 10% oil residue which can be reduced by a further 1-2% with an additional press (Gunstone, 2009). Heat treatment during mechanical pressing can increase efficiency leaving a press cake with 6-10% residue (Gunstone, 2009). Depending on the effectiveness of mechanical pressing and the value of extraction of oil from the press cake to the overall process, solvent extraction can be used to provide a more complete extraction; effective solvent extraction should result in less than 1% residual oil in the press cake (Dunford, 2016).

Safety and environmental concerns associated with solvent extraction have prompted research into alternative technologies. The supercritical carbon dioxide technique, which utilises carbon dioxide above its critical pressure and temperature as a solvent, has been the choice for the majority of edible applications (Dunford, 2012). The unique advantage of supercritical carbon dioxide is the easy removal of the solvent from the extract (Dunford, 2012). Due to higher costs associated with high pressure equipment and processing, this technology is mostly used for extraction of high-value products however it may be possible to keep costs similar to solvent extraction if heat recovery steps are taken. In another investigation, Ali and Watson (2014) reported that ultrasound-assisted extraction recorded higher extraction yields compared to conventional organic solvent methods. Microwave-assisted oil extraction showed faster extraction rates and used less solvent compared with other methods but the yield associated with ultrasonic-assisted extraction was highest (Ali and Watson, 2014).

When animal-derived fats are used as feedstock, a rendering process is initially undertaken which involves chopping animal tissue and fats (tallow, lard, bone fat, etc) into smaller pieces which are then boiled in open vats or cooked in steam digesters (Singh, 2016). The fat is freed from the cells and floats to the surface of the water where it can be collected. A screw press can be deployed to ensure a more complete separation. Compared with conventional methods, centrifugal systems have been developed which generate a higher yield of better quality fat and the separated protein has potential as an edible meat product as opposed to its conventional uses as feed and fertiliser (Singh, 2016).

Any feedstock that contains free fatty acids and/or triglycerides such as vegetable oils, waste oils, animal fats, and waste greases can be converted to biodiesel (Hada et al., 2011). Vegetable oils have a high content of unsaturated fatty acids, mainly oleic and linoleic acid,
while animal fat composition has a higher proportion of saturated fatty acids (Baadhe et al., 2014). The properties of the triglyceride and the biodiesel fuel are determined by the amounts of each fatty acid present in the molecules. Biodiesel is generally produced through transesterification, the reaction of a lipid with an alcohol to form esters which generates glycerol as a by-product. Fundamentally it is the displacement of one alcohol by another from an ester, referred to as alcoholysis (Fukuda et al., 2001). Suitable alcohols include methanol, ethanol, propanol, butanol, and amyl alcohol (Gabriel et al., 2015). The reaction is reversible, thus an excess of alcohol is usually used to force the equilibrium to the product side. The stoichiometry for the reaction is 3:1 alcohol to lipids however in practice this is usually increased to 6:1 to increase the product yield (Fukuda et al., 2001). For waste oil it can be higher: results indicated that a molar ratio of 9:1 for methanol to triolein for waste olive oil produced the highest biodiesel yield (Vasudevan and Briggs, 2008).

An acidic, basic, or enzymatic catalyst can be used to increase the rate of the reaction. The amount of catalyst depends on its type, the quality of substrates, reaction time, and temperature and varies from 0.2 to 2% by mass relative to the weight of oil (Dworakowska et al., 2011). Encinar et al. (2007) described how basic catalysts require short times to complete the reaction even at room temperature while acid catalysts such as sulphuric acid require higher temperatures (100 °C) and longer reaction times. The alkalis that are used generally include sodium and potassium hydroxides, carbonates, and alkoxides such as methoxide, ethoxide, propoxide, and butoxide (Fukuda et al., 2001). During the production of biodiesel using methanol one mole of triglyceride reacts with three moles of methanol to produce three moles of biodiesel (a mixture of fatty acid methyl esters) and one mole of glycerol (Figure 11) (Gabriel et al., 2015). After the reaction, the glycerol-rich phase is separated from the ester layer or crude biodiesel either by decantation or centrifugation. Crude biodiesel contains contaminants such as methanol, glycerides, soaps, catalyst, and glycerol and has to be washed and dried to comply with quality standards (Gabriel et al., 2015).
Biodiesel production generates about 10% (w w⁻¹) glycerol as the main by-product (Yang et al., 2012). In a bio-refinery scenario the opportunity exists to add value to this by-product and increase the profitability of the bio-refinery. Glycerol has a number of possible uses including as an animal feedstuff (Yang et al., 2012), but its alternative potential as a feedstock for the production of bio-chemicals through fermentation is gaining increasing attention. Yang et al. (2012) described anaerobic fermentation as the most promising biological conversion of glycerol, reporting high yields of 1,3-propanediol by *Klebsiella pneumonia*; 1,3-propanediol is widely used in solvents, adhesives, detergents, resins, and cosmetics (Clomburg and Gonzalez, 2013). Other potential products from glycerol fermentation include citric acid (by fermentation with acetate-negative mutants of *Yarrowia lipolytica* Wratislavia AWG7 strain) (Rywińska et al., 2009), propionic acid (using *Propionibacterium acidipropionici*), and polyhydroxybutyrate using *Methylobacterium rhodesianum* and *Ralstonia eutropha* (da Silva et al., 2009).

Hydro-processing may be used as an alternative to transesterification for the production of hydrogen-derived renewable diesel from triglycerides. Hydrogen is reacted with the triglycerides under high temperature and pressure in the presence of catalysts to hydrogenate the double bonds in the fatty acid chains in the triglyceride (Natural Resources Canada, 2012). The glycerol backbone is then broken and the oxygen removed via hydrodeoxygenation or decarboxylation, leaving paraffinic n-alkanes. Whereas transesterification results in the production of glycerol, the by-products of the hydro-processing route are propane, carbon monoxide, and carbon dioxide (Natural Resources Canada, 2012).

In addition to the traditional production of biodiesel and glycerol there are a number of other oleochemical routes which may add value in a bio-refinery scenario. In some application areas such as chainsaw oil, gearbox oils, hydraulic oils, and lubricants for crude oil directly.

![Reaction diagram](image_url)

Figure 11: Transesterification reaction to produce biodiesel (after Gabriel et al. (2015))
production, these oleochemical products are already well established (Hill, 2012). Oleochemically-based dicarboxylic acids such as azelaic, sebacic, and dimer acids are major ingredients in polymer production. The chemical nature (e.g. elasticity, flexibility, high impact strength, hydrolytic stability, hydrophobicity, lower glass transition temperatures, and flexibility) of these oleochemically-derived dicarboxylic acids can alter or modify condensation polymers, and therefore will remain a special niche market area (Hill, 2012).

Considerable amounts of protein-rich cake are generated as a by-product when oilseeds are used as a bio-refinery feedstock. Carrera et al. (2012) investigated 20 protein co-products and by-products of the biodiesel industry which have potential as ruminant feedstuffs and found that the digestive characteristics of some of the co-products could replace soybean meal as ruminant feed. Other applications include production of industrial enzymes, antibiotics, bio-pesticides, vitamins and other bio-chemicals (Ramachandran et al., 2007).

2.3.2.4.  Protein Platform

Protein is a valuable resource which is expected to be in short supply over the coming decades (Widya Sari, 2015). It is therefore vital to ensure proteins are recovered and used efficiently and effectively where possible. Some of the platforms discussed previously have shown that opportunities exist to recover proteins. The press cake from the oil platform is a high protein residue which offers great potential, for example. In an Irish context, additional protein sources resulting from an impending ban on fish discards which will ensure that discarded fish will be landed will present a new opportunity for protein recovery (English, 2015). By-products from the food processing industry, such as the potato and meat processing sectors, also contain protein-rich residues which could be a feedstock for a wide variety of other industries. Unlike some of the other bio-refining platforms which centre around one or a few similar feedstocks which would be processed into a variety of products, a protein platform concept is less mature and would involve feedstocks from a vast array of sources each unique in terms of protein composition and constituents (Bonsall, B., pers. comm., April 2016). Nevertheless, given that this is a valuable resource with a wide variety of applications, such a platform needs to be investigated.

To date most protein wastes are primarily used as animal feed or fertilisers. For example, distillers dried grains with solubles, a by-product from the bioethanol industry, is mostly sold as cattle feed although it is a poor nutrition source due to its low lysine and high fibre content (Kumar et al., 2015). Vinasse, a by-product from sugarcane-based bioethanol production,
been used as a fertiliser (Prieler and Fische, 2009) however such usage has been known to lead to ecological issues such as pollution in rivers as associated with nitrogen-containing fertiliser. Furthermore, certain by-products are prohibited by European legislation from being used as animal feed or fertilisers because they may cause infectious diseases in higher consumers if the food chain is completed (Kumar et al., 2015).

Kumar et al. (2015) investigated the valorisation of residual protein to bulk chemicals through enzymatic means, beginning with hydrolysis of proteins to amino acids through chemical (acid or alkaline) or enzymatic (proteinases) hydrolysis or a combination of both. The resulting mixture of amino acids can then be separated based on their size, solubility, hydrophobicity, and electrochemical characteristics. Once isolated, amino acids can be converted to different products such as flavours, drug intermediates, or bulk chemicals. For example, Pukin et al. (2010) demonstrated that lysine $\alpha$-oxidase could be used to oxidise lysine to produce 5-aminovaleric acid, a precursor of valerolactam which is a building block for nylon-5 production.

While it is possible to valorise proteins into value-added products, an important balance must be struck between the opportunity to develop sustainable bio-chemicals, for example, and the requirement to fulfil the dietary protein needs of the world. The global population is predicted to reach 9.7 billion by 2050 (United Nations Department of Economic and Social Affairs, 2015) and this combined with increasing incomes in the developing world is set to drive an ever-increasing protein demand. As the demand for food increases so too will the demand for animal feed. An idea suggested by Widya Sari (2015) which takes account of this potential feedstock conflict is the development of a protein bio-refinery that separates essential amino acids to be used for food and feed, and non-essential amino acids for the production of bulk chemicals. Under the scenario proposed by Widya Sari (2015) lysine, for example, would be retained for food and feed purposes while the focus for bio-chemical production would be on glutamic acid and other non-essential acids. With the chemical industry expected to replace fossil usage in chemicals by up to 20% by 2030, Widya Sari (2015) estimates that 13 million tonnes of protein per annum will be required by the nitrogen-containing chemical industry in Europe to fully substitute the use of naphtha for nitrogen-containing chemicals (assuming a protein extraction yield of 50%). To this end, Widya Sari (2015) points to glutamate as being a potential candidate for bulk chemical production as synthetic glutamic acid has already been studied for conversion to chemicals such as N-methyl pyrrolidone, succinonitrile, and acrylonitrile and indicates that work has been done in replacing synthetic glutamic acid with
one isolated from biomass. The concept of a protein platform bio-refinery for the production of food and feed from essential amino acids and chemicals from non-essential amino acids is still in the early stages, but over time it may offer a good opportunity to add value to by-products of other processes.

Many recent studies have focused on the opportunity to valorise fish processing residues including the potential to extract bioactive proteins from fish residues and underutilised fish. Processing of fish involves stunning, grading, slime removal, de-heading, washing, scaling, gutting, cutting of fins, meat-bone separation, and preparation into steaks and fillets and can result in between 20 and 80% by-product generation depending on the level of processing and type of fish (Ghaly et al., 2013). Residues from fish filleting units can be used in the production of fish meal or used directly in animal feeds but more frequently is simply discarded (Batista, 1999). Considerable amounts of fish processing by-products are generated annually in Ireland and the availability of this material is going to rise over the coming years with a discards ban due to take hold in 2019. Some of the valorisation opportunities associated with fish biomass are illustrated in Figure 12.

Fish frames contain significant amounts of highly nutritious and easily digestible muscle proteins which have a better balance of dietary essential amino acids compared to other animal protein sources (Ghaly et al., 2013). Proteins extracted from the fish muscle contain a number of peptides some of which have anti-hypertensive, anti-thrombotic, immunomodulatory, and anti-oxidative properties (Vignesh et al., 2011). The bioactive peptides obtained from fish muscle have anti-coagulant and anti-platelet properties, which are the main reason behind the capability of peptides obtained from fish to inhibit coagulation factors in the intrinsic pathway of coagulation (Ghaly et al., 2013). Amino acids from fish proteins can also be utilised for the production of jadomycin, an anti-microbial agent that has shown great potential as an anti-cancer drug (Ramakrishnan et al., 2013).
Fish proteins can be extracted using chemical and enzymatic methods. Solvent extraction is the usual chemical method and involves the grinding up of fish materials and the protein extracted using isopropanol. After grinding the supernatant is collected and extracted three times before the final supernatant fraction is collected, dried, milled, and screened to separate out bone particles (Ghaly et al., 2013). Enzymatic hydrolysis is commonly used in the production of protein hydrolysates via the addition of numerous enzymes such as alcalase, papain, pepsin, trypsin, etc. Ramakrishnan et al. (2013) investigated the extraction of proteins from mackerel fish processing residues using alcalase: the procedure looked at whole mackerel fish and fish parts (whole fish, head, fin, tail, skin and gut, and frames) and recorded maximum protein yields (76.3% from whole fish and 74.53% from the frame) using 2.0% enzyme concentration.

Chemical (acid or alkali) as well as enzymatic methods can be used for the hydrolysis of proteins to amino acids. Conventional acidic hydrolysis of fish proteins is carried out using 6 M HCl for 20-24 hr at 110 °C under vacuum resulting in the complete hydrolysis of asparagine and glutamine to aspartic acid and glutamic acid, respectively. Losses can amount to 5-10%, however, with tryptophan and cysteine completely destroyed and tyrosine, serine, and threonine partially hydrolysed (Ghaly et al., 2013). Alkaline hydrolysis of proteins can be carried out using sodium hydroxide, potassium hydroxide, or barium hydroxide and is

Figure 12: Fish processing by-products bio-refinery pathways
specifically used for the determination of tryptophan as the process destroys serine, threonine, arginine, and cysteine and racemises all other amino acids (Ramakrishnan, 2013).

In addition to proteins, some of the other components of fish processing residues and underutilised fish will also offer significant opportunity for development into value-added products in a bio-refinery scenario. Almost 50% of the body weight generated as waste during fish processing is seen as having great potential as a source of good quality fish oil (Ghaly et al., 2013). The fish oil consists of two main fatty acids, eicosapentaenoic acid and docosahexaenoic acid, which are polyunsaturated fatty acids and are classified as omega-3 fatty acids (Ghaly et al., 2013). The functional and biological properties of omega-3 fatty acids include the prevention of atherosclerosis, protection against arrhythmias, reduced blood pressure, protection against manic depressive illness, protection against chronic obstructive pulmonary diseases, reduced symptoms in asthma patients, alleviated symptoms of cystic fibrosis, improved survival of cancer patients, reduction in cardiovascular disease, and improved learning ability (Ramakrishnan et al., 2013).

Fish skin material is a good source for collagen and gelatine which are currently used in the food, cosmetic, and biomedical industries (Ghaly et al., 2013). Collagen is generally extracted with acid treatment and solubilised without altering its triple helix (Kim and Mendis, 2006). The internal organs of the fish are also a rich source of enzymes, many of which exhibit high catalytic activities at relatively low concentrations. The enzymes which are available in fish include pepsin, trypsin, chymotrypsin, and collagenase (Ghaly et al., 2013). Fish enzymes are suitable for many food processing applications and although marine fish-derived enzymes do not have direct applications in the functional food or nutraceutical industries they can be utilised to produce bioactive components (Kim and Mendis, 2006).

**2.3.2.5. Algal Platform**

Algae grow 20-30 times faster than food crops, contain up to 30 times more fuel than equivalent amounts of other biofuel sources such as soybean, canola, jatropha or palm oil, and can be grown almost anywhere, making this a particularly significant bio-refining platform (Ullah et al., 2014). There are more than 100,000 strains of algae each with differing ratios of three main types of molecule: oils, carbohydrates, and proteins (Ullah et al., 2014). Algae are typically divided into microalgae and macroalgae: microalgae are microscopic organisms that typically range from unicells to colonies and filaments of up to a few hundred cells and include prokaryotes (cyanobacteria and blue-green algae) and eukaryotes (green
algae, diatoms, red algae, and others) (Murphy et al., 2013). Microalgae tend to have high lipid levels: species such as *Botryococcus braunii*, *Nannochloropsis* sp., *Dunaliella primolecta*, *Chlorella* sp., and *Cryptcodinium cohnii* produce large quantities of hydrocarbons and lipids. The oil content of microalgal species reaches up to 80% and levels between 20 and 50% are quite common (Medipally et al., 2015). Microalgae also synthesise different bioactive compounds and therefore have varied applications in the nutraceuticals, pharmaceuticals, and food industries (Medipally et al., 2015). Macroalgae are multicellular, macroscopic organisms which are abundant in coastal environments, primarily in nearshore coastal waters with suitable substrate for attachment; such algae can also occur as floating forms in the open ocean. Macroalgae traditionally have not been considered as feedstocks for bioenergy production but have been used in food, in medicine, as fertiliser, and in the processing of phycocolloids and chemicals (Murphy et al., 2013). Macroalgae are suitable for biofuel production however they generally do not contain triglycerides; this makes them a potentially valuable feedstock for higher valuable chemicals through fermentation as well as for biogas or bioethanol rather than for biodiesel production (Murphy et al., 2013). Several polysaccharides and oligosaccharides derived from macroalgae are used for therapeutic applications due to their bioactivity, including fucoidan and fucan from brown algae, sulphated galactan and ulvan-like sulphated polysaccharides from green algae, and carrageenan and galactan from red algae (Jung et al., 2013); these substances are recognised to have anti-thrombotic, anti-viral, immuno-inflammatory, anti-lipidemic, and anti-oxidant activities.

The two main methods for cultivating microalgae are in open pond systems and photobioreactors. Currently about 98% of commercial algae are produced in open pond systems which are the oldest, simplest, and cheapest way for large-scale cultivation of microalgae (Medipally et al., 2015). Some common examples include raceways stirred by a paddle wheel, extensive shallow unmixed ponds, circular ponds mixed with a rotating arm, and sloping thin-layer cascade systems. Photobioreactor systems are generally available in the form of tubes, bags, or plates which are made of glass, plastic or other transparent materials. Algae are cultivated in these systems according to a specific supply of light, nutrients, and carbon dioxide (Medipally et al., 2015). Productivity is higher in the controlled, contained environment of a photobioreactor but capital and operating expenses are also substantially higher than for open systems (Murphy et al., 2013).
Obtaining macroalgal biomass means either harvesting natural stocks, which is the primary route in Europe, or cultivation which is predominantly practiced in Asia. Seaweed exploitation in Europe is currently restricted to manual and mechanised harvesting of natural stocks (Murphy et al., 2013). Macroalgae for biofuel purposes are mainly harvested from the wild. Traditionally harvest was done by hand but this has now largely been replaced by mechanical harvesting using trawler systems. Contrary to the global situation, Irish seaweed production is predominantly hand-harvested from wild resources, and mostly from the western/northern coasts (Irish Seaweed Research Group, 2014; Johnson, M. pers. comm., June 2016). The majority of Asian seaweed resources are usually cultivated for higher value purposes such as food or hydrocolloid production (Bruton et al., 2009). Macroalgae cultivation is still in its infancy in Europe. The main cultivated species are Saccharina latissimi and Undaria pinnatifida. In Ireland, Palmaria palmata farming is being investigated on the west coast but the potential appears limited (Netalgae, 2012). In order to generate significant volumes of biomass for any biofuel industry, cultivation will be required in the long-term (Murphy et al., 2013). The algae are then harvested: macroalgae are harvested either by hand or mechanically using nets while microalgae can be harvested by processes including filtration flocculation, centrifugation, foam fractionation, sedimentation, froth floatation, and ultrasonic separation (Behera et al., 2014); the selection of harvesting method depends on the type of algal species.

To prepare algae for processing within a bio-refinery it is essential to first fractionate into the constituent streams, particularly lipids, carbohydrates, and proteins as well as some minor but potentially valuable constituents. Often the focus of fractionation is oil extraction for conversion to biodiesel. These extraction methods can be mechanical, including pressing using screw, piston or expeller presses or ultrasonic-assisted, using cavitation bubbles which collapse near the cell walls creating shockwaves causing the disruption of cell walls and the release of contents (Rath, 2013), or chemical such as through hexane extraction, Soxhlet extraction (Rath, 2013), or supercritical fluid extraction (Gajendra Babu and Subramanian, 2013).

The optimal usage of the biomass is highly dependent on algal composition: species with high lipid content will preferably be used for biodiesel production while algae high in carbohydrates are more suitable for bioethanol, for example (Murphy et al., 2013). Combinations are also possible, such as the use of the lipid fraction for biodiesel while the remaining biomass is fermented for biogas production. It is also possible to produce protein-
rich feed for both animal and human consumption. Bio-refinery processing may therefore be the most economical method of producing algal biofuels as several commercial products can be obtained from the algal biomass (Murphy et al., 2013); some possible pathways of an algae platform bio-refinery are illustrated in Figure 13.

Higher value chemicals can also be produced: the possibility of producing polymers from both carbohydrate and oil components of algae is being considered under the SPLASH project. The building blocks for these polymers will be derived from the sugars (polyesters) and hydrocarbons (polyolefins) exuded by the algae: adipic acid from galactose; 2,5-furandicarboxylic acid from glucose, rhamnose, and fucose; 1,4-pentanediol from rhamnose and fucose; ethylene and propylene from green naphtha (Cordis Europe, 2013).

Transesterification for the production of biodiesel was discussed earlier in the lipid platform; this process also applies to the algae platform due to the significant oil content of microalgae. Due to their lower lipid contents, transesterification is not a commonly investigated method for processing macroalgae (Murphy et al., 2013). Anaerobic digestion is a potential option to extract energy from macroalgae however, and can also be applied to the residual fraction of microalgal biomass; the process to extract lipids from microalgae results in a residue which can account for approximately 65% of the harvested biomass (Park and Li, 2012).

Figure 13: Algae bio-refinery platform
Macroalgae with a low lipid content are especially suitable for biogas production using anaerobic fermentation however this process has some challenges, including a high saline content which may inhibit the growth or productivity of the microorganisms in the fermenter and the formation of H$_2$S due to high sulphate concentration in the case of green macroalgae (Murphy et al., 2013). This can be solved by using iron-based chemicals to bind H$_2$S, as has been applied in wastewater treatment systems (Murphy et al., 2013). Seaweeds have methane yields ranging from 0.14 m$^3$ kg$^{-1}$ to 0.40 m$^3$ kg$^{-1}$ volatile solids, similar to the methane yields from primary sewage sludge (Roesijadi et al., 2010). Volatile fatty acids such as acetic, propionic, lactic, and butyric acids can also be produced from macroalgae by using anaerobic digestion (Jung et al., 2013).

A number of thermochemical routes for algae processing have been investigated. Hydrothermal liquefaction (HTL) is a promising method of processing algae which takes advantage of the high moisture content of algae via supercritical state. The reaction can take place on wet biomass in water at critical conditions of temperature and pressure (Chiaramonti et al., 2015). The conversion efficiency of microalgae HTL depends on various parameters including reaction temperature, retention time, and feedstock composition (Chiaramonti et al., 2015). Under these conditions the bio-macromolecules in the microalgae break down to form a liquid energy carrier called “bio-oil” or “bio-crude” (Murphy et al., 2013). Maximum bio-crude yields ranging between 50 and 60% have been reported, and the use of several homogeneous and heterogeneous catalysts has explored though in a very early stage of development (Murphy et al., 2013). Bio-crude has an energy content of 70-95% of that of petroleum fuel oil and is similar in nature to a heavy crude (López Barreiro et al., 2013).

Gasification can be used to convert algae into a synthetic gas in the near absence of oxygen. Gasification of microalgae can result in clean H$_2$ production with yields ranging from 5 to 56% and CO yields ranging from 9 to 52%. Methane can be considered to be a co-product and is only produced in small amounts of approximately 2-25% (Murphy et al., 2013). Pyrolysis can also be used to generate higher value products from algal biomass. Pyrolysis occurs at temperatures between 400 and 600 °C and atmospheric pressure and requires prior drying of the feedstock. Miao et al. (2004) investigated the fast pyrolysis of microalgae (Chlorella protothecoides and Microcystis aeruginosa) in a laboratory fluidised bed reactor at 500 °C and recorded a bio-oil yield 17.5% and 23.7% higher than the lipid content of the original algae for Chlorella and Microcystis, respectively. The bio-oils obtained had a calorific value of 29 MJ kg$^{-1}$ and a density of 1.16 kg l$^{-1}$. 

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In addition to the production of energy and chemicals there has been an increasing focus on the production of bioactive compounds from algae. These components have a wide variety of potential applications including as ingredients for functional foods, nutraceuticals, and pharmaceuticals (Kadam et al., 2013). A variety of mechanical and chemical processes are used for the extraction of bioactive ingredients including Soxhlet, hydrodistillation, and maceration with alcohol (Kadam et al., 2013). Traditional techniques are often characterised by large solvent volumes and long extraction times and often produce low extraction yields of bioactives and present low selectivity (Ibañez et al., 2012). For sensitive bioactive components such as fucoxanthin for example, bioactivity is deteriorated by the heating process which leads to low extraction yields (Kadam et al., 2013). A number of alternative process routes are being developed and optimised to overcome these challenges. Supercritical fluid extraction (SFE) is based on the use of solvents at temperatures and pressures above their critical points; carbon dioxide is the solvent most commonly used to extract bioactive compounds using SFE (Ibañez et al., 2012). Enzyme-assisted extraction involves the application of enzymes such as carbohydrases and proteases at optimal temperature and pH conditions to break down algal cell walls and release the desired bioactive components (Kadam et al., 2013). In pressurised liquid extraction (PLE) pressure is applied to allow the use of liquids at temperatures higher than their normal boiling point. The combined use of high pressures and temperatures provides faster extraction processes that require small amounts of solvents: 20 minutes using 10-50 ml of solvent in PLE compared with a traditional extraction procedure in which up to 300 ml and 10-48 hours are required (Ibañez et al., 2012).

Some of the bioactives which can be extracted from algae include carotenoids which can be produced using traditional (solvent extraction using hexane) or novel (e.g. supercritical fluid extraction) methods (Kadam et al., 2013). Fucoxanthin is the main pigment found in brown algae and has been observed to be a very effective inhibitor of cellular growth and promotes apoptosis in human cancer cell lines (Ibañez et al., 2012). It also possesses anti-inflammatory, anti-diabetic, and anti-oxidant activities (Ibañez et al., 2012). Attention has also focused on n-3 polyunsaturated fatty acids in recent times, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), due to their association with the prevention and treatment of several diseases (atherosclerosis, thrombosis, arthritis, cancers, etc) (Ramakrishnan et al., 2013). Omega-3 fatty acids, especially EPA and DHA, are of increasing importance due to their reported role in diminishing cardiovascular risks.
Sterols are another attractive lipid compound which can be derived from algae. Sterols and some of their derivatives play an important role in lowering low-density lipoprotein cholesterol levels as well as possessing anti-inflammatory and anti-atherogenic properties (Ibañez et al., 2012). Essential amino acids such as histidine, leucine, isoleucine, and valine are present in many seaweeds which are therefore potentially valuable sources of protein. Histidine, for example, is found in Ulva pertusa at levels of 0.04 g amino acid g\(^{-1}\) protein, similar to the level in egg white proteins (Kadam et al., 2013). Certain amino acids found in algae, including taurine and mycosporine-like amino acids, also have potential biological activity as anti-oxidants (Kadam et al., 2013). Different carbohydrates including agar, carrageenan, and alginites are extracted from macroalgae and can be used in the food and pharmaceutical industries as functional ingredients. Macroalgal polysaccharides also have potential for use as prebiotics as they are not digested in the human gut and have a number of bioactive properties including immunomodulating, anti-cancerous, anti-inflammatory, antivirus, and anti-oxidant activities (Ibañez et al., 2012).

2.3.2.6. Thermal Platforms

There are various conversion technologies available which can be used to produce fuels to generate electrical or thermal energy from biomass. There are different levels of efficiency associated with each technology, which suggests that following the easiest route won’t necessarily provide the most benefit or the greatest energy. A number of the conversion technologies are listed in Figure 14 and are detailed in the following sections.

2.3.2.6.1. Combustion

Combustion of biomass involves the exothermic oxidation of biomass in an oxygen-rich environment to produce hot flue gas (Basu, 2013). Combustion is the oldest, easiest, and most widely-used method of converting solid material into energy. As an exothermic reaction, combustion generates heat as well as carbon dioxide and water. This thermal energy can be used directly for heat or indirectly for electricity generation, usually by driving steam turbines (Basu, 2013). When generating electricity on a large scale, biomass can be co-combusted with fossil fuels; co-firing of biomass with fossil fuels has a number of environmental benefits including reducing the carbon footprint of the electricity produced and reducing the emission of NO\(_x\), SO\(_2\), ash, and heavy metals as biomass emits less or none of these substances (Basu, 2013). Co-combusting is not without its challenges, however: introducing a different fuel will usually require the implementation of a new fuel feeding system which will
involve capital investment for plant alteration (Basu, 2013) and will potentially introduce an additional pre-treatment step to ensure the biomass is in optimal physical condition (e.g. particle size, moisture content, etc) for co-firing. This can add to the overall cost of energy generation.

The three peat-fired power plants in Ireland generate electrical power by means of fluidised bed combustion. Fluidised bed combustion is particularly suitable for feedstocks with high moisture content (Majanne, 2013), hence its use in electricity generation from peat. This process involves the suspension of the solid material by blowing air at a high velocity from below the bed of feedstock into the combustion chamber; the high levels of turbulence experienced in the fluidised bed ensures complete combustion with low levels of excess air required (Majanne, 2013). Low levels of excess air are also associated with good thermal efficiency and low NOx emissions (Majanne, 2013).

### 2.3.2.6.2. Pyrolysis

Pyrolysis involves the rapid heating of a solid material to a specified temperature in the complete absence of oxygen or air, and the maintenance of this temperature for a specified time to produce non-condensable gases, solid char, and a liquid product (Basu, 2013). A generalised formula to represent pyrolysis of biomass is given in Equation 1 (after Basu (2013)):

![Figure 14: Options for the conversion of biomass into fuel gases or chemicals (after Basu (2013))](image-url)
The relative amount of each product formed as a result of pyrolysis depends on several operational conditions, including the rate of heating, final temperature achieved, and biomass composition among others (Kantarelis et al., 2013). The liquid product, known as bio-oil, is the main product of commercial interest as it has approximately six times the energy density of the biomass from which it derived (Kantarelis et al., 2013), increasing transportation efficiency. Bio-oil can be used in heat or power generation or in the synthesis of biofuels or chemicals (Butler et al., 2013). The gas produced during pyrolysis of biomass consists of low molecular weight, non-condensable gases such as carbon monoxide, methane, and ethane (Basu, 2013). It can be combusted to generate heat and/or electricity (Kantarelis et al., 2013). The solid char fraction is carbon-rich and has potential as a soil amendment to improve soil physical conditioning and fertility (Kantarelis et al., 2013) and can contribute to carbon sequestration (Basu, 2013).

Heating rate and gas residence time have a significant influence on the product yield. Where char is the primary product of interest, pyrolysis generally occurs at a slow heating rate and a long gas residence time; where bio-oil is the product of interest the heating rate is high but the process temperature remains low and gas residence time is short; and where gas is the product of interest pyrolysis occurs at a low heating rate to a high maximum temperature, with a long gas residence time (Basu, 2013). The product of interest will also determine the type of pyrolysis reactor used. Fixed bed pyrolysers, which operate in batch mode, are generally used for char production due to the low heating rate achieved. Fluidised bed pyrolysers, of which bubbling and circulating are the main types, are generally used when bio-oil is the product of interest. The biomass is mixed with an inert solid bed which allows for uniform temperature control and high heat transfer to the biomass solids. Circulating fluidised beds have an advantage over bubbling fluidised beds in that char is easily separated and diverted to a separate chamber where it can be combusted to provide heat for the process (Basu, 2013), however circulating fluidised beds have a higher fluidisation gas demand than bubbling fluidised beds and the use of char for heat production eliminates the potential revenue stream generated by its sale as a soil amendment (Kantarelis et al., 2013).

Research into the application of pyrolysis for either energy or chemical synthesis in Ireland is currently ongoing in a number of third level institutions as well as in the private sector. There are no commercial pyrolysis enterprises currently operational in Ireland but a number are in
the planning and development stages. One such application is the conversion of organic material into useful energy and a conversion plant is currently under development at Tullamore, Co. Offaly. When operational, this plant will convert a mixture of biomass and organic waste into heat and electrical energy for use both on-site and by means of export to the national electricity grid (Glanpower Ltd., 2012).

Pyrolysis can also be used to convert raw materials into chemicals rather than electrical or heat energy. In 2014 it was announced that Trifol Resources Ltd intended to construct a number of plastic processing plants across the island of Ireland to convert end-of-life plastics into transport fuel. It is intended that the plants will handle 42,000 tonnes of plastic which cannot or can no longer be recycled, and the process will reclaim the calorific value of the plastics and convert it into a new product for use as transport fuel (Trifol Resources Ltd., 2015). Although the source material for this fuel is not biological, the production of road transport fuel falls under the remit of the EU Alternative Fuel Infrastructure Directive (2014/94/EU). Under this Directive, synthetic fuels which replace diesel or petrol can be manufactured from, among other source materials, plastic waste which is included in a list of renewable fuel sources highlighted to reduce the greenhouse gas emissions associated with European transport (European Parliament and Council of the European Union, 2014). Although this process falls outside the parameters of the BioÉire project due to its non-biological nature, such a production facility would contribute to the circular economy, would generate value from waste material, and would aid in the development of a novel processing technology which could be applied to biological feedstocks.

### 2.3.2.6.3. Torrefaction

Torrefaction of biomass is often considered a pre-treatment which occurs prior to the gasification of biomass or its co-firing with coal. Torrefaction involves the slow heating of biomass to a temperature below 300 °C and its maintenance at that temperature for a specified length of time with the aim of achieving near complete degradation of its hemicellulose content (Basu, 2013). Torrefaction increases calorific value, water resistance, friability, and grindability of biomass (Nordins et al., 2013), facilitating the grinding and pelleting of otherwise fibrous biomass. The process temperature is kept below 300 °C as heating to higher temperatures causes loss of lignin which makes pelleting difficult (Basu, 2013). The aim of torrefaction is to maximise energy and mass balances with the reduction of carbon-to-oxygen and carbon-to-hydrogen ratios (Basu, 2013).
Torrefaction can be either wet or dry: in wet torrefaction the biomass is heated in hot compressed water whereas in dry torrefaction the biomass is heated either indirectly or by a hot inert gas (Basu, 2013). The initial stage of torrefaction is drying to remove the inherent moisture content of the biomass. After this process, which occurs at approximately 140° C, the process temperature is raised to more than 200° C which drives off any physically-bound moisture which may remain in the biomass (Basu, 2013). Torrefaction itself begins when the biomass reaches 200° C; the degree of depolymerisation that occurs is dependent on both the final torrefaction temperature achieved and the length of time at which the biomass is held at the maximum temperature (Basu, 2013). The torrefied biomass can then be ground and pelleted for use in energy generation.

Torrefaction is not currently carried out on a commercial basis in Ireland. Plans have been submitted for the construction of a plant in Limerick to convert biomass into a smokeless fuel however most recent information indicates that as yet there has been no progress on this front. Separately, a torrefaction plant with the capacity to treat 20,000 tonnes of biomass per year is undergoing commissioning in Roscommon with production anticipated to be subsequently increased to 40,000 tonnes (Johnson, 2015). The aim of this torrefaction facility is to prepare high efficiency fuels for the domestic market.

2.3.2.6.4. Gasification

Gasification is the conversion of a solid or liquid feedstock into a gaseous fuel which can subsequently be burned to release energy or used as a feedstock for chemical synthesis such as in the bio-refining platforms described earlier (Basu, 2013). Gasification involves the addition of hydrogen and removal of carbon from the feedstock to produce gases which have a higher hydrogen-to-carbon ratio than the original feedstock. Gasification requires a gasification medium such as steam, air or oxygen to drive the rearrangement of the molecules of the feedstock (Basu, 2013). The gasification medium used affects the heating value of the gases produced; highest heating values are recorded when oxygen is used as gasification medium (Basu, 2013).

There are four, often overlapping, steps in the gasification process: the biomass undergoes some initial drying before pyrolysis or partial oxidation occurs. The volatile products of this phase undergo secondary reactions and finally the remaining solid material is gasified to produce synthetic gas (syngas) and residual unconverted carbon (Figure 15) (Basu, 2013; Garcia-Ibañez et al., 2004). The syngas, which is rich in hydrogen, carbon monoxide, and
methane, can then be combusted for electricity generation. The heat produced by the
gasification process can be captured and used either internally (such as during the drying of
biomass at the beginning of the process) or in district heating systems (Lettner et al., 2007).

Gasification reactors predominantly fall into one of three types: fixed bed, fluidised bed or
entrained flow (Higman and van der Burgt, 2011). In a fixed bed gasifier the feedstock is
supported on a grate which moves down through the gasifier as a plug (Basu, 2013). The
direction in which the gasification medium moves further subdivides the classification of
fixed bed gasifiers. In updraft gasifiers the gasification medium enters the reactor at the base
and moves upward while the feedstock moves downward, with the producer gas collected at
the top of the reactor (Basu, 2013). Updraft gasification is more suitable where the producer
gas is fired directly in an on-site furnace or boiler as high tar production is associated with
updraft gasification; this tar must be scrubbed from the gas if it is to be transported long
distances prior to use (Basu, 2013). In contrast to updraft gasifiers, in downdraft gasifiers the
gasification medium enters the reactor and travels in the same direction as the feedstock bed.
The producer gas passes through a zone of high temperature ash which facilitates cracking of
the tar; downdraft gasifiers have the lowest tar production in all types of gasifiers (Basu,
2013).

Excellent mixing and uniformity of temperature are associated with fluidised bed gasifiers
(Basu, 2013; Higman and van der Burgt, 2011); fluidised bed gasification is considered to be

Figure 15: Reaction sequence during gasification of biomass (after Basu (2013))
the most advanced method for thermochemical conversion of biomass for the generation of energy (García-Ibañez et al., 2004). In bubbling fluidised bed gasifiers the gasification medium enters the reactor in a number of places (Basu, 2013) to fluidise the feedstock and maintain the correct temperature and is targeted to convert any unreacted particles to optimise gasification efficiency. Circulating fluidised beds have higher fluidisation velocity than bubbling fluidised beds and are particularly suitable for biomass due to the long gas residence time (Basu, 2013). In circulating fluidised beds, unconverted solids are recycled to the base of the reactor to achieve low tar formation (Higman and van der Burgt, 2011). Circulating fluidised beds are less restrictive on feedstock particle size and are therefore more suitable than bubbling fluidised bed gasifiers for biomass and waste material gasification (Higman and van der Burgt, 2011).

Entrained flow gasifiers require feedstock particle sizes of 100 μm or less and, as in the case of fluidised beds, operate with feedstock and gasification medium moving in the same direction (Higman and van der Burgt, 2011). Entrained flow gasifiers have a very short residence time and therefore operate at a very high temperature to ensure maximum conversion. Although entrained flow gasifiers have the capacity to easily destroy tar, the requirement to process feedstock into small particles makes entrained flow gasification of biomass impractical due to the difficulties in grinding fibrous biomass (Basu, 2013).

Unlike pyrolysis and torrefaction, gasification is currently in use in Ireland and a number of companies are involved in the manufacture, supply, and distribution of gasification boilers throughout Ireland. Gasification boilers tend to be aimed at the domestic scale in Ireland, with most boilers in the range of 20 to 60 kW and are generally designed to gasify wood logs.

### 2.3.2.7. Bioenergy Technologies

The Sustainable Energy Authority of Ireland (SEAI) lists a number of technologies which can be used to convert the energy stored in organic material into electrical or heat energy (SEAI, 2015b). A number of these have been described previously and are not specific to organic material, e.g. gasification can be used to extract energy from coal as well as from biomass. Anaerobic digestion and combined heat and power, on the other hand, are processes which are specifically suited to convert energy stored in non-fossil sources into electrical or heat energy (Figure 16).
2.3.2.7.1. Biogas Production

Anaerobic digestion is the degradation of organic material by microorganisms in the absence of oxygen. Due to the prevalent anoxic conditions, the main gases produced as a result of anaerobic digestion are methane and carbon dioxide. Anaerobic digestion occurs naturally in various environments; in such a case the gases produced are released into the atmosphere. The conditions under which anaerobic digestion occurs can be replicated and controlled in specialised reactors to optimise the process with the capture of the resulting products: in addition to the gases released a residual digestate consisting of partially digested substances is also produced (Persson and Wellinger, 2006). Other resources which can be recovered from organic wastes which are digested anaerobically include nutrients such as nitrogen, phosphorus, and specific trace metals. Anaerobic digestion for the production of methane-containing biogas is a worldwide accepted technology for treatment of organic materials rich in carbon (Kleerebezem et al., 2015).

The process of anaerobic digestion requires different microbial populations namely acidogenic, acetogenic, and methanogenic bacteria to act in sequence to degrade complex substrates to produce methane and carbon dioxide (Cerrone et al., 2014). There are four steps in the anaerobic digestion process, as summarised in Figure 17. Hydrolysis is the first step in

![Figure 16: Technologies for the exploitation of energy in organic material (after SEAI (2015b))]
the process and involves the enzyme-mediated transformation of insoluble organic materials and higher molecular mass compounds such as lipids, polysaccharides, proteins, fats, nucleic acids, etc into soluble organic materials (Adekunle and Okolie, 2015). Hydrolysis is followed by acidogenesis which involves the conversion of the hydrolysed products into simple molecules with a low molecular weight like volatile fatty acids (e.g. acetic, propionic, and butyric acids), alcohols, aldehydes, and gases like CO₂, H₂, and NH₃ (van Haandel and van der Lubbe, 2012). Acetogenesis occurs next: acetate bacteria convert the acid phase products into acetates and hydrogen (Ziemiński and Frąc, 2012). Finally, methanogenic bacteria convert acetic acid into methane and carbon dioxide which is captured as biogas.

The process conditions of anaerobic digestion for biogas production must be strictly regulated as a number of parameters can interfere with the metabolic capacity of the microorganisms. Temperature, pressure, pH, nutrient concentration, and the loading rate of the digester all influence the production of biogas. A brief discussion of the optimal conditions for anaerobic digestion is presented in Table 7. The digester conditions should be controlled and maintained to ensure stable and optimal production of biogas. That being said, there are frequent peaks and troughs of demand for this biogas, thus it is essential that an anaerobic digester have the capacity to temporarily store biogas until it is needed.

Figure 17: The anaerobic digestion process including products of each stage
The simplest way of using biogas is direct burning in boilers or burners, the most common method when the biogas is produced for on-site use. Biogas can be burned for heat production either on site or transported by pipeline to end users. Combined heat and power (CHP) generation is a well-established and efficient route for increasing the energy production of biogas. An engine-based CHP power plant has an efficiency of up to 90% and produces 35% electricity and 65% heat (Karagiannidis et al., 2012). The heat can be used on-site to heat animal housing or for pasteurisation processes, etc, or can be used in district heating systems while the electricity produced can be exported to the national grid (Browne et al., 2011). Alternatively, the biogas can be upgraded to the composition of natural gas and be used in place of natural gas via injection into the national gas grid or can be compressed and used as renewable vehicle fuel (Persson and Wellinger, 2006). Prior to this use all contaminants including carbon dioxide must be removed; the content of methane is increased from the usual 50-75% to more than 95% (Persson and Wellinger, 2006). Carbon dioxide, which must be reduced to reach the required Wobbe index of gas (SEAI, 2012a), is generally removed using either absorption (water scrubbing, organic solvent scrubbing) or adsorption. Other methods which are less frequently used are membrane separation, cryogenic separation, and process internal upgrading which is a relatively new method currently under

Table 7: Optimised conditions for anaerobic digestion of biological materials (after Sorathia et al. (2012))

<table>
<thead>
<tr>
<th>Operation Parameter</th>
<th>Ideal conditions for biogas production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Between 29 °C and 41 °C (‘mesophilic’) or between 49 °C and 60 °C (‘thermophilic’)</td>
</tr>
<tr>
<td>Pressure</td>
<td>Approximately 1.1 to 1.2 bars absolute</td>
</tr>
<tr>
<td>pH</td>
<td>Between 7.0 and 8.0 ±0.5. In the initial acid-forming stages of digestion the pH value may reduce to 6.0 or less however during methane formation a pH value higher than 7.0 should be maintained</td>
</tr>
<tr>
<td>Solids concentration and loading rate</td>
<td>The recommended loading rate is approximately 0.2 kg m$^{-3}$ of digester capacity; under- and overloading reduces biogas production. The loading of feedstock should be carried out at the same time every day to ensure a constant solids concentration</td>
</tr>
<tr>
<td>Retention period</td>
<td>From 35 to 50 days depending upon the climatic conditions. A longer retention period requires a larger digester but allows more complete digestion</td>
</tr>
<tr>
<td>Nutrient concentration</td>
<td>The major nutrients required by the bacteria are nitrogen, phosphorus, sulphur, carbon, hydrogen, and oxygen</td>
</tr>
<tr>
<td>Agitation of the contents</td>
<td>Agitation can prevent the formation of a hard scum on the surface which prevents the release of biogas</td>
</tr>
</tbody>
</table>
development (SEAI, 2012a). Once the carbon dioxide has been removed the biomethane can then be compressed to pipeline pressure and injected and distributed through the natural gas grid. Biomethane can be distributed and used through the same infrastructure used for natural gas as a vehicle fuel (SEAI, 2012a). Biomethane vehicles have substantial benefits compared to petrol or diesel vehicles including lower carbon dioxide emissions, lower particle emissions, and lower NOx and non-methane hydrocarbon emissions (Al Seadi et al., 2008).

The solid residual material which remains after anaerobic digestion is nutrient-rich and can be used as a fertiliser, replacing synthetic fertilisers and/or soil conditioners. It contains important plant nutrients including nitrogen, phosphorous, potassium, magnesium, sulphur, and trace elements in a more available form compared with the undigested materials (Monnet, 2003). The nutrient content of any digestate is dependent on the nature of the feedstock subjected to digestion (Monlau et al., 2015). As is the case for the biogas, digestate is produced year round and must therefore be stored until required as the timing of its application is restricted by international legislation (Al Seadi and Lukehurst, 2012).

Currently anaerobic digestion is used in Ireland for the treatment of organic waste though its reach is very limited. Common feedstocks treated in on-site digesters include farm wastes such as poultry litter, animal manures, and slaughterhouse waste (SEAI, 2015c). Commercial digesters usually treat larger volumes of waste and have been successfully used for the treatment of organic municipal waste, energy crops, catering waste, etc, either solely or in a mixture to optimise the nutrient content of both the feedstock and the resulting digestate; co-digesting also maximises the potential biogas yield (Ward et al., 2008). According to a report issued by the Environmental Protection Agency in 2014, a total of four merchant facilities in Ireland accepted organic material for anaerobic treatment; this figure does not include any facility which solely digests waste which arises on-site (EPA, 2014) nor does it include the facilities treating solid materials extracted as a result of wastewater treatment, of which there were seventy in 2013 (rx3, 2013).

The biological treatment of degradable wastes is encouraged by European waste legislation: the EU Landfill Directive (1999/31/EC) set targets to reduce the amount of biodegradable waste being disposed of in landfills using 1995 as a base year. In 2010 no more than 75% of the total consigned to landfill in 1995 could be landfilled; in 2013 no more than 50% of the total consigned to landfill in 1995 could be landfilled; and in 2016 no more than 35% of the total consigned to landfill in 1995 can be landfilled. The targets for 2010 and 2013 have been achieved (McCoole et al., 2014) by diverting this waste to composting and anaerobic
digestion facilities, among other treatment options. Decomposition occurs naturally in landfill sites and methane can also be captured directly from these sites; there are 24 landfill gas generators currently connected to the distribution grid for electricity generation in Ireland. Although this arises from the natural degradation of waste rather than from human intervention, landfill gas is considered a renewable gas (Dineen et al., 2015) and is therefore a biological source of energy, however the capacity to increase the capture of landfill gas is unlikely to increase as the targets imposed by the Landfill Directive point towards reductions in the volume of biodegradable waste being consigned to landfill (Dineen et al., 2015).

2.3.2.7.2. Thermal CHP Technologies

Combined heat and power generation using organic materials as feedstock predominates in the wood processing industry and in district heating systems (SEAI, 2015d). Some of the surplus material which arises from wood processing is used for the production of panelboards, pallets, etc where the quality and size specifications of the raw material are not as stringent. The material which cannot be used in these step-down industries can be channelled into energy generation, which represents a viable alternative to disposal and adds value to the wood production chain. CHP generation is achieved through combustion of the organic feedstock, often crop- or wood-based materials, with the production of heat. This heat is used either directly for space heating purposes or is used to generate steam to power a turbine which in turn generates electricity (SEAI, 2015d). It was reported that 7.4% of the electricity generated in Ireland in 2013 was associated with CHP; co-firing with peat was responsible for 215 GWh of electricity while 14 GWh of electricity was associated directly with biomass CHP (Dineen et al., 2015). An additional 24 GWh of electricity was generated from sewage sludge gas CHP units.

In 2006 a grant aid scheme was announced to support the establishment and development of small-scale CHP in Ireland; this scheme closed in 2010 with support for biomass CHP now financed through the REFIT 3 scheme (Holland and Howley, 2014). According to Holland and Howley (2014) there are no operational biomass CHP plants in Ireland supported by this scheme yet. Twelve new units came into operation in 2013 producing a combined total of 4.0 MWe; most of these units are in the services sector. The total installed capacity of CHP in Ireland at the end of 2013 was 334 MWe, an increase of 1.2% from 330 MWe in 2012 (Holland and Howley, 2014). The Aughinish Alumina plant is the single largest CHP installation and accounts for 160 MWe. This plant is fuelled by natural gas, which is the
preferred fuel (92%) for installed CHP capacity in Ireland followed by oil fuel (2.9%) and biogas (2.0%) (Holland and Howley, 2014). Although CHP with natural gas is an efficient method of generating electricity and heat, biomass CHP represents a more sustainable and renewable form of energy generation and there is significant scope to increase the penetration of renewable CHP in Ireland to achieve the renewable heat targets outlined by the Renewable Energy Directive.

2.4. Current Outputs of the Irish Bioeconomy

2.4.1 Agriculture Supply Chain

The Irish agriculture supply chain has a significant number of output types, including animals, cereals, and horticultural produce; this list is representative of the outputs that derive from the Irish agricultural sector and additional by-products such as animal manures are also considered to be outputs of this industry. Although they may be unavoidable and unintentional, this does not imply that there is no value associated with these by-products. As such, each of the output types associated with the agriculture supply chain is presented and discussed. Estimations of the overall value of (intended) gross output from Irish agriculture at producer prices are outlined in Table 8 which also presents agricultural output in 2014.

2.4.1.1 Quality Assurance in the Irish Agriculture Supply Chain

Ireland has a long standing history of agriculture production and is known globally for its high quality produce. A number of measures have been implemented at national level to protect and maintain this reputation. Describing each of the measures in place would be a formidable task; instead, a select few which relate directly to the outputs of the agriculture sector are described briefly.
Numerous steps and stakeholders can be involved in the movement of animals from farmer to end consumer. Generally speaking the more steps and intermediaries that are involved the greater the challenges of disease control and maintaining traceability. As such, many farmers in Ireland sell directly to abattoirs to assist with disease control and other matters of biosecurity. Wider supports and structures are also in place in Ireland to maintain the reputation of high quality animal outputs from the agricultural sector. This includes a sophisticated cattle movement and monitoring system (CMMS) that allows for the rapid identification of animal origin should any breach of biosecurity occur; this system proved particularly successful during the BSE crisis, for example. While Ireland has operated a cattle identification and tracing system using tags and cards since the 1950s, the CMMS was established in January 2000 to act as a centralised, computerised database tracking all movements of bovine animals nationally (Teagasc, 2015f). This system provides credible assurance to the safety, quality, and traceability of Irish beef. Additional quality criteria and standards are also operational in the country that further boost the reputation of Irish agricultural output. This includes the EUROP grading system for uniform carcass classification and the Economic Breeding Index used to identify the most profitable and optimal animals for breeding in the dairy sector.

Thorough inspections and standards regarding the somatic cell count and total bacteria count in milk are also commonplace in Ireland, providing assurances regarding levels of on-farm hygiene and animal health. The Bord Bia Quality Assurance scheme imposes minimum standards in animal health, welfare, and traceability, water and feed, environmental management, pasture management, and farm safety across participating agricultural sectors in

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>% Change 2014 over 2013</th>
<th>Share of GO/Inputs (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Volume</td>
<td>Price</td>
</tr>
<tr>
<td>Gross output at producer prices</td>
<td>7,057.1</td>
<td>-2.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Cattles and calves</td>
<td>2,010.6</td>
<td>-6.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Pigs</td>
<td>471.3</td>
<td>-0.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Sheep and lambs</td>
<td>232.7</td>
<td>14.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Poultry</td>
<td>137.2</td>
<td>4.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Milk</td>
<td>2,077.9</td>
<td>0.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Cereals</td>
<td>233.8</td>
<td>-19.1</td>
<td>3.5</td>
</tr>
<tr>
<td>Potatoes</td>
<td>88.7</td>
<td>-46.1</td>
<td>-2.6</td>
</tr>
<tr>
<td>Fresh vegetables and fruit</td>
<td>262.4</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Forage plants</td>
<td>1,127.9</td>
<td>-2.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Other</td>
<td>403.7</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Ireland. All of these standards directly influence the amount farmers pay, and are paid, for animals. Accreditation is open to producers across the spectrum of agricultural produce including lamb, beef, dairy, pig meat, poultry, eggs, and horticulture producers.

### 2.4.1.2. Animals

#### 2.4.1.2.1. Cattle

The importance of cattle in the Irish agricultural supply chain cannot be underestimated. Beef and dairy farming accounts for approximately two thirds of all farm types in Ireland with specialist beef production constituting 55% of all farms and dairy farming a further 11% (CSO, 2012a). A number of stakeholders can be involved in cattle production from calving stages to the finished animal, with the potential for animals to be born on one farm, reared on another, and final fattening (finishing) taking place on a third. The Irish beef and dairy industries are thus considered to be highly specialised (Garnett, 2007). The density of cattle per hectare of agricultural land in Ireland is considerably high at 1.40 cattle ha
\(^{-1}\) relative to the global average of 0.32 cattle ha
\(^{-1}\) recorded in 2011 (FAO, 2014). The Irish reputation for high animal welfare standards, sustainable grass-based systems, and a wider clean, green reputation has resulted in widespread demand for Irish beef worldwide.

Irish beef farming can be subdivided into suckler producers, fatteners, and cattle finishers with implications for profitability and quality associated with each farming system (DAFM, 2015b). The most popular beef breeds in Ireland which are bred specifically for their meat yielding capacity include the Charolais, Limousin, Angus, Belgian Blue, and Hereford. Suckler calves in the beef industry are fed on their mother’s milk for the first six months before being weaned. In weaning and finishing stages, beef cattle grow rapidly, gaining up to 1.5 kg day
\(^{-1}\) in muscle mass (Garnett, 2007). This finishing stage can take place with the original breeder or when sold onto another farm. Garnett (2007) reported that in the UK bulls are slaughtered by the age of 12-15 months while heifers and steers reach slaughter weight at a slower pace, typically slaughtered around 18-24 months.

In addition to transferring animals to other farms for finishing, links also exist between beef and dairy farmers, with any male calves born on dairy farms being transferred to the beef sector. In the UK, Garnett (2007) mapped trends associated with pure dairy-bred calves entering the meat chain, estimating that these calves account for approximately 65% of all meat output. Dairy cows that have reached the end of their productive life in terms of milk
yields also enter the meat chain though their bodies produce little meat due to genetic makeup and breeding patterns focusing on milk rather than muscle production (Garnett, 2007). Dairy cows thus receive a lower price at the slaughtering stage compared to beef cattle. The most common dairy breed in Ireland is the Holstein-Friesian, with a need for herds to be restocked at a rate of approximately 20% a year to replace cows that no longer produce milk as a result of ill health, old age, or low yield (Garnett, 2007).

The EUROP grading systems provides a means by which to calculate the amount to be paid to the farmer for each animal entering the food chain. This system grades the animal according to its conformation class (including the shape of the carcass and amount of flesh relative to the size of the bones) and fat class (the amount of fat visible on the outside of the carcass). The price a farmer receives for each animal is then calculated by multiplying the carcass weight by the classification price for a particular category of animal (that is, heifer, steer, bull, or cow). In August 2015 the majority of steers received a base price of approximately €4.05 kg$^{-1}$ while the average price for heifers was closer to €4.15 kg$^{-1}$ (Bord Bia, 2015b). It was noted that selected steers and heifers achieve higher prices, while the figures also exclude bonuses payable on Quality Assured animals. Overall, carcass classifications have shown improvements in conformation and fat across cattle categories since 2010. Heifers have shown the most improved conformation in recent years with almost 15% classified in high quality E and U grades in 2014 as opposed to just 7% in 2010 (Bord Bia, 2015c).

DAFM (2015b) estimates that there were 6,926,000 cattle in Ireland in 2014, down from 7,016,000 in 2004. It was further estimated that approximately 1.75 million head of cattle were sent for slaughter in Irish slaughterhouses and meat processing plants in 2014, categorised as steers (37%), cows (22%), heifers (26%), young bulls (11%), and mature bulls (3%) (DAFM, 2015c) with the vast majority slaughtered at export-approved meat plants (approximately 552,000 tonnes) compared to local abattoirs (approximately 31,000 tonnes) (Bord Bia, 2015c). While some farmers sell directly to abattoirs, over 60 livestock-related co-operative mart centres operate in Ireland providing farmers with a means to join together to create economies of scale and engage in transparent methods of selling. Over one million cattle in Ireland are sold in co-operative livestock marts each year (ICOS, 2015). In recent years farmers have come together on a regional basis to promote Protected Designation of Origin products, differentiating and marketing their livestock on a geographical basis. This is framed as a significant growth opportunity for Irish livestock farmers by the ICOS (2015).
A distinct seasonality to livestock production exists meaning that weekly cattle availability for processing can fluctuate between 25,000 and 38,000 head (Enterprise Ireland, 2009). Figures from August 2015 highlight cattle supplies of approximately 29,700 head at export meat plants in Ireland (Bord Bia, 2015b). Figure 18 provides an overview of the beef supply chain in Ireland, including detail on tonnes processed, imported, exported, and consumed domestically.

Beef production in Ireland was up by 13% in 2014 (DAFM, 2015c), reaching a total of 585,000 tonnes. In addition to beef products and exports (discussed in detail in the food supply chain section of this report), live animal exports accounted for 2% of overall agri-food exports in 2014 (Bord Bia, 2015a). This small figure should not be underestimated, however: live exports represent an important additional market and stable income for Irish farmers, particularly in times of volatile beef prices and considerable market strength possessed by a small number of powerful domestic beef processors (Flanagan, 2015). In 2014 live exports

Figure 18: Overview of beef supply chain in Ireland (after Bord Bia (2015c))
included approximately 240,000 head of cattle (DAFM, 2015c), up from 200,000 head annual average in 2010 (DAFF, 2010a). In economic terms, this equated to a value of over €172 million (DAFM, 2015b), up from €160 million averaged in 2010 (DAFF, 2010a). Live cattle exports have increased by 48% between 2012 and 2014 with the exportation of calves increasing almost three fold in this period (Bord Bia, 2015c).

The recent growth in live exports was partially facilitated by improvements in transport capacity that led to an increase of 61% in live cattle exports to the UK in 2014 (DAFM, 2015c), while low milk replacer costs (one of the main production costs) has also bolstered demand for calves for veal production (Bord Bia, 2015c). Additional trade in live exports also took place to Belgium, Spain, and the Netherlands, increasing by 11%, 20%, and 21% respectively in 2014 while shipments to non-EU markets grew by 21% in 2014 driven largely by an increase in exports to Libya and Tunisia. Most live exports to EU destinations consist of calves and weanlings (weaned young adult cattle) while trade to non-EU markets tends to consist of cattle that have reached final production stages. This latter situation means that any potential value addition through processing is not retained in Ireland despite investment in the animal to its finished stage. Approximately half of the overall live export trade (101,600 head) in 2014 were calves while a further 75,336 exported animals consisted of weanlings and stores (grown but not finished animals up to two years of age) (Bord Bia, 2015c). This leaves 60,191 heads of finished cattle being exported, equivalent to approximately 25% of overall live cattle export trade (Bord Bia, 2015c). Longer term trends in live cattle exports are outlined in Figure 19, detailing fluctuations in live export categories between 2005 and 2014.

Figure 19: Irish live cattle exports 2005-2014 (after Donnellan et al. (2015))
2.4.1.2.2. Pigs

Traditionally, pig rearing in Ireland was characterised by the presence of a small number of pigs on a large number of farms, with only one or two sows per farm household (Lafferty et al., 1999). Considerable changes have ensued since the 1970s as profitable pig production became increasingly interlinked with a need for more animals per farming unit. Modern pig farming is now a highly specialised and intensive activity in Ireland, dominated by a small number of large producers: CSO (2012a) recorded 1,200 farms containing pigs in Ireland in 2010, however the Teagasc National Farm survey of 2011 showed that the overwhelming majority of pig meat produced in Ireland originates from just 290 commercial herds (ENFO, 2015). Reflective of the increased intensification and industrialisation of pig production since the 1970s (Lafferty et al., 1999) these large commercial units contain approximately 520 sows per farm.

Total pig numbers in Ireland in 2014 were 1,555,000, down from 1,653,000 pigs in 2004 (DAFM, 2015b). Compared to pig numbers of 26,900,800 in Germany (The Pig Site, 2012) pig production in Ireland can thus be considered to be reasonably small scale. From an economic standpoint however, pig production ranks third in importance behind beef and dairy production in Ireland (ENFO, 2015), and pig meat accounted for approximately 8% of the output value of the agri-food sector in Ireland (excluding forage) in 2014 (DAFM, 2015b). Irish pig production is considered to be a highly efficient, technical, and regulated industry (Teagasc, 2008). The top Irish producers achieve an output of 23.1 pigs per sow per year, comparable with best practice internationally (ENFO, 2015). The latest figures released from DAFM report that there are approximately 440 commercial pig producers in Ireland producing 3.5 million pigs per year. DAFM (2015c) states that approximately 3.04 million pigs were slaughtered in 2014.

Based on the latest pig census conducted by DAFM the average size of an active pig herd in Ireland in October 2014 was 668 pigs (based on a farmer response rate of 88%) (DAFM, 2014g). Almost 50% of active herds report hosting 20 pigs or less however, while only 1.8% of active herds keep over 10,000 pigs. These 40 herds are responsible for more than 40% of total pig production in Ireland, highlighting a system with many small players at one end of the scale and significantly intensified production at the other. As in the beef industry, animals are classified according to their weight and conformation, with implications for the type of meat production pursued. For example, larger pigs are typically sent for ham production while smaller weights are sent for pork production. The type of meat production pursued has
implications for the farmer in terms of housing and feed costs in particular. The average carcase weight of a pig slaughtered in Ireland in 2014 was 80.5 kg, with net production totalling 254,000 tonnes of pig meat. An overview of the pig meat supply chain is outlined in Figure 20, highlighting the dominance of export meat plants for processing; details on the tonnes of pig meat exported, imported, and consumed in Ireland is also included in the figure.

2.4.1.2.3. Poultry

In the past, poultry were kept on a free range basis on many farms throughout Ireland, providing a much needed additional source of income for farmers. Similar to Irish pig production trends, modern poultry production has become increasingly specialised and concentrated in Ireland, though poultry are still often also kept on specialist dairy and mixed grazing farms (Lafferty et al., 1999). Poultry production represents a particularly important industry in the northeast of Ireland with chickens, geese, turkeys, and ducks fattened for meat

![Figure 20: Overview of pig meat supply chain (after Bord Bia (2015c))](image)
production and hens and ducks kept for egg production (ENFO, 2015). Poultry represents one of the few meat sectors to experience robust growth in the EU between 2000 and 2011 (FAO, 2014), perceived as a cost-effective and healthy source of protein (DAFM, 2015b).

It is estimated that 70 million chickens in addition to 4 million turkeys are produced every year in Ireland (Teagasc, 2015g). Approximately 76.17 million birds were slaughtered in 2014 (DAFM, 2015c) with annual output value of the poultry sector reaching €137.2 million. The industry accounted for 2% of overall agricultural output (DAFM, 2015b) and equated to approximately 166,000 tonnes of poultry meat (Bord Bia, 2015c). Broiler chickens account for the vast majority of poultry production in Ireland (85%) followed by turkeys (8%), ducks (5%), and hens (2%) (Bord Bia, 2015c). There has been a 14% decline in the number of birds processed in Ireland since 2012, with the 2014 figure representing the lowest level of throughput since 2010 (Bord Bia, 2015c). Output value has also decreased, with the average output value of poultry production in Ireland standing at approximately €150 million in 2010 (DAFF, 2010a). Approximately €120 million of this value derived from poultry meat while €30 million was associated with egg production (DAFF, 2010a). Irish poultry is usually reared for a pre-agreed price under contract to processors and is thus not subject to the same price fluctuations as other meat sectors (DAFM, 2015c).

In contrast to Irish beef farmers who export 90% of their output, the predominant market for Irish poultry and in particular fresh, raw Irish product lies in the domestic retail market. Whole chickens constitute the largest proportion of retail poultry sales, followed by chicken fillets and chicken legs and wings; the remainder of sales is made up of value-added chicken, turkey, and duck (Bord Bia, 2015c). By contrast, the vast majority of poultry meat used in the Irish food service sector is imported (DAFM, 2015b), perhaps representing an untapped niche market for Irish poultry farmers. Competition from cheap imports represents one of the most significant challenges facing the Irish poultry sector in recent years, representing a threat to indigenous poultry farming now and in the future. Increased consumer awareness regarding the origin of meat coupled with increasingly stringent country-of-origin labelling laws may encourage domestic poultry purchases in the Irish food service sector.

The Irish egg sector is estimated to account for approximately €49 million of agricultural output. About 250 egg producers operate across Ireland with a further 800 people employed in packing and ancillary activities (DAFM, 2015b). Teagasc (2015g) reported that the annual production of eggs in Ireland derives from 2 million hens each year. The domestic market is most important within the egg sector with 85% of the total eggs consumed in Ireland
produced domestically (DAFM, 2015b). Excellent *Salmonella* status and the support of renowned quality assurance schemes further the popularity of Irish eggs, with an estimated 45,000 tonnes of eggs produced in 2011 (FAO, 2014).

### 2.4.1.2.4. Sheep

Traditionally the sheep sector has not been as important as cattle in Irish agriculture and has witnessed a number of periods of expansion and decline over the last 100 years (Lafferty *et al.*, 1999). A distinct geography exists to sheep farming in Ireland, with two principal types of sheep production dominating. Lowland sheep farming utilises more concentrated feed as an input with the Easter lamb market the primary output focus, in contrast to sheep production on hillsides and in mountainous regions which tends to be less intensive, using less concentrated feed and different breeds of sheep. This latter form of production represents an important agricultural activity in more remote regions in Ireland with unsuitable grazing or tillage characteristics. Less demanding in housing, feedstuffs, and capital investments, sheep have the capacity to utilise poorer quality grazing land and withstand harsher weather conditions better than other animal sectors. Carrying out essential land management functions on hillsides, sheep are also an important source of income on part-time farms as well as on some mixed large-scale farms (Teagasc, 2008). Margins are considerably tight in sheep farming, however, and it is a sector that is heavily reliant on subsidies and external support.

The total number of sheep in Europe has reached approximately 83 million (European Commission, 2015a). Almost 5,000,000 of these were in Ireland in 2014, down from 6,777,000 in 2004 (DAFM, 2015c). According to ENFO (2015), the Irish sheep flock contracted by one fifth between 2005 and 2010 due largely to heavy labour demands, an aging sheep farmer population, and poor returns. Some increases in stock began to occur in 2010 for the first time in over ten years, in response to a tightening global supply. Irish flocks tend to be very small scale compared to international standards: while Scotland averages a flock size of over 200 and New Zealand boasts flock sizes of 1,400, 50% of sheep flocks in Ireland are made up of less than 50 ewes (ENFO, 2015). Geographically, over one third of total sheep numbers are concentrated in the northwest and west of Ireland (Bord Bia, 2015c). Approximately 2,492,690 sheep were slaughtered in Ireland in 2014 including some 373,530 animals imported directly for slaughter from Northern Ireland (DAFM, 2015c). Output value of the Irish sheep sector increased in the same year, experiencing a 14% rise in 2014 (DAFM, 2015c). This was largely driven by a 3.5% increase in the average factory price of sheep
meat. Primary output from the sheep sector was worth €230 million in 2014, a value that has grown considerably of late according to DAFM (2015b). In contrast to other livestock sectors, only three dedicated manufacturing plants operate in Ireland to handle sheep and lamb throughput (Enterprise Ireland, 2009). Sheep meat is therefore often also processed in facilities that handle both beef and lamb outputs, including in some of the 30 licenced beef slaughtering facilities (Enterprise Ireland, 2009). In 2014, 13% of total sheep disposed in Ireland were ewes and rams, 23% were hoggets (young sheep typically between 9 and 18 months of age), and 64% were lambs (Bord Bia, 2015c), highlighting the significance of the Irish lamb market. Net sheep meat production totalled 58,000 tonnes in 2014 and was processed, exported, and consumed alongside a low volume of imports (Figure 21).

With the EU only 88% self-sufficient in sheep meat (European Commission, 2015a), opportunities for Irish sheep meat exports have emerged in recent decades. Ireland is in the top eight sheep meat-producing states in the EU despite its apparent small scale production.

Figure 21: Overview of sheep meat supply chain in Ireland (after Bord Bia (2015c))
Limited domestic demand for sheep meat, with only 30% of overall production consumed domestically (DAFM, 2015b), results in two out of every three sheep in Ireland being exported (ENFO, 2015; DAFM, 2015b). Live sheep exports from Ireland have increased substantially in recent years from approximately 17,094 head in 2011 to 46,745 head in 2014. In economic terms, this live export trade equated to a value of around €7 million in 2014. Record levels in 2013 (almost 70,000 head) were largely driven by new trade with Libya (Bord Bia, 2014) though this effect had already begun to ease by 2014 (Bord Bia, 2015c). The highest proportion of live sheep from Ireland go to continental Europe, primarily France, Germany, and Italy (Bord Bia, 2015c).

Producing sheep meat also generates another potentially valuable output: wool. According to the FAO (2014) 14,000 tonnes of wool were produced in Ireland in 2011. Only six wool mills were in operation in 2011 according to Feller (2011), with just three of these commercially producing yarn for hand knitting. This compares to the 1900s when most towns in Ireland had a mill of some size, reflecting the declining importance of raising sheep for wool as opposed to for meat (Feller, 2011). This decline is compounded by the low selling price obtained for wool that often results in Irish farmers selling this output at a loss. While an average sheep produces 2.5-3 kg of wool, even the top prices paid for high quality lowland wool (approximately €1.20 kg⁻¹ in 2014) often does not cover the costs of shearing (€2-3 head⁻¹) (ICAS, 2014).

2.4.1.3. Milk

Due to the grass-based nature of the system, milk production in Ireland is a highly seasonal activity with a peak-to-trough ratio of 7:1 (May vs January) (IFA, 2014). This is primarily due to farmers adjusting calving dates to maximise the use of grazing in an effort to produce milk at the lowest possible cost (DAFM, 2015b). Ireland benefits from a long growing season compared to other countries, reducing the costs of production for Irish dairy farmers (Lafferty et al., 1999). In keeping with trends evident in other Irish agricultural sectors, milk production has become increasingly concentrated and specialised in recent years. Despite significant declines in dairy farmer numbers since the introduction of the European milk quota regime in 1984, the average quantity of milk delivered by each producer has increased, resulting in relatively static milk production volumes over the past decade. The milk quota regime also brought stability to the sector in the last few decades by restricting output growth (Prospectus, 2003). The recent abolition of milk quotas forms a central feature and focus of
all national agricultural policies and strategies developed in recent years (DAFM, 2015b; DAFF, 2010a) and will have implications for herd densities in the near future. The current scale of dairy farming in Ireland has been classed as moderate by Enterprise Ireland (2009) with average herd sizes of 40 cows compared to 110 in the UK and 170 in New Zealand.

Two key systems of milk production operate in Ireland. The first constitutes the liquid milk supply which accounts for almost 10% of overall milk production. Bord Bia (2015c) estimate this production figure to stand at approximately 480 million litres, leaving 5.7 billion litres for further processing into products such as cream, butter, cheese, and milk powders. Liquid milk must be produced year round to meet demand and thus farmers engaged in this activity often receive a premium payment from processors to cover extra feeding, housing, and milking costs. Milk sent for further manufacturing can be more seasonal in terms of supply, although this creates complications from a capacity and handling perspective, as will be discussed later. There are a total of 13 milk powder plants, nine butter plants, eight cheese plants, and four infant formula factories across the country (ICOS, 2015).

The average number of cows per dairy farm in Ireland increased by 89% between 1991 and 2001 from 24.2 to 45.7 cows, though average milk yield increased by only 14% to 180,000 litres by 2001 (Prospectus, 2003). By comparison, figures from 2015 highlight an average milk yield of 300,000 litres of milk per dairy farm, with herds averaging approximately 50 cows in 2015 (ICOS, 2015). This highlights increased efficiencies within the Irish dairy sector in recent years. Scope for further efficiencies remains however, with the average dairy cow in Ireland yielding 4,429 litres of milk compared to 8,495 litres in Denmark and 9,314 litres in the USA (ICOS, 2015); the Irish figure is higher than observed yields in New Zealand (3,650 litres), however. This difference in yields may be more symptomatic of the milk solids payment schemes operating at a processing level in New Zealand whereby value is attributed to percentage levels of protein and fat as opposed to volume. This has led farmers in New Zealand to opt for a Jersey cow or a cross between Jersey and Friesian, renowned for their high fat but low volume milk yield (Prospectus, 2003).

Overall, figures from 2015 indicate just over 17,000 dairy farmers in Ireland milking 1.1 million cows and supplying 5.5 billion litres of milk (ICOS, 2015). The imposed milk quota regime has certainly restricted output growth in this sector in recent decades. For example, Prospectus (2003) reported an overall milk production volume of 5,338,000 tonnes in 2001, similar to European counterparts such as Denmark (4,418,000 tonnes). By contrast, in New Zealand where there was no cap, production levels reached 12,322,000 tonnes in the same
year, a 74% increase on their 1991 levels. This highlights a previous restriction in the Irish dairy sector; the abolition of milk quotas will level the playing field internationally somewhat. Government targets established in Food Harvest 2020 (DAFF, 2010a) aim to increase milk production in Ireland by 50% by 2020, increasing milk output to over 8 billion litres. Current milk production in Ireland accounts for just 0.75% of the global milk supply, producing just 5.5 billion litres of the 720 billion litres of milk produced annually (ICOS, 2015). Even with the abolition of milk quotas, while important in a national context, the Irish dairy sector will still only account for a little over 1% of the global milk supply. Although Irish dairy farms produce enough milk to feed 52 million people (ICOS, 2015), Irish milk production can be considered small scale in a global context.

The importance of the dairy sector in Ireland must not be underestimated however, with beef and milk production accounting for approximately 60% of Irish agricultural output at producer prices (ICOS, 2015). In 2014 Irish milk output (whole milk only) was valued at €2.09 billion driven by strong milk prices during peak production, continued good weather conditions, and increases in production in the run up to the abolition of quotas (DAFM, 2015c). Overall, however, farmers were paid an average of €0.383 l⁻¹ in 2014, down 3% compared to the €0.395 l⁻¹ paid in 2013 (DAFM, 2015c). Worrying predictions by Donnellan et al. (2014) estimated a further price drop of up to 28% in 2015 with world dairy markets reported to be in a state of oversupply. These predictions have come true, with the Dairygold co-operative paying just €0.27 l⁻¹ in June 2015 (Halleron, 2015). This has significant implications for any future increased output from the Irish dairy sector and highlights the price volatility experienced by Irish dairy farmers. It also re-emphasises the vulnerability of Irish agriculture operating in global markets.

2.4.1.4. Cereals

The most suitable land for tillage in Ireland lies in the south and east of the country due to favourable soil and climatic conditions. As such, 80% of the total land area devoted to cereals in Ireland in 2010 is located in the southeast (CSO, 2012a). Arable farming has played a minor role in the history of Irish agriculture in the past, accounting for just 8.8% of total area farmed in 1991 (Lafferty et al., 1999). Cereal production accounted for 77% of this production, with barley and wheat the most popular crops. The situation has remained largely unchanged in the decades that followed, with an estimated 8% of land (378,000 ha) devoted to crop production in 2015; cereals account for more than 80% of this total (DAFM, 2015j).
Similar to the dairy sector, Irish tillage production is highly concentrated and comprises approximately 11,000 growers (DAFM, 2015b). Less than half of these farmers practice tillage as the primary farm enterprise (approximately 4,000 growers) meaning tillage farming is often carried out in conjunction with other farming activities such as beef or dairy production. An additional 15,000 people are estimated to be employed in the crop-based processing sector (DAFM, 2015j). Specialist tillage farms produced 64% of all Irish cereals in 2010 despite constituting only 40% of farms growing cereals (CSO, 2012a). On average total crop output equates to between 2 and 2.5 million tonnes per year in Ireland (DAFM, 2015j). Despite boasting some of the highest cereal yields in the world, Irish output accounts for just 1% of EU production, ranking Ireland as small scale in terms of tillage production in Europe. Prospects for further increased yields remain positive, with DAFM (2015j) estimating potential increases by up to 1% per annum. One of the principal features of the Irish tillage sector, however, is that 50% of tillage production takes place on leased land. This has implications for the future expansion, competitiveness, and profitability of this agricultural sub-sector.

The principal market for Irish cereals lies in the provision of animal feedstuffs, with an estimated 75% of the cereal harvest going to sustaining the livestock sector (DAFM, 2015j). The remainder is used in the malting, milling, and food processing industries. A key opportunity identified in Food Wise 2025 for this sub-sector lies in the creation of direct linkages between Irish tillage and livestock farms for the simultaneous trade of organic manures to reduce fertiliser costs on tillage farms and direct provision of domestic feed for Irish livestock (DAFM, 2015b). To support tillage farmers, Teagasc issues a number of crop reports each year providing the most up-to-date information on crop disease and pest control, recommendations for treatment, as well as information on the growth status of Irish crops. These reports are issued every three weeks during the growing season with additional supplements on seeds, autumn crops, and final harvest figures provided throughout the year.

At a European level, cereal production reached record highs in 2014 due to favourable weather conditions, with production up more than 50 million tonnes on 2012 figures to reach 327 million tonnes (DAFM, 2015c). This productivity was mirrored on a global scale, with cereal production estimated to be up 10% in 2014, exceeding 2 billion tonnes for the first time in history (DAFM, 2015c). In an Irish context, cereal volumes totalled 2.56 million tonnes in 2014, far exceeding the average annual harvest of 2 million tonnes (DAFM, 2015c). DAFM (2015b) reports this as the highest cereal production figure in Ireland since 1985.
Despite such increases in overall volume and productivity however, the total value of the cereals sector in Ireland in 2014 was down 19% to €234 million due to continued decline in world cereal prices (DAFM, 2015c).

Increased yields and efficiencies in the sector in 2014 were bolstered by an increased focus on the production of winter cereals. Expansion of winter barley has been actively encouraged at the national scale in recent years for example, with the area devoted to this crop increasing from 15,000 hectares in 2006 to approximately 42,000 hectares in 2014 (DAFM, 2014b). Total barley production was up 5% in 2014 to 1.7 billion tonnes, making it the most cultivated cereal crop in Ireland and accounting for approximately two thirds of cereal production (214,000 ha) (DAFM, 2015j). While the majority of barley output is used as animal feed, a significant proportion (23,500 ha) is utilised in the malting and roasting industries. Demand in both industries is expected to increase in the coming years under governmental plans for growth in the agri-food and beverage sectors, with aims to double exports of Irish whiskey to 12 million cases per annum by 2020 and expand the number of Irish distilleries from four to 20 in the near future (DAFM, 2015b; DAFF, 2010a). Such growth must be cognisant of the different quality requirements for cereals depending on intended final use, such as the moisture and protein content.

Total production of wheat in Ireland in 2014 reached 706,000 tonnes, an increase of 32% on 2013 primarily driven by increased winter wheat yields (DAFM, 2015c). This equated to approximately 70,000 ha dedicated to wheat production in 2014 though this figure has fluctuated considerably in recent years both in terms of area planted and yield achieved (DAFM, 2015j). Such fluctuations are primarily influenced by variable winter wheat production due to poor weather conditions. A high cost crop in relation to fertiliser, fuel, and crop protection inputs, Irish wheat is utilised both as animal feed and for milling purposes (approximately 50,000 tonnes annually) (DAFM, 2015j). Achieving consistent quality in Irish wheat production remains a challenge, resulting in significant proportions of the wheat yield often being rejected by the milling industry due to excessive sprout damage or poor seed specific weights. There is potential to increase wheat yields in Ireland to displace imported feeding costs as livestock sectors expand (Teagasc, 2008), particularly as Ireland is considered only 80% self-sufficient in grain (DAFF, 2010a). Such expansion may be constrained by the associated high input costs and emerging fungicide resistance in wheat varieties (DAFM, 2015j), however.
A domestic demand for approximately 160,000 tonnes of oats is reported for Ireland (DAFM, 2015j), however Irish oat production decreased by 22% in 2014 to 146,000 tonnes (DAFM, 2015c). Most of the oat output is used for food purposes (principally porridge) though the crop is also used as a premium feed for sport horses while lower quality grades are utilised as ruminant rations. Decreasing oat production in the US and Canada highlights export opportunities for Irish oats in the future, though there is a need to diversify away from the traditional Barra variety to improve disease resistance, oat durability, and yields (DAFM, 2015j). Further demand for oats is predicted due to their health and nutritional benefits.

The volume of grain exports emerging from Ireland fluctuates considerably but usually amounts to between 200,000 and 300,000 tonnes per annum (mostly wheat and barley). The majority of this grain is sent to Northern Ireland and Great Britain for use as animal feed (DAFM, 2015j). A further breakdown of oat, wheat, and barley output is provided in Table 9.

Additional protein crops, oilseed rape, maize, and beet are also cultivated in Ireland though in much lesser volumes. Table 10 highlights the volumes of pulses, oilseed rape, and maize produced in the Irish agricultural supply chain and their relative position to the dominant crop types. Projections for further growth in the Irish tillage sector by 2020 are also included in this table, though DAFM (2015j) are keen to highlight that these volumes do not represent targets and will be influenced by competition for other land uses such as the expected expansion in dairy. Such figures nonetheless highlight the opportunities for growth in the wider Irish tillage sector, with the potential for increased production to replace a proportion

Table 9: Area, yield, and production of cereals in Ireland in 2014 (after DAFM (2015c))

<table>
<thead>
<tr>
<th></th>
<th>Production '000 tonnes</th>
<th>Area '000 ha</th>
<th>Yield t ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>655</td>
<td>64</td>
<td>10.2</td>
</tr>
<tr>
<td>Spring</td>
<td>51</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Total Wheat</td>
<td>706</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>553</td>
<td>60</td>
<td>9.3</td>
</tr>
<tr>
<td>Spring</td>
<td>1,158</td>
<td>154</td>
<td>7.5</td>
</tr>
<tr>
<td>Total Barley</td>
<td>1,711</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>85</td>
<td>10</td>
<td>8.6</td>
</tr>
<tr>
<td>Spring</td>
<td>61</td>
<td>8</td>
<td>7.3</td>
</tr>
<tr>
<td>Total Oats</td>
<td>146</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Total Cereals</td>
<td>2,563</td>
<td>302</td>
<td></td>
</tr>
</tbody>
</table>
of the cereals currently imported for animal feed, underpin expansion in the Irish dairy and livestock sectors, and further provide high quality, traceable raw materials for both food (e.g. malting, milling, distilling, and oils) and non-food (e.g. bio-chemical and biofuels) uses. Recent efforts to develop the links between human health and cereal consumption also present an opportunity in the tillage sector from a food use perspective.

Irish agricultural land dedicated to oilseed rape has increased in Ireland in recent years, though weak market prices have led to fluctuating commitment to this crop (DAFM, 2015j). Oilseed rape production has expanded from 2,300 ha in 2003 to between 8,000 and 12,000 ha in recent years, with the winter crop deemed particularly successful accounting for two thirds of total production (DAFM, 2015j). Increasing interest in the use of oilseed rape as a food ingredient highlights further opportunities to expand production in the future, though there is a distinct need to secure a stable market for this output and bring necessary investment to related processing infrastructure and into research and development activities. Maize, by comparison, is predominantly grown for whole crop silage production with approximately 20,000 ha dedicated to maize cultivation in Ireland. Producing a high energy animal feed, maize can provide a lower cost option for fodder production with low transport density costs and only one harvest necessary per year (DAFM, 2015j). Investment is required to develop alternative maize varieties which are more resistant to seasonal variability, however. Finally, although sugar beet production ceased in Ireland in 2006, beet production for animal feed continues in Ireland, occupying about 8,000 ha. Recent political agreement to abolish sugar quotas by 2017 has renewed interest in this tillage sub-sector. In 2006, Irish beet production occupied 35,000 ha resulting in an output of 1.2 million tonnes (DAFM, 2015j). To replicate and increase this production will require significant future investment, viable commercial propositions, and robust business cases to develop growing and processing opportunities for the beet industry.

Table 10: Crop yield and area potential 2008/11-2020 (after DAFM (2015i))

<table>
<thead>
<tr>
<th>Crop</th>
<th>2008/11 tonnes</th>
<th>2020 tonnes</th>
<th>2008/11 ha</th>
<th>2020 ha</th>
<th>2020 increase (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>1,288,900</td>
<td>1,755,500</td>
<td>184,000</td>
<td>223,660</td>
<td>39,660</td>
</tr>
<tr>
<td>Wheat</td>
<td>820,400</td>
<td>1,109,400</td>
<td>91,800</td>
<td>105,800</td>
<td>14,000</td>
</tr>
<tr>
<td>Oats</td>
<td>158,420</td>
<td>246,320</td>
<td>21,100</td>
<td>34,860</td>
<td>13,760</td>
</tr>
<tr>
<td>Pulses</td>
<td>18,700</td>
<td>64,700</td>
<td>3,560</td>
<td>10,300</td>
<td>6,740</td>
</tr>
<tr>
<td>OSR</td>
<td>32,300</td>
<td>287,300</td>
<td>8,100</td>
<td>59,900</td>
<td>51,800</td>
</tr>
<tr>
<td>Maize</td>
<td>313,000</td>
<td>463,000</td>
<td>20,875</td>
<td>30,875</td>
<td>10,000</td>
</tr>
</tbody>
</table>
There are additional opportunities in the Irish tillage sector to increase the production of energy crops as part of the drive towards renewable energy and projected increases in the use of transport biofuel in particular (Burke, 2008). Teagasc (2008) envisaged that the land area devoted to tillage and energy crops in Ireland could increase by 40% by 2020 from the current 330,000 hectares. More specifically, Burke (2008) proposed that 200,000 hectares could be transferred from dry stock farming to the production of biomass crops without significantly impacting food and feed production in Ireland. Burke (2008) further proposed that 500,000 hectares could be usefully converted for biomass production by 2030. The environmental impacts of such transfers would need to be evaluated as well as the geographic positioning of production sites next to appropriate power stations (Burke, 2008). There is also the potential to develop more native protein crop sources in an Irish context as part of wider European drives for more sustainable protein options (DAFM, 2015b). Issues with price volatility, climate, disease control, and high input prices represent key future challenges for the growth and future development of this agricultural sub-sector, however (DAFF, 2010a). Current levels of energy crop production and the possibilities for the use of this biomass are discussed in further detail earlier in the report.

Although costly to produce due to high input costs for fuel and fertiliser, the Irish tillage sector represents a potential source of material for further bio-refining. Bonsall (2015b) reports an estimated two million dry matter tonnes of cereals available in Ireland for further processing with its homogenous character reinforcing its suitability for further bio-refining. Movements to resurrect the sugar beet industry in Ireland are also considered to have significant potential to diversify agricultural revenues and create high value bioeconomy outputs (for instance, creating bio-chemicals or bio-polymers). For example, one million tonnes of beet utilised as table sugar earns approximately €450 t⁻¹. By comparison, further refining and fermenting of its sucrose content such as extracting lactic acid derivatives could earn approximately €1,200 t⁻¹ (Bonsall, 2015b). The potential is high for this industry to emerge in Ireland following the abolition of sugar quotas in the EU in 2017.

2.4.1.5. Fruit and Vegetables

Traditionally occupying a very small portion of Irish agricultural land, the Irish horticultural sector accounts for a noteworthy proportion of total agricultural output: occupying 0.14% of land in 1997, for example, but producing 4% of total agricultural output (Lafferty et al., 1999). Such importance continues to 2014, with the horticulture sector estimated to
contribute over €400 million to agricultural output at a national scale. Compared to other agricultural sectors in Ireland horticulture is a labour intensive industry particularly in planting and harvesting operations, with a number of crops such as soft fruits still hand harvested (Safefood, 2007). The importance of the sector in generating ancillary employment in areas such as preparing, packing, distribution, and retail is also considerable (DAFM, 2015b). According to Bord Bia (2015d) horticultural crop production takes place throughout Ireland but the most intensive field vegetable production takes place in Leinster and Munster with the most intensive fruit production occurring in Leinster. There is considerable variation in type, scale, capital investment, and end profits of farms in this sector: some soft fruits require extensive glasshouse protection, pest management, and high energy inputs but have considerably more associated profits than volatile, outdoor potato farming, for example. Ryan (2014) described the Irish berry sector as “one of the most challenging, rewarding and profitable in Irish horticulture”.

The overall output value of the horticultural sector in Ireland including fruit and vegetables, cut foliage, flowers, and nursery crops is outlined in Table 11. This table illustrates the improved conditions experienced in the outdoor fruit crops and foliage sectors between 2013 and 2014, as well as continued growth in the Irish mushroom sector.

Potatoes and, more recently, mushrooms represent two commonly grown vegetables in Ireland while apples and soft fruits such as strawberries, raspberries, and gooseberries are popular varieties of fruit cultivated nationally (Lafferty et al., 1999). Broadly speaking the costs of horticultural production and the value of output are heavily influenced by prevailing weather conditions, with favourable conditions in 2014 resulting in reasonably good harvests for the year (DAFM, 2015c). This comes after many challenging years weather-wise in the run up to 2013. The sector also experiences significant volatility due to the power of

<table>
<thead>
<tr>
<th>Product</th>
<th>Value €m 2013</th>
<th>Value €m 2014</th>
<th>% Change year on year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mushrooms</td>
<td>121.5</td>
<td>133.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Field vegetables</td>
<td>59.7</td>
<td>61.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Protected crops</td>
<td>82</td>
<td>85.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Outdoor fruit crops</td>
<td>7.7</td>
<td>9.8</td>
<td>26.9</td>
</tr>
<tr>
<td>Bulbs, outdoor flowers, foliage</td>
<td>4.5</td>
<td>5.9</td>
<td>30.3</td>
</tr>
<tr>
<td>Hardy nursery crops, Christmas trees and honey</td>
<td>38.2</td>
<td>40.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Total</td>
<td>313.6</td>
<td>336.1</td>
<td>7.2</td>
</tr>
</tbody>
</table>
multinational retailers in tendering and contract processes. This impact is magnified by the reliance of Irish horticulture producers on domestic retail and food service sectors as the most important markets for fresh horticulture produce (DAFM, 2015b). A vegetable price war among retail multiples in Ireland in December 2013 which resulted in significant impacts on grower prices illustrates this vulnerability (DAFM, 2015c). At an international level, the 2014 ban on EU fruit and vegetable imports into Russia due to political reasons and the sanctions imposed on Russia over conflicts in the Ukraine, while not initially having a direct impact on Ireland, may present problems as different products come into season across the EU; fruit and vegetable surpluses are a possibility in this instance (DAFM, 2015c).

Investigating the structure of the Irish horticulture sector the CSO (2012a) reported 1,560 farms growing just under 12,200 ha of potatoes in 2010, with over 75% of this land located in the southeast. More recently it was estimated that there were 10,700 ha of potatoes under cultivation in 2013 (DAFM, 2015b) while figures for 2014 highlight a further drop of 9% in the land area dedicated to potato cultivation to just under 10,000 hectares. This decline represents a continuous trend in recent years in Ireland, attributed to poor potato prices. A notoriously volatile sector, lower prices for potato growers are emerging as a result of weakening domestic consumer demand coupled with the absence of a strong export market and weak prices across Europe. Globally, however, the FAO continues to promote the potato as a forerunner for improving food security in developing countries due to the fact that 80% of the crop is suitable for human consumption, a much higher proportion than cereals such as wheat or maize (Teagasc, 2008). While Ireland does not typically export potatoes at present, demand for potatoes is expected to grow in the coming decades. Additional opportunities to add value through novel processing and extraction techniques also exist in the future bioeconomy: a company in the Netherlands is extracting vegetable-derived protein from potatoes for use in the food industry as an alternative to animal-derived protein, for example (Teagasc, 2008). The Rooster variety of potato dominated 60% of the overall production area for potatoes in 2014.

Growth in the mushroom sector marks another significant development in Irish horticulture of late, constituting over 50% of exports from this sub-sector in 2014 (Bord Bia, 2015a). Mushroom exports are reported to have grown over 5% in 2014, aided by an increase in product value (Bord Bia, 2015a). There are approximately 75 mushroom growers in Ireland who have witnessed steady growth in the value of their outputs up to 2014 (DAFM, 2015c). A specialist trade, mushroom cultivation is also a highly capital intensive practice resulting in
additional entry barriers in this sub-sector compared to others in the horticultural sector. The volume of mushrooms produced in Ireland increased 3% in 2014 (DAFM, 2015c) with mushrooms destined specifically for the UK market contributing in excess of €115 million (DAFM, 2015b). The growth of this sub-sector has been further fuelled since 2013 by Bord Bia’s *Just Add Mushrooms* promotional campaign, designed to promote Irish mushroom consumption.

Horticultural products are estimated to account for 2% of all Irish agri-food exports (DAFM, 2015b); the value of edible horticulture and cereal outputs was reported to be up 4% in 2014, reaching €230 million (Bord Bia, 2015a). Irish fruits and vegetables are subject to intense competition from cheaper imports however, with high input costs and a lack of scale also reported to hinder the horticultural sector (DAFM, 2015b; DAFF, 2010a). The cost of energy particularly influences horticulture margins in Ireland, especially for farmers cultivating crops under heated glass (DAFM, 2015c). Investments in renewable energy sources are predicted in this sector alongside further investments in energy saving measures. More broadly, opportunities offered by plant genetic research for new products will frame the future viability and profitability of the sector. DAFM (2015b) highlights the potential to increase the value of this agricultural sub-sector to over €500 million in the medium term, if appropriate policy and infrastructural support measures for the commercialisation and implementation of new technologies and production techniques are introduced.

### 2.4.1.6. Grass

A pivotal input into the Irish agricultural supply chain, grass should be considered a valuable output of Irish agriculture. Grass is an abundant natural resource in Ireland with the temperate climate and fertile soils enabling high and consistent yields year on year. Grass is a renewable raw material with opportunities to become a principal source of biomass in the country as well as the basis for a range of bio-products and bio-services.

While farm slurry is typically viewed as the principal feedstock for on-farm anaerobic digesters, grass boasts significant potential for the whole crop to be used for anaerobic digestion and the creation of bioenergy. This process would bring additional benefits on-farm including increased biodiversity levels by returning unmanaged grassland to active management. According to a report commissioned by Enterprise Ireland, annual dry matter output from grassland can range from 5,000 kg ha\(^{-1}\) to 18,000 kg ha\(^{-1}\) depending on fertiliser input and soil characteristics (ADAS/NNFCC, 2008). The higher end of this range proffers a
potential biogas output of 10,000 m$^3$ ha$^{-1}$ year$^{-1}$. This is higher than energy yields associated with livestock slurry produced after grass has been consumed by livestock. Biogas yields following anaerobic digestion can also be improved when materials are mixed, such as combining manure with crops or fruit and vegetable waste to ensure the ideal carbon to nitrogen ratio for digestion is achieved.

The potential also exists to add a greater level of value to grass through bio-refining, which offers opportunities for the use of both grass fibres (e.g. silica and cellulose) and juices (e.g. sugar proteins, colourants, alkaloids, and insulin). Bio-refining grass can also generate platform chemicals which have the potential to form the foundation of a number of biochemicals. This is a common feature of many lignocellulosic feedstocks whereby sugars are released from the biomass during the fermentation process, producing monomers that can be used as platform chemicals (ADAS/NNFCC, 2008). Bio-refining platforms are discussed in detail earlier in this report.

While the primary use of grass in the Irish agricultural supply chain is as an input as animal feed, the above examples highlight the potential opportunities that are available when grass is considered as an output leaving the farm gate. A number of barriers may hinder this future development, however: the need to control the level of nitrogen inputs applied to high productivity grassland is obvious and will require careful attention to avoid negating the environmental benefits associated with using this biomass resource as a sustainable alternative feedstock for bio-refining (ADAS/NNFCC, 2008). The scale and context of future grass bio-refineries are also essential to allow bio-processing plants to compete with prevailing bulk chemical competitors; the need to de-water wet grass on-farm may also be crucial to reduce the costs associated with transportation to centralised bio-refineries. The seasonality and variegated quality of grass will also require attention in any future development scenario for this renewable resource, including the development of quality grade bands in relation to sugar, dry matter, and fibre content for example, and the exploration of alternate or mixed feedstocks to supplement processing in the winter months when grass is not available (ADAS/NNFCC, 2008).

2.4.1.7. Agricultural Waste

Approximately 132 million tonnes of agricultural slurries, wastewaters, effluent, and sludge are generated in Ireland on an annual basis. Forty million tonnes of this is made up of animal slurry that requires active management. Dairy cow waste is expected to increase in coming
years due to the abolition of milk quotas. Development of opportunities in the waste sector is therefore essential for a sustainable future Irish bioeconomy. As detailed in the Science and Technology Select Committee report considering the role of waste in stimulating the development of the bioeconomy and addressing potential competition between feedstock sectors, “waste bio-refining has the potential to completely eliminate the competition for land that is inherent in the use of most other feedstocks, such as food crops. This may result in waste becoming the most sustainable feedstock of all” (Science and Technology Select Committee, 2014).

A number of by-products and co-products demonstrate particular potential for further processing in the Irish agricultural supply chain, transforming waste outputs “from a problem into a resource” (Science and Technology Select Committee, 2014). This holds true at the farm level with opportunities for animal manure primarily residing in the N, P, and K value that it retains, making it a suitable nutrient supplement in an era of escalating fertiliser prices and energy costs. Further use of animal manure for bio-refining are principally discounted by ADAS/NNFCC (2008), deeming it an inappropriate feedstock for further development though its value as a feedstock for anaerobic digestion with association renewable energy benefits is highlighted. This offers a potentially effective waste management solution for Irish farmers as well as adding value through the production of bioenergy. Rich in nitrogen, animal-derived wastes need to be combined with carbon-rich feedstocks such as food wastes or the sugary liquor generated when dewatering grass to achieve optimum biogas production. The resulting biogas can then be used to generate electricity or heat or as a transport fuel, though this is less common (ADAS/NNFCC, 2008). Issues of scale and context are important when considering the development of anaerobic digestion for the treatment of agricultural waste, with a distinct advantage where there is an abundance of livestock farms in one location which can ensure a consistent feedstock supply for a localised digestion facility.

Additional organic wastes from the Irish bio-based sectors which could be diverted from current processing options to bio-refining are outlined in Table 12; this table describes the type of residues available in Ireland, their estimated quantities in dry matter tonnes, and examples of how such by-products are currently being underutilised. Table 13 describes the biomass potential of a number of the sectors in the Irish bioeconomy and identifies opportunities for bio-refining and the development of biofuels, bio-chemicals, bioenergy, and bio-materials from the products and by-products of these sectors, highlighting the large number of non-food opportunities that could be explored in the future Irish bioeconomy.
<table>
<thead>
<tr>
<th>Residual</th>
<th>Quantity (m$^3$ DM)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Livestock/Dairy/Poultry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Manures/litters</td>
<td>2,000,000</td>
<td>Manures/litters land spread</td>
</tr>
<tr>
<td>• Meat and Bonemeal</td>
<td>100,000</td>
<td>MBM exported</td>
</tr>
<tr>
<td>• Paunch contents</td>
<td>20,000</td>
<td>Paunch contents underutilised</td>
</tr>
<tr>
<td>• Dairy whey and WWT fats</td>
<td>Delactosed whey supplied as low value animal feed</td>
<td></td>
</tr>
<tr>
<td><strong>Tillage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Straws/stovers/husks</td>
<td>1,000,000</td>
<td>Straw/stover used as compost and animal bedding</td>
</tr>
<tr>
<td>• Spent grains</td>
<td>150,000</td>
<td>Spent grains supplied as animal feed</td>
</tr>
<tr>
<td><strong>Forestry pulp and paper</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Recovered paper</td>
<td>500,000</td>
<td>Mixed paper exported at low value</td>
</tr>
<tr>
<td>• Forestry product residues</td>
<td>1,000,000</td>
<td>Pulpwood/sawdust/chippings used in renewable energy; bark used in landscaping; branches unharvested</td>
</tr>
<tr>
<td><strong>Horticulture</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Spent mushroom compost</td>
<td>300,000</td>
<td>Landspread or disposal</td>
</tr>
<tr>
<td>• Apple pomace</td>
<td>5,000</td>
<td>Low value animal feed</td>
</tr>
<tr>
<td><strong>Landfill gas</strong></td>
<td>80,000,000 m$^3$</td>
<td>Landfill gas flared if not recovered for CHP</td>
</tr>
<tr>
<td><strong>Source separated food waste</strong></td>
<td>40,000</td>
<td>AD or composted</td>
</tr>
<tr>
<td><strong>Organic MSW – RDF</strong></td>
<td>430,000</td>
<td>OFMSW to be separated/stabilised before landfill; RDF exported</td>
</tr>
<tr>
<td><strong>Aerobic WWT COD</strong></td>
<td>75,000</td>
<td>WWT constraint due to EPA discharge limits</td>
</tr>
<tr>
<td><strong>Aerobic WWT sludges</strong></td>
<td>100,000</td>
<td>ABP requires heat treatment prior to land spread</td>
</tr>
</tbody>
</table>
Table 13: Biomass potential of agriculture, forestry, and marine feedstocks

<table>
<thead>
<tr>
<th>Resource</th>
<th>Estimated quantity (m³ DM)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass/silage*</td>
<td>20,000,000</td>
<td>4.4 m ha of available land, very high biomass growth but variable in character; good alternative value in grass-based livestock system</td>
</tr>
<tr>
<td>Tillage cereals</td>
<td>2,000,000</td>
<td>378,000 ha in tillage: costly to produce, homogenous character facilitates easier processing. High value as drinks/food ingredient</td>
</tr>
<tr>
<td>Tillage oilseed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tillage sugar beet</td>
<td>0</td>
<td>Movement to resurrect sugar beet production</td>
</tr>
<tr>
<td>Forestry harvest</td>
<td>3,700,000</td>
<td>Set to grow to ~7,000,000 over next 10-12 years due to private forest growth. Primary roundwood use is construction materials. Near term demand may exceed supply - opportunity for peat co-firing/RES obligation</td>
</tr>
<tr>
<td>Energy crops</td>
<td>40,000</td>
<td>Strong SRC energy crop potential - Market economics favour grassland as feed, establishment grants available but need market outlet</td>
</tr>
<tr>
<td>Marco algae</td>
<td>40,000</td>
<td>Long shoreline offers aquaculture opportunity. A cottage industry, manual harvesting and environmental issues drive cost concerns</td>
</tr>
<tr>
<td>Micro algae</td>
<td>0</td>
<td>Potential indigenous production but subject to capital investment and availability of external heat - cost considerations</td>
</tr>
</tbody>
</table>

*10 month growing season and rainfall generates highest biomass growth rates (plant matter per hectare) of any country in Europe
2.4.1.8. Current Levels of Value Added by Agriculture in Ireland

Assessing Gross Value Added (GVA) includes measuring the output of the agriculture sector taking into account the cost of intermediate consumption (inputs consumed at the farm level). While difficult to isolate the specific contribution made by agriculture on its own, DAFM (2015c) reports that the agri-food sector as a whole accounted for approximately 7.7% of GVA in Ireland in 2013. The combined primary production sectors of agriculture, fisheries, and forestry accounted for approximately 2.4% of national GVA. Output value of the agriculture sector is reported to have increased by 30% between 2010 and 2014, representing a significant success for the agricultural sector and forming an important part of national economic recovery (DAFM, 2015b).

Specific agricultural sectors in Ireland have witnessed an increase in value in recent years. The latest export statistics from Bord Bia (2015a), for example, reveal a 54% increase in the value of meat and livestock exports since 2009 from €1.3 billion to €3.6 billion by 2014. This accounts for 35% of all Irish food and drink exports. Dairy exports have also witnessed an increase in value, up 55% from €1.96 billion in 2009 to €3.06 billion in 2014. Such trends, and the reasons behind them, are explored in more detail in the food supply chain section of this report.

Food Wise 2025 establishes further aims to increase GVA for the agri-food, fisheries, and wood products sectors by 70% by 2025, with a strong emphasis on adding value by delivering new and innovative food solutions to consumers (DAFM, 2015b). This would drive value-added levels of the sector from the 2012 baseline figure of €7.5 billion to more than €13 billion in the next decade. The strategy also aims to increase the overall value of exports by 85% by 2025 to reach €19 billion per annum from the current baseline of €10.5 billion. Finally, the strategy aims to increase the value of primary production by 65% to reach almost €10 billion. Such ambitious aims, if achieved, will have significantly positive benefits for the agricultural sector and associated stakeholders, with numerous direct and indirect employment and economic benefits in reach.

2.4.2 Food Supply Chain

The division imposed by the reference framework for this report identifies the food supply chain as being a secondary processing sector of biological materials; that is, it is responsible for outputs of rather than inputs into the bioeconomy. The food supply chain is an essential
facet of the bioeconomy and as such will be afforded the same in-depth analysis here as was provided for the primary processing sectors in earlier sections of this report.

2.4.2.1. The Importance and Relevance of the Food Supply Chain in Ireland

“Everyone takes part in the food chain. Even if you’re not directly involved in the production, processing or distribution of food, you are part of the food chain as a consumer” (European Commission, 2015b)

The food supply chain is an essential element of everyday life. While food can reach consumers directly from the producer, the intensification, modernisation, and globalisation of food production in recent decades means that this type of transaction is less commonplace today (European Commission, 2015b). Instead, a number of actors operate throughout the food supply chain to process, package, transport, distribute, and market food to the end consumer.

All food and drink is processed in some manner before it is consumed. Primary processing involves the cutting, cleaning, packaging, and refrigeration of raw agricultural output while secondary processing (thermal or bio-chemical processing, for example) transforms the food or drink material into a new product. This includes a range of canned, frozen, baked, fermented or convenience items for consumers to enjoy. As detailed by the European Information Council, the role of food processing has thus moved far beyond its original purpose of preserving food beyond a product’s normal shelf life or place it was grown (EIC, 2015). Given that 3% of the European population produces 75% of the region’s food with the remainder imported from all over the world, food processing techniques have had to develop alongside these trends to meet the ever-changing needs and demands of consumer populations. Demographic and lifestyle changes in recent decades have also resulted in an increased demand for more convenience foods, further influencing the shape of the modern food processing industry (EIC, 2015). More recently, the ability of the food processing sector to add value to raw agricultural output has been emphasised, particularly in an Irish context in times of economic recession and new consumer demand. The food sector is now also increasingly recognised as a platform for supporting the pharmaceutical, tourism, biotechnology, bioenergy, and health and wellness sectors with potential for new and exciting synergies between sub-sectors in the Irish bioeconomy (DAFM, 2015b).
Assessing the current status of the food supply chain in Ireland is thus essential to understanding development opportunities for the future. Food production and processing, as well as value-added food processing, are highlighted by Teagasc (2008) as two central elements in developing the knowledge-based bioeconomy in Ireland. The production of high quality, safe, and traceable food is deemed a particular strength of the Irish food industry, utilising the expertise and skills of a number of millers, meat processors, and dairies to convert raw agricultural outputs into desirable consumer products. Teagasc (2008) also specifically emphasised companies that operate at the boundary of medicine and food to produce innovative and customised ingredients for global leaders in the functional food, bioactive constituents, cosmeceutical, formulated food, and beverage industries. Leveraging across sectors in this way presents distinct opportunities for Irish firms (Bell and Shelman, 2010; Teagasc, 2008). Teagasc (2008) further highlighted a need to move away from a focus on attracting foreign direct investment to Ireland to instead fostering innovation within indigenous bio-resource industries to secure future economic growth and competitiveness in international markets. Such developments will be crucial to the success of the future food supply chain in a sustainable, low carbon bioeconomy.

Aside from the provision of safe, high quality, and nutritious food for domestic populations, key achievements of the Irish food industry in recent years include unprecedented growth in food and beverage exports between 2009 and 2014, a value that has increased 45% in the five year period (DAFM, 2014c). According to Teagasc (2012) the food sector represents the third largest merchandise export sector in Ireland, experiencing faster export growth rates than any other export sector in the country despite the economic crash in 2008. This places the food and beverage sector at the heart of Ireland’s economic recovery (DAFM, 2015b). Acting as a pivotal value generator in the food supply chain, food processing provides much needed employment and economic stability nationwide, particularly in remote and rural areas (Teagasc, 2012). Plans to further enhance and achieve growth in the industry have been laid out by the Irish government in the Food Wise 2025 strategy (DAFM, 2015b). This strategy places a renewed emphasis on increasing value-added outputs in the Irish food supply chain (by 70% by 2025), the value of primary production outputs (by 65%), and overall agri-food exports (by 85% by 2025, to a value of €19 billion) (DAFM, 2015b). The development of innovative food solutions forms the foundation of such growth strategies, putting pressure on the food industry to invest in research and development to deliver novel products, but with an infinite number of benefits once achieved. Attracting and retaining a talented and skilled
workforce throughout the food supply chain will be pivotal to this success, alongside a renewed focus on tracking and meeting consumer demands and desires. Each of these aspects is highlighted in the Food Wise 2025 strategy as being worthy of investment to safeguard the future of the Irish food supply chain. Productivity and efficiency improvements will also be key to ensuring the sustainability of any future food industry growth.

2.4.2.2. Structural Features

The food industry in Ireland is highly fragmented, consisting of a mosaic of multinational companies, small- and medium-sized enterprises (SMEs), and a number of local businesses and entrepreneurs. Drawing on data from the CSO’s Business Demography survey, DAFM (2015c) reports a total of 1,200 enterprises in the food and beverage sector in Ireland. This includes all business types from small farmhouse producers to large scale multinational processors. A narrower definition adopted in the Census of Industrial Production (CSO, 2012b) focusing on businesses employing three or more people estimated that there were 662 food and beverage manufacturing units in Ireland. This is broken down into 131 meat manufacturing units, 66 dairy units, 32 drinks units, and 433 “other foods” units including prepared consumer foods (PCF) and other processing companies. A distinct geography applies to the distribution of these food and beverage units, with the majority of meat units concentrated in the mid-east, southeast, and border regions for example (DAFM, 2015c).

As a result of the differentiated geography, size, scope, and purpose of food businesses in Ireland, processing capabilities vary considerably across business categories both in terms of volume capacity and operational conditions. A year-round five day operating week is not standard, for example, with several opening just three or four days each week depending on the season (DAFF, 2009b). This has implications for the volume of output produced and further undermines processing efficiency. Despite this, the majority of companies nonetheless operate with a global reach in terms of product exports. Overall, however, most food processing companies in Ireland, including many of the large multi-national operations, operate below production capacity. In the meat and livestock sector, for example, the IIAP (2010) reported the pig meat processing sector to be operating at approximately 75% of its operating capabilities, with average weekly slaughterings of 50,000 head in 2010. Plans to increase operations to full capacity to slaughter 80,000 head per week by 2015 were established by the IIAP (2010). An annual slaughter figure of 3.04 million (max of 58,000
head per week) in 2014 implies that this target has not yet been met, however (DAFM, 2015c).

Enterprise Ireland reported a total of 28 companies operating in the pig meat processing space though 70% of primary pig meat processing is dominated by three large companies. Four players dominate the added value processing space in the pig meat industry while a tier of domestic orientated processors also exist (Enterprise Ireland, 2014). This highlights the fragmented nature typical of many sub-sectors in the Irish food processing sector. Beef processing in Ireland similarly comprises of approximately 30 EU-licensed slaughtering facilities (Enterprise Ireland, 2009). A number of beef boning and added value processing businesses are also in operation that do not carry out any slaughtering processes. A further three dedicated plants operate to handle sheep and lamb throughput in Ireland, though sheep meat is also processed in facilities that also handle beef (Enterprise Ireland, 2009). A distinct seasonality is associated with all livestock production in Ireland as a result of the low cost, grass-based agricultural system in operation. This results in weekly cattle availability fluctuating between 25,000 and 38,000 head per week, for example. This impacts the processing capabilities of slaughterhouses and beef processing plants with some facilities lying dormant at certain times of the year. DAFF (2009b) reported overall Irish capacity utilisation in the beef sector at around 60%, however also reported that this falls to below 50% during periods of short supply. Levels of live trade further impact cattle availability for Irish processing units, with both finished animals and young calves being exported (Enterprise Ireland, 2009). Nevertheless over 10,000 people are directly employed in the Irish meat industry with a further 10,000 jobs in indirect employment (FDI, 2015).

A similar seasonality in milk production due to cattle grazing and breeding patterns associated with grass-based production systems also has a significant impact on processing capabilities in the dairy sector, with a peak-to-trough ratio of 7 to 1 persisting in the sector (May vs January) (IFA, 2014). While lowering production costs for farmers, this seasonality comes at a high cost to the dairy industry and causes an underutilisation of expensive processing assets at certain times of the year. Drawing comparisons to processing infrastructure in New Zealand, Denmark, and the Netherlands (considered to be Ireland’s main dairy competitors), Enterprise Ireland (2014) also criticised the relatively fragmented nature of dairy processing in Ireland. According to DAFM (2014h), almost 18,000 milk suppliers operate in Ireland in total, selling to 90 registered milk purchasers. In 2013 82% of Irish milk output was processed by just six dairy co-operatives, a situation that has remained
largely unchanged since 2003 (DAFM, 2014h). This is in stark contrast to international industries, with DAFM (2015b) highlighting the tendency for large single players to dominate dairy markets internationally such as Arla in Denmark processing over 90% of the national milk pool and Friesland Campina in the Netherlands handling over 60% of the domestic milk pool.

The IFA (2014) highlighted a total of thirteen major firms processing Ireland's milk to produce liquid milk, cheese, butter, powders, and other products for domestic and international consumption. This includes a mixture of private companies and farmer owned co-operatives. In terms of efficiency, a review of the dairy sector undertaken in 2003 highlighted that the average output of cheese plants in Ireland was approximately 12,000 tonnes per plant (Prospectus, 2003), compared to 24,700 tonnes per plant in the Netherlands. While output has been increasing in Ireland, in the last decade EU counterparts such as Denmark and the Netherlands have increased at approximately twice the Irish rate (Prospectus, 2003). This situation has changed in the run-up to dairy quota abolition, however, with government and industry investments in dairy infrastructure and processing capacity increasing efficiencies within the sector. €25 million was recently invested to create a new Dairy Processing Technology Centre at Teagasc Moorepark, with a further €10 million invested in research facilities, for example (Enterprise Ireland, 2015). Such measures have been taken in anticipation of maximising the opportunities associated with increased milk output in the post-quota era. This commitment recognises the importance of both industry and research and development facility investment to the future success, efficiency, and innovative capacity of food supply chain sectors. From a market perspective, Kerrygold is considered to be Ireland’s only truly global food brand, supplying over 50 countries with dairy products and holding a top three position in 27 of these destinations (ICOS, 2015).

A number of large global companies dominate the PCF sector, producing a range of chilled and frozen foods as well as ambient products such as snacks, confectionary, and baked goods (Enterprise Ireland, 2014). According to DAFM (2015b) approximately 500 manufacturing units operate in the PCF industry in Ireland with 76% of these described as small companies (employing 4,950 of the total 20,600 estimated to be employed in the Irish PCF sector). Nineteen percent of companies are considered medium sized enterprises (employing 8,850 people) while 5% are large companies (employing the remaining 6,800). Enterprise Ireland (2009) highlighted such fragmentation as a key weakness of the Irish PCF sector, preventing economies of scale particularly for supplying export markets.
The speciality foods sector represents another growing food arena in Ireland and includes all premium products with unique characteristics that command a premium price (Teagasc, 2012). The number of speciality producers supplying products in this sphere has increased from approximately 60 in 2006 to 350 in 2012 (Teagasc, 2012). Ninety percent of the resulting produce is destined for the domestic market. Operating at an even smaller scale, artisan producers represent a particular subset of the speciality foods sector, accounting for 23% of the speciality market in Ireland (Teagasc, 2012). Artisan food businesses have increased in scope and popularity in Ireland in recent decades, producing food in batch sizes with distinctive tastes, flavours, and food personas (Teagasc, 2012). A highly fragmented sector, artisan businesses supply a diverse range of foods across the bread, meat, cheese, produce, and preserve categories and can have a turnover of up to €2 million per business (DAFM, 2015b). Producing food and drink in limited quantities (with weekly average volumes under 1,000 kg or litres), they make significant contributions to local employment nationwide, employing up to 10 people per microenterprise. They typically engage traditional methods and utilise local ingredients sourced within 100 km (DAFM, 2015b). Artisan food businesses thus have a considerable impact on local economies, often linking with local farms and farmers’ markets and responding to growing consumer demand for niche food and drink products and short supply chains. There are approximately 70 producers in this category in Ireland, with farmhouse cheese, smoked salmon, baked goods, and chocolate representing the most high profile groups (Teagasc, 2012). The structure of the Irish chocolate industry, for example, includes one large scale manufacturer, three premium confectionary players, and 30 artisan producers (Bord Bia, 2015a). This illustrates the volume of speciality producers in this particular food industry sub-sector. Comparing the Irish speciality foods sector with its international counterparts it is obvious that there is room for further growth in this area. For example, the Netherlands, which has less than half the land area of Ireland, hosted over 100 farmhouse cheese producers in 2013 compared to 50 in Ireland (Teagasc, 2015h). Similarly, New Zealand, with a similar population size to Ireland, hosts over 2,000 speciality food producers (excluding wine) compared to 350 in Ireland (Teagasc, 2015h). The speciality food market is far from saturation point according to Teagasc (2015h). Rising consumer interest in the provenance, health impacts, and environmental implications of food coupled with increased desires to support local businesses will frame future growth and demand in this sector.
Small enterprises of less than ten employees typically dominate the seafood processing sector (DAFM, 2014i); just 8% of seafood processing companies in Ireland employed more than 50 people in 2011. DAFM (2014i) estimated that 169 companies are engaged in the handling, processing, distribution, and marketing of seafood in Ireland, a figure that has remained largely unchanged since 2009. Shellfish companies represent the largest proportion of fish processing companies in the country. By contrast, the Irish drinks manufacturing industry is dominated by non-SME subsidiaries of multinational corporations (Enterprise Ireland, 2014) and are divided into a range of brewing companies (e.g. beer and cider), distilled spirits, liqueur, and soft drink businesses. Heavy investment by established players as well as a number of new entrants into this sector of late has brought a new era of growth to this category. According to Bord Bia (2015a) there are nine active distilleries in Ireland with eight more planned to open by the end of 2015. In addition while there were less than ten microbreweries in operation in 2013, more than 50 were active in 2014. Reflective of continued growth in the whiskey and craft beer industries in particular, a total of €315 million has been invested in the beverage industry between 2013 and 2015, with a further €1 billion to be invested within the next decade (Bord Bia, 2015a). Further aims to double the number of craft breweries to 100 by 2020 are also outlined in the Annual Review and Outlook for Agriculture 2014/2015 (DAFM, 2015c).

In terms of wider food industry growth, DAFM (2014c) noted a recent increase in the level of activity in the entrepreneurial and new start-ups space in the food industry in Ireland. In the past an average of three to four high potential start-ups would be funded by Enterprise Ireland annually; this average had increased to seven to eight high quality, high potential start-ups by 2014. This pipeline is fostered by the Competitive Start Funds of Enterprise Ireland while the collaborative Food Works Programme between Teagasc, Bord Bia, and Enterprise Ireland is also thought to be having an impact on the development of the Irish food supply chain (DAFM, 2014c). Despite growth in the food and beverage sector as a whole, however, the high cost base for processing in Ireland represents a significant challenge facing the food supply chain and undermines competitiveness and potential for growth across all food categories (Enterprise Ireland, 2014; IIAP, 2010). For example, according to the Irish Association of Pigmeat Processors (a lobby group for pig meat processors) processing costs in the Irish pig meat sector are approximately 40% higher than those of the UK and other EU competitors (IIAP, 2010). This includes labour, energy, and waste disposal costs with industrial electricity prices estimated to be 35% more expensive than the EU average in 2009,
for example (IIAP, 2010). This issue must be addressed if food and beverage processing activity is to be further developed in Ireland. Investment in processing infrastructure will also be required to facilitate growth and match any increases in future agricultural output. This does not necessarily equate to a need to build new plants but rather maximising the operating capacity of those existing. Along these lines, DAFM (2014c) reported commitments from Glanbia Ingredients and the Dairygold Co-Operative Society to invest in infrastructure to deal with the expected rise in milk output post-2015. This included a €150 million investment by Glanbia in a new dairy processing centre while Dairygold invested over €117 million expanding its milk processing facilities in Cork. This follows a €100 million investment by Kerry Foods to develop its Global Research and Innovation Centre in Co. Kildare.

Although the physical fragmentation of the Irish food industry is generally deemed to represent weakness in the Irish food supply chain, government and industry suggestions for increased consolidation and centralisation in the Irish food industry (as proposed by Enterprise Ireland (2014) and DAFM (2015b)) must be approached with caution. While presented as a measure to develop scale and reduce operating costs, any such changes must be cognisant of their impact on local employment and wider rural development. As much as 85% of food and beverage enterprises are located outside of Dublin (DAFM, 2015c), highlighting the importance of the food sector to rural economies in Ireland (Teagasc, 2012). Figure 22 highlights the unique geographical distribution of food and drink enterprises

![Figure 22: Regional dispersion of food and beverage units compared to other manufacturing industries in Ireland in 2012 (after DAFM (2015c))](image-url)
throughout the country compared to other manufacturing units (reproduced from DAFM (2015c)). Changes in industry structure would thus have direct impacts on local communities which must be recognised in any strategic plans or future directions for the Irish food supply chain.

2.4.2.3. Economic Profile

2.4.2.3.1. Turnover and Employment Rates

CSO (2012b) reported that the food and beverage sector accounted for 24% of all industry turnover in Ireland, with food and beverages also responsible for 22% of all gross industry output in the country. Enterprise Ireland (2014) similarly highlighted the food industry as pivotal to the Irish manufacturing landscape, reporting annual turnover in excess of €26 billion with exports in the region of €10 billion. The food sector accounts for approximately 88% of overall turnover of the combined food and beverages sector with meat and dairy production responsible for just over one third of this figure (DAFM, 2015c). This highlights the continued importance of meat and dairy in the Irish food supply chain. Beef, in particular, is responsible for almost 52% of total turnover in the meat category (DAFM, 2015c).

DAFM (2015b) reports a total of 47,500 people working in the food industry in Ireland with a further 6,500 employed in beverages. This constitutes approximately 33% of overall jobs in the agri-food sector in Ireland (total employment of 163,000 people (DAFM, 2015c)). It also represents a 16.6% increase on food and beverage employment figures recorded in 2010 (DAFM, 2015c). Drawing on industry surveys conducted by Enterprise Ireland, DAFM (2014c) highlighted an increase in employment in food and beverage companies (excluding seafood processing) from 38,784 in 2009 to 42,212 in 2013. Employment in seafood processing increased by 450 people in this period (DAFM, 2014c) with total employment in the Irish seafood processing sector estimated at 2,860 across 170 processing companies in 2014 (BIM, 2015). Recent employment trends in the Irish food and beverage sector are mapped in Figure 23, illustrating an overall upward trend in food industry employment in Ireland of late despite the economic recession.

The 2012 Census of Industrial Production showed that despite representing just 15% of all manufacturing units in Ireland the food and beverage sector is responsible for approximately 25% of manufacturing employment (CSO, 2012b). This figure is potentially even higher on consideration of employment in the speciality and artisan food industry, given that the Census
figures only include businesses that employ three or more people. The report indicated that 41% of people engaged in the sector were employed by 5.4% of the units, typically representing large companies and co-operatives. A further 16.5% worked in smaller companies that employ less than 50 people (representing 72% of all local manufacturing units).

Given the complex nature of the food supply chain it is difficult to delineate precise employment figures relating to the contribution of each sub-sector to the overall supply chain. According to the FDI (2015) the meat industry accounts for approximately 27% of gross agricultural output and provides direct employment for over 10,000 people. Enterprise Ireland (2009) reported the employment of 4,000 people directly in the dairy industry while DAFM (2015b) indicates that the PCF sector employs approximately 20,600 people in the creation of value-added food and beverages in Ireland. The value of the speciality foods sector in Ireland was estimated at approximately €615 million in 2012 while the artisan food industry is estimated to be worth approximately €450 million (ICOS, 2015). With 90% of speciality food output reported to be sold locally Teagasc (2012) estimated that the speciality foods sector results in an additional €1.125 billion in revenue for the local economy. Increasing the share of such foods in national grocery and food service markets thus represents a priority to retain monetary gain in local communities, with the potential to add a further €2 billion to local economies if market share of speciality foods is increased from 3%.

![Figure 23: Employment in the Irish food and drink sector 2010-2014 (reproduced from DAFM (2015c))](image-url)
to 6%. One thousand new job opportunities could also be created should the market share of specialty foods double in the future (Teagasc, 2012). The ability to realise these gains is feasible given the current high level of interest in the speciality food sector and existing levels of entrepreneurship.

DAFM (2014i) reported a total turnover in the Irish seafood processing sector of €559 million in 2011. In 2014, 3,065 people were employed in seafood processing with 2,405 of these employed full-time and 660 part-time. This figure is slightly down on 2011 figures which reported 3,270 working within the sector (a figure that had consistently increased since 2008 despite the economic downturn). DAFM (2015c) highlights additional job creation in the sector in recent years, attributing this to increased investment in areas of technology and value addition. Typically more males than females are employed in this sub-sector, with an average ratio of 70:30 respectively (DAFM, 2014i).

### 2.4.2.3.2. National Contribution

The overall economic reach and impact of the food industry in Ireland was emphasised by Enterprise Ireland (2014) in their assessment of the sector prior to the publication of Food Wise 2025. The organisation highlighted the unique ability of the food sector to impact every part of Ireland, both urban and rural, by providing much-needed employment in remote areas but also as a result of the sector spending a high proportion of its revenues locally (Enterprise Ireland, 2014). DAFM (2015c) highlights the significantly high percentage of Irish economic expenditure (IEE), that is, expenditure on Irish resources including wages, Irish raw materials, and national services by food and beverage companies in Ireland. Far above the average rate of 43% in the overall manufacturing sector in Ireland, IEE represents 74% of total expenditure by food and beverage companies. Furthermore, the food and drink industry accounts for 73% of total manufacturing consumption of Irish raw materials (DAFM, 2015c). This signals the importance of the food and drink sector in absorbing outputs of national primary production and highlights the importance of maintaining and enhancing this sector in an Irish context. The economic impacts of the food industry thus extend far beyond the measure of its outputs and contribution to exports.

The overall importance of the food and beverage sector to the indigenous economy is outlined in Figure 24 which details the breakdown between Irish- and foreign-owned factories across a range of key variables. More than 70% of manufacturing units operating in the country are Irish-owned and account for more than 60% of total food and beverage
industry employment. The comparatively high percentage (75%) of net food and beverage output by foreign establishments can be explained by the small number of large enterprises operating in Ireland (DAFM, 2015c).

2.4.2.4. Inputs

2.4.2.4.1. Animals

Cattle, pigs, sheep, and chickens represent the primary livestock categories in the Irish food supply chain. Drawing on data provided by DAFM (2015b), DAFM (2015c), and Bord Bia (2015c) Table 14 outlines the number of animals sent for slaughter from Irish farms in 2014. As described earlier in this report, a degree of seasonality is associated with livestock production in the Irish food chain, resulting in fluctuations in animal availability to processing factories. DAFF (2009b) reported that national capacity utilisation in the Irish beef processing sector stood at approximately 60%, dropping to 50% in periods of limited supply. The overall slaughtering capacity in the beef sector is estimated at approximately 3 to 3.5 million animals per annum, compared to the 1.5 to 2 million head currently slaughtered. This extra capacity has direct implications for operating costs within processing facilities, increasing costs by 12-15% (DAFF, 2009b). Such implications have resulted in government discussions and grant aid supports for the increased consolidation of processing facilities in Ireland. Live trade additionally impacts on supply lines to the meat processing industry.
including the export of young and finished animals.

2.4.2.4.2. Milk

According to the Irish Co-operative Organisation Society, 5.5 billion litres of milk are produced annually on Irish farms, accounting for 0.9% of the global milk supply (ICOS, 2015). Government targets established in Food Harvest 2020 to increase milk production by 50% could increase output to over 8 billion litres by 2020 (DAFF, 2010a). Total milk output available for processing in Ireland (including imports) in 2014 was approximately 6.1 billion litres (Bord Bia, 2015a).

2.4.2.4.3. Cereals

The total volume of Irish cereals harvested in 2014 was 2.56 million tonnes, far exceeding the average annual harvest of 2 million tonnes (DAFM, 2015c). DAFM (2015c) reports this as the highest cereal production figure since 1985 in Ireland. Total production of wheat in 2014 was 706,000 tonnes, barley production reached 1.7 billion tonnes, and oat production amounted to 146,000 tonnes (DAFM, 2015c). Cereal volumes produced in Ireland are in constant flux with some yields up significantly on 2013 figures (wheat increased 32% in the year) while others have dropped (oat production was down 22% in 2014). Approximately 75% of cereal output is used as animal feed (DAFM, 2014f), limiting the amount currently available for further processing and value addition for human consumption.

In addition to the traditional cereal types approximately 18,700 tonnes of pulses, 32,300 tonnes of oilseed rape, and 313,000 tonnes of maize are also produced in Ireland; there are expectations that these crop yields will increase up to 2020 (DAFM, 2014f). Growth in the Irish sugar beet production and processing industry is also predicted on abolition of sugar quotas, with expectations to return to 2006 production levels of 1.2 million tonnes, and the potential to increase production beyond these levels (DAFM, 2014f).

Table 14: Animal slaughterings in Ireland in 2014 (after DAFM (2015b; 2015c) and Bord Bia (2015c))

<table>
<thead>
<tr>
<th>Livestock category</th>
<th>Number slaughtered (millions)</th>
<th>Weight (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>1.75</td>
<td>585,000</td>
</tr>
<tr>
<td>Pigs</td>
<td>3.04</td>
<td>254,000</td>
</tr>
<tr>
<td>Poultry</td>
<td>76.17</td>
<td>166,000</td>
</tr>
<tr>
<td>Sheep</td>
<td>2.49</td>
<td>58,000</td>
</tr>
</tbody>
</table>
2.4.2.4. Fruits and Vegetables

The principal horticulture clusters dominant in Ireland include apples, mushrooms, potatoes, field vegetables (particularly cabbage and carrots), other outdoor fruits, and protected crops (primarily tomatoes but also lettuce, cucumbers, celery, peppers, and strawberries) (Safefood, 2007). In terms of overall volumes produced, Bord Bia (2012) reported an average fresh produce yield of 633 million kilogrammes in Ireland in 2012, a slightly increasing trend up from 605 million kilogrammes in 2010. Fruit account for 35.4% of this fresh produce volume, 27.6% was potatoes, and 37% other vegetables. The domestic market, and major retail multiples in particular, are the largest market for fresh Irish produce (valued at €1.2 billion in 2012), limiting the amount sent for processing or further value addition (Bord Bia, 2012). The fruit and vegetable processing sector has nonetheless experienced growth in recent years due to increased demand for salads, pizza toppings, and prepared foods (Safefood, 2007).

2.4.2.5. Outputs

2.4.2.5.1. Meat

Ireland boasts a number of comparative advantages in domestic meat production including pasture-based production systems, a positive animal welfare reputation, and high standards of food safety and quality throughout production and processing phases. Overall, the meat industry is estimated to represent approximately 27% of all gross agricultural output in Ireland (FDI, 2015). Outputs from the meat processing sector include a variety of meat products ranging from beef carcass sides to processed meat pizza toppings as well as a number of ‘fifth quarter’ outputs including organs, blood, hides, and bones (up to 54% of live cattle weight according to Rabobank (2012)). Bord Bia (2015c) report that over one million tonnes of meat were produced in Ireland in 2014 including 585,000 tonnes of beef, 254,000 tonnes of pig meat, 58,000 tonnes of sheep and goat meat, and 166,000 tonnes of poultry meat. Meat production levels have been relatively stable from 2000 to 2011, with the biggest drop in production evident in the sheep and goat meat sector (down 4.8% in this period) (FAO, 2014).

2.4.2.5.1.1. Beef

Highlighting the importance of the beef sector in the Irish food supply chain and wider economy, beef exports accounted for approximately 34% of all gross outputs from the
agriculture sector (excluding forage) and constituted 22% of total agri-food exports in 2014 (Bord Bia, 2015a). This equates to 524,000 tonnes of beef leaving the country in 2014 with a total value of €2.27 billion (Bord Bia, 2015a). This figure represents a 50% increase in value compared to that achieved for beef exports in 2010 (DAFM, 2015b). Ireland can meet domestic demand for beef seven times over (DAFM, 2015c), thus 90% of the beef produced nationally is exported to more than 50 countries globally (ICOS, 2015). As a result Ireland is the largest net exporter of beef in the European Union and the fifth largest globally (DAFM, 2015b). Beef exports represented the second most valuable export sector in Ireland in 2014 (Bord Bia, 2015a), evidence of the growing demand for Irish beef worldwide. Ambitions to continue to grow the output value of Irish beef remain a central focus of agricultural strategies nationally, representing a distinct feature of both Food Harvest 2020 and Food Wise 2025. Food Harvest 2020 aims to grow the output value of this sector by 40% compared to 2007-2009 baseline figures without necessarily increasing the output volume (Enterprise Ireland, 2014). Irish beef enjoys a comparative advantage in its sales price, typically commanding a 5% premium against the average EU sales price (Enterprise Ireland, 2014).

In addition to meat outputs, further processing of fifth quarter products can also add value in the beef processing sector. This includes both red and white offal (edible constituents such as organs and entrails), co-products (indirectly edible constituents such as bones, skin, fat, and hides that can be further processed into edible products), and animal by-products (constituents unsuitable for human consumption but that can be used for other industrial purposes). According to O'Callaghan et al. (2014), approximately 263 kg per head of cattle are currently sent to rendering for pet food or simply wasted and sent to landfill. Accounting for 54% of live animal weight, there is potential to extract further value from this raw material output with the possibility of exploiting niche markets worldwide where specific red offal meat (including the tongue, heart, or ears) is viewed as desirable speciality foods. Failing this, value can be added to fifth quarter output through further processing creating higher demand products across the food, pharmaceutical, chemical, and energy industries (O'Callaghan et al., 2014). Specific ingredients may be extracted from fifth quarter material (for example, proteins from blood or lungs) for use in functional foods, cosmetics or pharmaceuticals. Alternatively, some types of edible offal could be added as a highly nutritious ingredient to another processed food product, such as incorporating the heart or lungs into mince. Such opportunities are currently underexploited in an Irish context (O'Callaghan et al., 2014; Enterprise Ireland, 2014).
The UK remains the single largest export market for Irish beef, making up approximately half of the total trade volume for Irish producers (DAFM, 2015c). Concerns have been raised that 55% of Irish beef cuts exported to the UK are sold at a lower price point as mince while British beef sold as whole joints commands a much higher price (Moran, 2015). This is an issue that requires addressing according to Moran (2015), who describes the potential for tailored marketing strategies to ensure higher earnings for Irish beef farmers in the future. Competition from cheaper imports also represents a significant challenge for the Irish beef sector, most notably from South America. Overall 95% of Irish beef exports are destined for EU markets with 82 European retail chains stocking Irish beef in 2014 (Bord Bia, 2015a). Such conditions, coupled with continuing developments with regard to global market access, enable Irish beef to reach more countries and customers than any other national beef supply chain (Bord Bia, 2015a).

2.4.2.5.1.2. Pig Meat

With an output of 254,000 tonnes in 2014, the Irish pig industry is Ireland’s third largest sector in terms of gross agricultural output, behind dairy and beef (Enterprise Ireland, 2014). Pig meat constituted 6% of the total value of agri-food exports from Ireland in 2014 (Bord Bia, 2015a), totalling €570 million (DAFM, 2015c). This is a figure that continues to grow: since the 2007-2009 baseline figures established in Food Harvest 2020 (DAFF, 2010a) the output value of the pig meat industry in Ireland has increased by 54% while a growth in output volume of 18% has also been recorded (DAFM, 2014c). The growth and development of the Irish pig meat sector has been particularly noteworthy between 2008 and 2013, with the volume of exports to China growing nine fold in this period (DAFM, 2014c).

The domestic market absorbs the majority of Irish pig meat with approximately 148,000 tonnes consumed in Ireland in 2014 (Bord Bia, 2015c). Additional pig meat is also imported into Ireland for further processing (Bord Bia, 2015c) with imports from Denmark particularly dominant in this sub-sector; much of this is re-exported as final product, totalling 207,000 tonnes in 2014 (Bord Bia, 2015c). When exported 76% of Irish pig meat is destined for Europe (Bord Bia, 2015a) with the UK representing the largest single market for Irish pig meat (DAFM, 2015c). The value of trade to the UK is estimated at approximately €330 million with 87,000 tonnes of pig meat exported to this market in 2014 (DAFM, 2015c). By comparison, 41,000 tonnes of Irish pig meat were exported to the rest of continental Europe to a value of €95 million in 2014. International market volumes reached approximately
70,000 tonnes with an approximate value of €140 million (DAFM, 2015c). Markets outside of the EU are nevertheless becoming increasingly important to the Irish pig meat sector with growing demand in Asia (China, Japan, and South Korea in particular) especially prominent. The value of pig meat exports to Asia doubled in 2014, mostly driven by increased exports to Japan (Bord Bia, 2015a). New market opportunities are also continually developing for Irish pig meat, with Ireland securing access to markets in Vietnam and the Philippines in 2014 for example (DAFM, 2015c).

2.4.2.5.1.3. Poultry

As highlighted by Bord Bia (2015c) approximately 76 million birds were processed in Ireland in 2014, the lowest level of throughput for the previous five years from a peak of 88 million in 2012. Broiler chickens account for the vast majority of poultry processing in Ireland (85%) followed by turkeys (8%), ducks (5%), and hens (2%) (Bord Bia, 2015c). The significant potential to add value through processing in the poultry sector is reflected in the fact that the value of Irish poultry exports has grown approximately 20% since 2013 to €310 million in 2014 (DAFM, 2015c). This is a reversal of value trends experienced in previous years and was driven by strong growth in processed product exports (DAFM, 2015c). Since the establishment of Food Harvest 2020 (DAFF, 2010a) the poultry industry is reported to have experienced a growth in volume of 9% since its 2007-2009 baseline figures, with a 9% increase in value also achieved (DAFM, 2014c). Overall, poultry constituted 3% of the total value of agri-food exports in 2014 (Bord Bia, 2015a).

The predominant demand for raw Irish chicken is from the domestic market. Of the 122,000 tonnes of poultry exported from Ireland in 2014, 97% was destined for European markets with 75% destined for the UK (Bord Bia, 2015c). Approximately 60% of the value of the Irish poultry market resides in chicken fillets, though increasing demand from Asian markets offers particular potential for the Irish poultry sector, providing potential additional outlets for the sale of fifth quarter products, legs, feet, and wings which are currently not as popular in domestic or European contexts (DAFM, 2015b).

Competition from cheaper imports represents the biggest challenge for the Irish poultry sector, a sector already characterised by low profit margins. Irish imports of poultry are estimated to have increased by over 10% in 2014 though some of this produce is processed here before being re-exported as final product (Bord Bia, 2015c). Imports from Brazil and Thailand particularly dominate poultry imports into the EU though increasing poultry trade to
Africa and Asia has resulted in simultaneous increases in exports from the EU in recent years, with EU poultry imports and exports both increasing by approximately 4% in 2014 (Bord Bia, 2015c). The global reputation of poultry as a low cost, protein-rich, and versatile food should ensure its continued consumption worldwide and its positioning as the preferred meat in Europe. Nevertheless, retail chicken prices continue to run at 80% of average retail beef prices (Enterprise Ireland, 2014), potentially limiting further growth opportunities in an Irish context. A continued focus on product innovation and diversifying product lines is essential to add value in the future (Enterprise Ireland, 2009).

2.4.2.5.1.4. Sheep Meat

In stark contrast to the poultry sector, limited domestic demand for sheep meat results in two out of every three sheep being exported from Ireland (DAFM, 2015b). Irish sheep meat exports totalled 44,759 tonnes in 2014 amounting to an export value of €218 million (DAFM, 2015b). This equated to just 2% of the total value of Irish agri-food exports in 2014 (Bord Bia, 2015a). Opportunities to add value have nonetheless emerged in the sector in recent years, particularly with regard to boneless products that accounted for approximately 65% of sheep meat exports in 2014 (DAFM, 2015b). By 2014 the value of sheep meat had increased 19% since 2007-2009 baseline figures despite a 6% decrease in output volume (DAFM, 2014c).

France and the UK are the greatest export markets for Irish sheep meat, with 60% of total sheep meat exports destined for these countries (Bord Bia, 2015a). French markets usually import twice that of the UK, evidence of the reputation for high quality Irish sheep meat in France (DAFM, 2015b). Exports to markets outside of these two countries are on the rise, with Irish sheep meat reaching markets outside of France and the UK increasing from 22% in 2009 to 40% by 2014 (Bord Bia, 2015a). Additional growth markets in Europe include Sweden, Belgium, and Germany while opportunities for Irish sheep meat outside of the EU, although limited, include exporting produce to Hong Kong, Canada, and North Africa. Efforts to open US and Chinese markets are ongoing and may represent potential growth markets in the future (DAFM, 2015b). New Zealand represents the largest competitor to Irish lamb with 51% of New Zealand lamb destined for EU markets (Kelly, 2015b). Decreases in export lamb production in New Zealand are forecast for 2015 and 2016 however, due to poorer grazing practices and increased retention of hoggets for breeding (Kelly, 2015b). A 36 month pan-European lamb campaign launched by Bord Bia in June 2015 may further the
appeal and growth of Irish sheep meat exports in the near future (Fitzgibbon, 2015). This campaign aims to increase the consumption of lamb meat amongst young consumers (25-45 year olds) as approximately 80% of current lamb sales are attributed to consumers over the age of 45 (Fitzgibbon, 2015).

2.4.2.5.2. Dairy

As documented in Food Wise 2025 (DAFM, 2015b) the dairy industry is central to the Irish agri-food sector, representing one of Ireland’s most important indigenous industries. In the past Ireland’s dairy product mix was weighed heavily towards commodity output. More recently, however, the focus has moved to adding value with significant growth experienced in the areas of infant formula production, premium butters and cheeses, and broader nutrition products and ingredients (DAFM, 2015b). The strongest performing categories in the Irish dairy sector include cheese, infant formula, casein, skim milk powder, and milk proteins (Bord Bia, 2015a).

In 2014 total milk output available for processing in Ireland was approximately 6.16 billion litres, with approximately 5.5 billion of this produced nationally (Bord Bia, 2015e). The majority of milk imports come into Ireland from Britain and Northern Ireland, driven by over-supply in these regions, a shortage of processing capacities in the UK, and resultant cheap import prices for Irish processors (McCullough, 2015). Mulhern (2014) described how processors from Northern Ireland hold about a 25% share of the drinking milk market in the Republic of Ireland. There are concerns regarding the rising importation of milk into Ireland in the post-quota era, at a time when domestic farmers continue to receive low prices for their milk output. Additional concerns relating to how such imports could undermine Bord Bia’s Sustainable Dairy Assurance Scheme also persist, though assurances have been given that any produce manufactured using imported milk must be labelled as such (McCullough, 2015). Of the total available milk supply in Ireland, 480 million litres is estimated to be consumed as liquid milk (Bord Bia, 2015e), leaving 5.68 billion litres available for processing and value addition. As a result, in 2014 an estimated 166,000 tonnes of butter were produced in Ireland alongside 215,000 tonnes of cheese and 71,000 tonnes of skim milk powder (Bord Bia, 2015e); quantities of these and other dairy products manufactured in Ireland are outlined in Figure 25.
The infant formula industry represents a unique commercial success story, with Ireland providing approximately 10% of global infant milk formula despite producing only 1% of the global milk supply (Bord Bia, 2015a). DAFM (2014c) reported that infant formula sales constituted approximately 26% of the total value of Irish dairy exports in 2013. Sales to China have been particularly impressive since 2009, accounting for almost 80% of the total value of Irish dairy exports to this region (DAFM, 2014c). The majority of these trading relationships involve Irish dairy processors supplying milk powder and ingredients to large, branded, multinational dairy corporations who then produce the final infant milk formula. Building relationships with leading infant formula and dairy companies in China has remained a central focus of Irish government and industry in the last decade, an investment that is now reaping dividends given the continued growth in sales to this region (DAFM, 2014c).

The Irish dairy industry is primarily an export driven sector, exporting over 85% of its milk output as cheese, powders, and butters worldwide (ICOS, 2015). Dairy products and ingredients represented the most valuable export of all agri-food sub-sectors in 2014, constituting 29% of the total value of agri-food exports that year (Bord Bia, 2015a). Total dairy and ingredients exports reached €3.06 billion in 2014, representing a 55% rise in value since 2009 and the publication of Food Harvest 2020 (Bord Bia, 2015a). The volume of dairy production (primarily milk output) also increased 10% in this period. This formed part of the soft landing strategy devised in the lead up to the abolition of milk quotas in 2015. The FAO (2014) reported Ireland to be the sixth leading exporter of dairy products amongst EU and European Free Trade Association countries behind significantly larger players (the United States, France, the Netherlands, Belgium, and Italy).

Figure 25: Annual quantities of dairy products produced in Ireland (tonnes per annum) (after ICOS (2015))
Irish dairy products are exported to almost 130 countries worldwide (DAFM, 2015c). They continue to perform strongly in mature markets such as the UK and the EU, though an increasing emphasis is being placed in political and industry circles on the potential that lies in emerging markets in Asia, the Middle East, and Africa (DAFM, 2015c). These latter regions are considered centres of growing dairy demand and thus are pivotal markets for any future increased output from the Irish dairy sector. Overall, the top five markets for Irish dairy are the UK, China, Germany, the Netherlands, and the United States (Bord Bia, 2015a). Increasing 30% on the previous year, exports to Asia amounted to approximately €530 million in 2014, two thirds of which were destined for China (Bord Bia, 2015a). Exports to the Middle East were up 19% and North America by 18% (Bord Bia, 2015a), highlighting the importance of international markets for Irish dairy. Trade to international markets beyond the EU constituted 40% of all dairy exports in 2014, valued at €1.24 billion (Bord Bia, 2015a).

The abolition of milk quotas in 2015 is considered to present both opportunities and challenges for the future of Irish dairy, with ambitions in place to increase national dairy production by 50% to over 8 billion litres by 2020 (Bord Bia, 2015a). A need therefore exists for appropriate supports for dairy processors in Ireland to harness the growth opportunities available. This includes building scale and increasing efficiencies to ensure sufficient and sustainable milk processing as well as ensuring plentiful markets for any increased dairy output. The Food Wise 2025 strategy also reports a need for dairy industry growth to not occur unbridled but with environmental and social sustainability in mind (DAFM, 2015b). Priority actions outlined in the strategy appropriate to the dairy processing sector include ensuring the environmental sustainability of dairy farming practices, furthering the reputation of Irish dairy on global markets, managing price volatility, and continuing to add value through research and innovation (DAFM, 2015b). Increased consumer demands for both health and convenience products also pose opportunities for the dairy sector in Ireland: an international study conducted as part of the Tetra Pak Dairy Index 2015 highlights continued consumer positivity around milk, with 84% of participants expressing no doubts over the goodness of milk and 84% planning to continue consuming milk as normal (Tetra Pak, 2015). Growing consumer trends and awareness and acceptance of functional foods and related ingredients also hold significant promise to add value in the Irish dairy industry.
2.4.2.5.3. Functional Foods

According to Enterprise Ireland (2009) functional foods include “any ingredient, food or beverage that contains specific physiologically active components that provide health and wellbeing benefits beyond basic nutritional functions”. While the definition of functional foods, and the associated legislation, varies across geographic regions it is universally recognised that functional foods are growing in popularity with consumers and represent a highly lucrative market. Ireland is particularly well positioned to provide functional ingredients and products in the dairy sector with products marketed to date including probiotic yoghurts, ingredients for sports drinks, cholesterol lowering spreads, high calcium cheeses, yoghurts for elderly nutrition, and fortified infant formula and milk drinks. The majority of current Irish manufacturing capability in the functional foods arena resides in a limited number of large dairy companies and SMEs (Enterprise Ireland, 2009). Continued investment in the dairy industry is therefore crucial to realise the opportunities associated with the functional foods market and increased consumer demand for healthy, nutritious, and convenient products.

At a national level the functional food sector in Ireland was estimated to be worth in excess of €100 million in 2009 (Enterprise Ireland, 2009). This includes both indigenously produced functional products as well as those that are imported. Irish food processing companies are considered to be particularly well placed to create impact in this sector, and potentially to substitute imports with indigenous products in the future. This reputation emerges as a result of the strong food and pharmaceutical industries base in Ireland and the availability of high quality raw materials here as well as national research facilities and capabilities (Enterprise Ireland, 2009). Opportunities have been recognised by the Irish government and related authorities such as Bord Bia and Enterprise Ireland particularly in the arena of nutrition in ageing, with aims of meeting the ever-changing demands and needs of an ageing global population for nutritious and high performing foods to ensure optimum health and disease prevention. Plans to develop innovative food products and businesses in this area remain a priority in the Irish food supply chain research and commercial context. Food for Health Ireland, for example, was established in 2008 as a multi-disciplinary technology and innovation centre with the aim of identifying novel milk ingredients for use in the functional foods industry. Co-funded by Enterprise Ireland and dedicated industry partners, it connects the work of over 75 scientists across a number of public research organisations with research
focusing on infant nutrition, appetite modulation, healthy ageing, and performance nutrition (FHI, 2015).

A number of sub-sectors of the Irish food industry have potential to feed into the functional foods arena. The ability to harness an increasing number of bioactives from dairy processing waste streams has emerged as a distinct research focus for example, with a variety of national research institutions including Teagasc investigating the commercialisation potential. For example, work is ongoing to extract human milk oligosaccharide bioactives from farm mammal milk for use in infant formula to bring about a number of prebiotic, health, and postnatal development benefits. Similar drives to extract whey protein isolate as a by-product in the production of cheese have also proven successful in an Irish commercial context with multiple uses in the sports nutrition industry (DAFM, 2015b).

The extraction of bioactive compounds from marine species for use as functional food ingredients also holds potential in the Irish context and represents a key focus of NutraMara, the Marine Functional Foods Research Initiative. NutraMara is a multi-centre research consortium that focuses on the identification and characterisation of novel bioactive compounds from marine resources as potential ingredients in functional foods. A number of companies in Ireland are interested in developing marine-origin functional food ingredients including Marigot Ltd. which was established in 1992. Its innovative Aquamin product range, for example, is derived from a unique raw material, the red alga Lithothamnion. Due to its composition which includes calcium, magnesium, and 72 trace minerals Aquamin can be used in foods, drinks, and dietary supplements (Marigot Ltd., 2016) where it has been shown to deliver bone and digestive health benefits. In addition, the world’s largest biomarine ingredients company, BioMarine Ltd., is set to open in Donegal in 2016. This company aims to derive functional food ingredients from marine resources including boarfish and blue whiting for use in sports nutrition and health.

2.4.2.5.4. Prepared Consumer Foods

The definition of prepared consumer foods varies both nationally and internationally, with differing views persisting across policy, commercial, and academic contexts as to what should be included in this category (DAFM, 2014c). In an attempt to rectify this in an Irish setting, a number of state organisations and industry leaders devised a list of 15 categories to define the boundaries and context of the Irish PCF sector. This list includes biscuits; breads; cereal-/chocolate-/sugar-/fruit- and vegetable-based products; dairy/meat/other food...
preparations; extracts/sauces/soups; fruit-based confectionary; frozen confectionary; savoury snacks; pizza/quiche; and waters/juices/soft drinks (DAFM, 2014c). More broadly, Enterprise Ireland (2015) classifies the PCF sector as including chilled foods (e.g. salads, soups, cooked meat products), frozen foods (e.g. ready meals, pizza), and ambient products (e.g. snacks, sauces, confectionary). Bord Bia (2015a) similarly includes baked goods, snacks, confectionary, ambient grocery, chilled foods, ready meals, and cooked meats in their definition of the sector. In their ten year strategy developed for the PCF sector Food and Drink Ireland include both value-added seafood and non-alcoholic beverages in their definition (FDI, 2014). Their focus for PCF is on any company that produces value-added food or beverages and is similar to the approach adopted in the Food Wise 2025 strategy (DAFM, 2015b). Such variances in definition must be noted given the impact this may have on statistics and comparisons made within this sub-sector.

According to Food Wise 2025 (DAFM, 2015b), and thus including all value-added food and beverage processing but excluding dairy products, the PCF sector achieved a gross output value of €4 billion in 2014. Of this, Irish PCF exports are estimated to exceed €2.1 billion (FDI, 2014) and have grown by 18% since 2009 (DAFM, 2015b). Highlighting a unique characteristic of this sub-sector to retain economic gains nationally, Irish PCF sales command a 40% share of the domestic PCF market (DAFM, 2015b). PCF imports nonetheless continue strongly in this sector, with the trade deficit of PCF amounting to approximately €700 million in 2014 (DAFM, 2015b).

By comparison, adopting the more restrictive definition of PCF but including dairy-based powders, Bord Bia (2015a) reports the value of PCF exports as €1.8 billion. The best performing categories in 2014 included bread and baked goods (which doubled in value to €150 million), chocolate confectionary, dairy-based enriched powders (40% of the total reported value), and meat-based products. Eleven per cent of prepared food exports emerged from the chocolate confectionary industry (Bord Bia, 2015a) while overall, prepared foods accounted for 17% of the total value of agri-food exports in 2014 (Bord Bia, 2015a). This makes the prepared foods sub-sector the third largest export category in terms of economic value and highlights the significant potential of value addition through processing in this category.

One of the biggest challenges facing the PCF sector in recent years revolves around reduced consumer demand, particularly in domestic markets, perhaps due to economic restraints as well as growing consumer scepticism around a variety of convenience foods. Some recovery
in the sector was noted by DAFM (2014c) however, associated with the recovery of the domestic and international economy. Recent PCF growth rates are still nonetheless below peak 2006 levels according to DAFM (2015b), highlighting some way to go before returning to previously achieved growth and sales. Food Wise 2025 aims to address this issue, maximising opportunities for import substitution in the PCF sector to increase the sector’s share of the domestic market (DAFM, 2015b). Enterprise Ireland (2009) highlighted a number of distinct strengths afforded to the PCF sector in Ireland including the ready supply of high quality ingredients, national reputation for safe, high quality food, and convenient market access to the UK. A need to address some of the weaknesses evident in the sector remains nonetheless, including facing global competition in both domestic and export markets, addressing the relatively high Irish cost base for manufacturing, and reassuring increasingly cost conscious consumers. PCF industry members are encouraged by Irish government to enhance innovation, productivity, and brand development.

The potential for the use of fifth quarter products such as offal (organs and blood) and other co-products in the PCF sector must not be overlooked from an economic and environmental perspective. Recent research in Teagasc highlights the potential for greater consumer acceptance of these elements when presented within processed products (for example, in mince) (O’Callaghan et al., 2014). This could create new products, markets, and growth in the future of the PCF industry.

2.4.2.5.5. Beverages

Beverages accounted for 12% of the total value of agri-food exports in 2014, making it the fourth largest food sub-sector in an Irish export context, valued at €1.2 billion (Bord Bia, 2015a). Whiskey, cream liqueurs, and beer account for 75% of total beverage exports from Ireland with the remaining 25% including a range of waters, cider, and juices. Whiskey is the most popular Irish beverage export, accounting for 30% of total beverage exports in 2014. This is closely followed by Irish cream liqueur (26%) and beer (19%) (Bord Bia, 2015a). Overall, beverage exports exceed imports in Ireland with a relatively high domestic content also evident in alcohol exports (DAFM, 2015b). Meanwhile, the Irish craft beer industry experienced significant growth between 2013 and 2014, with less than ten microbreweries active in Ireland in 2013 jumping to more than 50 operating in 2014. Craft beer is denoted as a significant growth area in the future of Irish beverages. Whiskey remains the dominant beverage within an Irish export context, representing the fastest growing spirit in the world.
according to Bord Bia (2015a) and with a value up 60% since 2009 to reach a total of €365 million in 2014. Seven million whiskey cases each with a capacity of nine litres were exported in 2014, with this figure projected to increase to 25 million cases by 2030 (Bord Bia, 2015a). The potential to increase beverage exports and further diversify markets is thus apparent for the future of the Irish beverage industry, particularly with regard to high value, branded alcoholic products that are less susceptible to fluctuating global commodity markets (DAFM, 2015b). DAFM (2015b) highlights plans to double whiskey exports by 2025 and increase the number of microbreweries operating in the country to 100.

The potential to harness the number of by-products and co-products that emerge from the fermentation processes in a number of Irish breweries and distilleries also raises significant opportunities for further growth and value addition in the Irish beverage sector. For example, Clancy (2015) highlights opportunities within the Irish whiskey industry to recover co-products and waste streams for use in animal feed and biofuels, rather than simply composting these high value elements. Similarly, Byrne (2015) highlights the feasibility of spent distillers grain being utilised as animal feed, highlighting its potential as a by-product rather than a waste while simultaneously reducing feed imports in the Irish agricultural sector. Clancy (2015) also reports the potential to recover the water utilised in whiskey processing units.

Irish beverage processors export produce to 125 markets globally with the UK, the US, Canada, Germany, and France representing the top five destination markets (Bord Bia, 2015a). A total of €560 million worth of Irish beverages are sold in international markets, indicating the extensive global reach of the beverage industry compared to other sub-sectors in the food supply chain that depend largely on European markets. The growth of the craft alcohol market in the United States as well as sales potential associated with emerging markets in Asia are highlighted in Food Wise 2025 as providing opportunities for the Irish beverage sector (DAFM, 2015b). Such developments must be supported by a strong base of grain growers and dairy farmers to provide quality inputs to this sub-sector.

2.4.2.5.6. Fish, Shellfish, and Algae Products

Once landed, the ability to add value to fish, shellfish, and algae products through processing represents an important source of economic activity in Ireland, providing employment in many coastal areas and generating substantial export earnings (DAFM, 2014i). This includes seafood processing for human consumption as well as emerging opportunities to extract
bioactive compounds for use in the food, feed, pharmaceutical, and cosmeceutical industries. Ireland’s natural 7,500 km coastline which is rich in aquatic life adds to the potential and realisation of such opportunities (Bord Bia, 2015a). According to DAFM (2015b), Ireland’s processing share of the 1.2 million tonnes of fish caught in the productive fishing grounds around Ireland equates to approximately 315,000 tonnes or approximately 25% of total allowable catches. This does not include output from the valuable inshore fisheries operating in the country including whelk and lobster, for example (DAFM, 2014i).

According to DAFM (2015b) sales from the seafood sector were valued at €850 million in 2014. Of this, €540 million can be attributed to seafood exports, representing approximately 5% of the total value of Irish food and beverage exports (Bord Bia, 2015a). The seafood sector has experienced significant growth in recent years (second only to beef in terms of gains achieved (DAFM, 2014c)) with the value of seafood exports increasing by 70% between 2009 and 2014 (Bord Bia, 2015a). In volume terms, DAFM (2015c) estimates that 255,841 tonnes of seafood were exported in 2013, including a variety of pelagic trade (e.g. mackerel, herring, and sardines), whitefish exports (e.g. cod, haddock, whiting, hake), shellfish, and salmon. Pelagic trade accounted for the majority of exports in 2014 according to DAFM (2015c), amounting to 178,864 tonnes in 2014 to a value of €219 million. Shellfish exports tracked second in terms of importance, valued at €176 million in 2014. The best performing export categories of shellfish included Dublin Bay Prawns (€41 million), crab (€34 million), and oysters (€30 million) with unusually low harvest volumes of mussels noted in 2014 (€12 million). Increased exports of whelk and clams to Asian markets were a distinguishing feature of 2014, valued at €18 million and €7 million respectively. Overall whitefish exports were valued at €45 million in 2014, while 5,329 tonnes of salmon brought in €44 million. Both of these categories have been affected by supply side issues and restricted fishing opportunities in recent years (DAFM, 2015c).

Ireland exports seafood to 80 countries worldwide with France, the UK, Spain, Nigeria, and Italy representing the top five export destinations (Bord Bia, 2015a). Recent growth in exports to Asian and African markets earmark progress in the sector, with Irish seafood exports to Asia increasing 25% in 2014 led primarily by increased pelagic and shellfish exports to China which increased 35%, and exports to Africa up 12% incorporating a trebling of trade to Egypt (Bord Bia, 2015a). Cultural preferences for seafood in the East are predicted to further drive Irish seafood exports in the future (DAFM, 2015b). The majority of seafood exports are sold within the EU however, amounting to 63% of all Irish seafood exports in
2014 (Bord Bia, 2015a) and equating to approximately €336 million (DAFM, 2015c). It is envisaged that further growth in the seafood sector will be driven by rising global demand for sources of more sustainable, convenient, and nutritious protein (DAFM, 2015b). As outlined in Food Wise 2025 it is estimated that global consumption of fish will increase by 17 kg per person per annum up to 2030 (DAFM, 2015b). This equates to a requirement for an additional 40 million tonnes of seafood with Ireland considered well positioned to meet this demand as a leading producer of seafood products (DAFM, 2015b). The potential also exists to tap into other large international markets, including the United Arab Emirates which imports 75% of its seafood products, and the USA which imports 90% by weight (DAFM, 2015b). These markets are currently open but underdeveloped from an Irish export context: an Irish company, Connemara Abalone Ltd., exports abalone to the UAE in both a natural form and as a canned product.

Issues of processing industry fragmentation, availability of trained staff, scale, and leadership deficiencies in Ireland must be addressed and invested in to fully realise the potential of the Irish seafood sector (DAFM, 2015b). In addition, there is a need to map the marine natural resource base and shoaling patterns of currently underutilised fish such as boarfish and blue whiting. Although quota restrictions on wild species may prevent further volume growth, there are prospects to add value in this sector alongside opportunities to process new species. Food Harvest 2020 established a need to increase the share of catch landed and processed in Ireland from both Irish and non-Irish vessels (DAFF, 2010a). As a result, in 2010 17% of the Norwegian blue whiting catch was processed in Killybegs, Co. Donegal, equating to 35,000 tonnes (DAFM, 2014c). This figure rose to 80,000 tonnes in 2012 before dropping back to 35,000 tonnes in 2013 due to higher fish meal prices in Norway (DAFM, 2014c). This example is indicative of the expansion potential, albeit with vulnerabilities, associated with seafood processing dependant on non-Irish vessel landings. A €10 million deal between the Castletownbere Fishermen’s Co-Operative and a large Spanish retail outfit has resulted in landings from up to four Spanish vessels being processed in the southwest of Ireland (DAFM, 2014c). This represents an area of potential expansion for value addition in the seafood sector.

Bolstered by a strong reputation in the marine biological sciences and research fields, opportunities associated with marine biotechnology are also apparent in the Irish context. This includes the potential to add value to Irish marine discards and waste. For example, Baron (2015) outlines the opportunities that arise from recovering high value organic matter
from the effluent or wastewater associated with fish processing, with 100 tonnes of protein potentially available for recovery for every tonne of herring processed. Hayes (2015) and Kirke (2015) also highlight the potential to harness and optimise bioactive compounds from marine cut-offs and algae sources for use as ingredients in nutraceuticals, cosmeceuticals, pharmaceuticals, bioenergy enzymes, and bio-polymers. Similarly, Børresen (2015) recognises the need for omega-3 rich feed in the aquaculture sector to ensure an omega-3 rich output, reporting the potential for closed feedback loops within this sub-sector. Finally, fish shells have been found to be rich in chitin which represents a useful starting material for further chemical conversions and the development of speciality bio-chemicals (Sieber, 2015). Aside from the direct environmental and economic benefits, use of marine materials in such ways also enables cost savings for seafood processing companies in an era when landfilling and sea dumping of waste material is increasingly restricted.

There are a number of potential limitations regarding the development of such industries in Ireland for the production of bio-materials and food products from marine waste streams, however. For example, the quantity of raw material available in Ireland for further processing is unknown at this time and may be too small to be economically viable. Approximately 10 kg of crab and prawn shell waste materials are required to generate 1 kg of chitin; chitosan can command as much as €2 per gram of material depending on the quality of the product with food-grade chitosan normally costing between €120-150 kg$^{-1}$. In addition, extraction methods utilised to date to generate chitin from crab and prawn shellfisheries wastes often involve harsh acids and basic solvents. There are limitations and costs associated with the neutralisation of these solvents and their disposal, not least from environmental, health, and safety perspectives. These limitations are not as prominent in regions such as South East Asia, Newfoundland, and Norway where chitin and chitosan production plants already exist. A distinct need thus remains for increased research and the development of pilot plants and commercial demonstration projects in Ireland to investigate and realise future feasibility in this area.

From an infrastructural perspective, plans by Bio-Marine Ingredients Ireland (BII) to develop state-of-the-art processing facilities in Killybegs holds further promise to increase the processing capability of the seafood sector and maximise the use of raw marine materials available in Ireland (Whooley, 2015). A key element of this proposed €40 million project includes the development of a bio-marine ingredients plant which will process up to 50,000 tonnes of raw material per annum with the intention of extracting oils, calcium, and high-end
protein for use in food ingredients, nutritional supplements, and medicinal elements (DAFM, 2015b). Converting low value raw material into high value ingredients and novel products, BII plans to enter full production by the end of 2016.

### 2.4.2.6. Value Added by the Food and Beverage Industry in Ireland

Assessing gross value added by the food and beverage industry provides a means to assess its contribution to the wider economy. As highlighted by DAFM (2014c), “value added principally results from taking a raw commodity and changing it to produce an enhanced product which meets the tastes or preferences of consumers”. The processing industry operating as part of the food supply chain in Ireland thus plays a crucial role in determining GVA for the overall agri-food sector. Since the publication of Food Harvest 2020 (DAFF, 2010a) significant progress has been made in this area by the Irish food and drinks industry due to an increased focus on innovation and new product development in an effort to meet ever-changing consumer needs and desires. As stressed by DAFM (2014c), the need for the food industry to identify, track, and predict consumer trends is paramount to success in the value-added arena, with the industry highlighted as “the direct interface between consumers and producers and…in the front line when it comes to changing consumer tastes or retail demands”.

Overall, the food and beverage industry accounted for approximately 4.8% of GVA in Ireland in 2013 (DAFM, 2015c). In monetary terms, DAFM (2014c) estimated the value added by food and beverage products in 2014 to be in the region of €7.5 billion, up 20% from the €6.05 billion baseline recorded prior to the publication of Food Harvest 2020. Meat and dairy accounted for 12% of total GVA with beef representing the most important sub-component of the meat sector in Ireland, responsible for 44% of GVA in this category (DAFM, 2015c). Beverages accounted for a further 19% of total GVA (DAFM, 2015c), highlighting the significant potential to add value in this category particularly with regard to high-end alcoholic beverages. GVA by the seafood processing sector in 2011 was estimated at €99.3 million (DAFM, 2014i). Unsurprisingly, the “other foods” category which includes PCF and other processed food products was responsible for the highest proportion of total GVA standing at 61% or €4.6 billion.

The need to add value is apparent across all sub-sectors of the food supply chain discussed in this report, but is more necessary and applicable to some than others. For instance, marginal profitability is particularly associated with the dairy processing sector with a good year of
dairy production and output resulting in an approximate 4% margin, with average years generally yielding a mere 2% (Enterprise Ireland, 2009). Bad years, such as that experienced in 2008, can even result in operators merely breaking even or incurring substantial losses. The need to develop innovative products and derive ingredients that add value to this sector is thus especially important. It is generally agreed that the more original or unique the application, the higher the profitability margin that can be achieved, with products in the dairy category commanding margins in the range of 10-40%. This level of profitability can be directly related to its stage in the product lifecycle as well as the level of originality associated with its use (Enterprise Ireland, 2009).

Investment by Enterprise Ireland in a number of Irish firms is partly responsible for the increase in GVA in the food and beverage sector in recent years, providing crucial assistance to the industry to expand and modernise facilities through a number of grant and support schemes. The organisation is reported to have invested in more than 70 projects with large food companies in Ireland, leveraging a total investment of €700 million in the industry and a commitment for over 2,000 new jobs in the medium term (DAFM, 2014c). The most significant gains in GVA were observed in beverages (up 33%) and fish products (up 25%), though declines were apparent amongst dairy products (down 40% due to fluctuating and decreasing prices) and meat (down 1.8%). The higher economic profile achieved by the food industry since 2009 is nonetheless still praised by DAFM (2014c) despite these variances in GVA performance, with the food and beverage industry highlighted as an essential stimulus for economic recovery in recent years. Total turnover of the agri-food manufacturing industry is estimated to be approximately €26 billion, with the sector also responsible for 12.3% of overall merchandise export values (DAFM, 2014c).

Targets to increase GVA in the agri-food industry to €8.57 billion by 2020 set within Food Harvest 2020 (DAFF, 2010a) have been surpassed by new aims established in Food Wise 2025 (DAFM, 2015b). While difficult to separate precise figures for the food and beverage industry in particular, this new strategy aims to increase overall GVA for the agri-food, fisheries, and wood products sector by 70% by 2025 with a strong emphasis on adding value by delivering new and innovative food solutions to consumers. This would drive added value of the sector from the 2012 baseline figure of approximately €7.5 billion to more than €13 billion in the next decade. The strategy also aims to increase the overall value of food and beverage exports by 85% by 2025 to reach €19 billion per annum from the current baseline of €10.5 billion. Such commitments are testament to the continued emphasis on and confidence
in the performance of the food supply chain in Ireland, positioning it as a priority area for growth and development for many years to come.

2.4.3 Forestry Sector

In 2010 the value of outputs from the forestry growing sector was estimated to be €673 million (Casey, 2013). Casey (2013) reported that although the demand for higher value timber for construction in the domestic market has fallen, the demand for forest-based biomass and firewood remains significant. In 2014 3.04 m m$^3$ of woody material (including firewood) was harvested in the Republic of Ireland (Knaggs and O'Driscoll, 2014). Outputs of the forestry growing sector feed into the wood processing sector, which includes primary (sawmilling), secondary (panelboards), tertiary (furniture and wood craft) (DAFF, 1996), and, more recently, wood energy including bioenergy and specialities sector (including the wood (fibre) bio-refinery platform).

2.4.3.1 Sawmilling and Board Manufacturing

In 2014 Irish sawmills processed 1.82 m m$^3$ of roundwood to produce 904,000 m$^3$ of sawn timber; 75% of this material was sourced from Coillte with the balance being supplied by imports and by the private forestry sector (IFFPA, 2016). Five large- and three medium-sized companies account for more than 90% of the sawmilling industry in Ireland, all of which are FSC and/or PEFC certified (IFFPA, 2016). The main products manufactured by the Irish sawmill sector include construction/structural timber, pallet/packaging timber, and fencing products. Until recently structural timber was largely sold on the domestic market with pallet and fencing products contributing to sawn timber exports (IFFPA, 2015). During the downturn years the domestic sawn timber market declined by 53% but sawn timber exports grew by 60% (Knaggs and O'Driscoll, 2014). Northern Ireland, France, and the UK are the most important export markets for Irish sawn softwood; between 2007 and 2014 the market share of Irish sawn softwood in the UK market increased from 3.34% to 5.77% and in 2014 Ireland was the fourth largest exporter of sawn softwood to the UK (IFFPA, 2016).

The wood-based panel sector produced a combined output of 773,000 m$^3$ in 2014, processing a total of 1.39 m m$^3$ of wood fibre to do so. The vast majority (86%) of this material was exported at a value of €198 million (IFFPA, 2016). In addition to being the fourth largest exporter of sawn softwood to the UK, Ireland was also the second largest exporter of particleboard and orientated strand board (OSB) and the largest exporter of medium density
fibreboard (MDF) to the UK (IFFPA, 2016). Recent years have seen considerable investment in the sector to develop new products and markets, particularly within the UK and French markets. One notable new product which has shown significant growth is Medite Tricoya Extreme, produced by Medite Europe, a subsidiary of Coillte. The Building Research Establishment (BRE) in the UK described Medite Tricoya Extreme as having a durability equivalent to that of teak and more than that of oak (Medite Tricoya, 2015). BRE concluded that Medite Tricoya could meet the demands for a desired service life of 60 years when used in exterior applications.

2.4.3.2. Forestry and Bioenergy

Forest-based biomass has an important role to play in the renewable energy targets set out by Directive 2009/28/EC. Ireland has a strong comparative advantage in the growing of wood fibre, with growth rates of certain species well in excess of those achievable in some other European countries (Duesberg et al., 2013); this will benefit both the renewable electricity and renewable heat sectors as well as the overall economy by contributing to carbon sequestration. In 2012 over 35% of the total roundwood harvested in Ireland was used directly in the generation of heat and/or power, primarily within the forestry sector where it is mainly used to dry biomass (COFORD, 2014). 230,000 m$^3$ of firewood was consumed in Ireland in 2013 at a value of over €33 million, primarily sourced from first thinnings (ODriscoll, 2015); wood for energy is also sourced from wood residues from the processing sector and post-consumer recycled wood. In addition to the revenue directly provided by the use of wood products for renewable energy, the greenhouse gas emissions saved by the use of these products were valued at over €10 million (COFORD, 2014). The profile of the use wood products for renewable energy in Ireland is outlined in Table 15.

Table 15: Use of forest-based biomass for renewable energy in Ireland (after O'Driscoll, 2015)

<table>
<thead>
<tr>
<th>End Use</th>
<th>'000 m$^3$ over bark</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>2011</td>
</tr>
<tr>
<td>Wood-biomass use by the energy and forest</td>
<td>572</td>
</tr>
<tr>
<td>products industries</td>
<td></td>
</tr>
<tr>
<td>Roundwood chipped for primary energy use</td>
<td>41</td>
</tr>
<tr>
<td>Domestic firewood use</td>
<td>215</td>
</tr>
<tr>
<td>Short rotation coppice</td>
<td>5</td>
</tr>
<tr>
<td>Wood pellets and briquettes</td>
<td>129</td>
</tr>
<tr>
<td>Charcoal</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>966</td>
</tr>
</tbody>
</table>
2.4.3.3. Forestry as a Feedstock Source

In the forest sector transformative technologies promote novel and strategic uses for wood-based material (Natural Resources Canada, 2015). Transformative technologies can be used to implement new methods of producing, using, or packaging existing wood products. They can also shift the focus to non-traditional products and new markets for forest-derived materials (Natural Resources Canada, 2015). Such technologies can provide the key to extracting more value from the forest resource. Various forces are pushing transformative technologies to the forefront of the forestry sector including competitiveness of the forest sector, climate change and its ramifications for the sector, the need for continuous improvement in sustainable land use, the limited and depleting supply of non-renewable fossil fuels, and the growing demand for products that have a low environmental impact (Natural Resources Canada, 2015). The Canadian forestry industry has identified four examples of transformative technologies that could be adopted in the next 10 years which will change the way traditional products are processed: the use of sensors to measure wood quality which would facilitate new, specialised uses for wood; wood connection technologies that increase wood use in multi-residential and institutional construction; coatings and surface treatments based on nanotechnology that give the appearance of high-grade finishes and prevent discolouration from sunlight; and new paper grades for publishing using high mineral content and for high-performance packaging (Natural Resources Canada, 2015).

Technologies that create new products such as biofuels, bio-chemicals, and bio-polymers will move the forest sector to the next level by opening up new markets for forest-derived materials (Natural Resources Canada, 2015). As well as creating new uses for forest materials, technologies which use organic materials for the production of plastics, for example, will contribute to reducing dependency on fossil fuels (Álvarez-Chávez et al., 2012). Processes are being developed to combine wood fibre with plastics like polyvinyl chloride and polypropylene to produce new materials with enhanced durability and strength (Natural Resources Canada, 2015). Research is also ongoing into the possible uses of fibre-bio-plastic composites created entirely from renewable resources which could serve as renewable alternatives to fibre-plastic composites. The development of such products will create new opportunities for the forest sector to improve competitiveness while at the same time lowering dependence on fossil fuels and reducing greenhouse gas emissions (Natural Resources Canada, 2015).
The rising cost of fossil-derived products has given indirect support to the development of transformative technologies which can create new uses for forest-derived products. Lignin, a complex carbon molecule that makes up the cell walls of trees and rigid plants, accounts for 30% of a typical tree but is currently treated as a waste product of the pulping process (Natural Resources Canada, 2015). To obtain value from this material, research is ongoing into the use of lignin as an innovative replacement for carbon black, a petroleum product used in making car tyres. Carbon black gives rubber its strength and pigment and helps reduce thermal damage to the tread and steel belts (Lakehead University, 2010). Carbon black currently comes from crude oil but research indicates that replacing it with a renewable material has real potential with the benefits of a new market and revenue stream for the forestry sector as well as reducing the use of fossil-derived materials.

Nanocellulose is an innovative new material which can be derived from woodpulp and used in a variety of different applications; fundamentally it is wood fibres broken down to the nanoscale (US Forest Service, 2012). It is unique among nanomaterials in that it is bio-based, renewable, biodegradable, and has high strength and stiffness (Salas et al., 2014). Cellulose nanocrystals are extremely strong and have unique electrical and optical properties; they also carry a charge, are chemically active, and can be modified for use in a wide range of applications including oil and gas, adhesives, paints and coatings, composites, and much more (Salas et al., 2014). The US Forest Service have estimated that nanocellulose could add $600 billion to the US economy by 2020 and describe how research and development into “new lightweight, high-performance wood-derived products can help reduce fossil fuel consumption and greenhouse gas emissions while increasing the potential for rural manufacturing opportunities, including the creation of many new high-paying jobs” (US Forest Service, 2012) Some of the novel applications of nanocellulose which are currently in use or being pursued are listed in Error! Reference source not found..

Millions of tonnes of saw dust are produced by sawmills and lumber yards when producing wood. Approximately eighty percent of this saw dust cannot be used in products such as roof shingles and wood panels because the dust is too fine or does not have the right fibre content. This volume of processing by-product can instead be used in the manufacturing of bio-coal by torrefaction. Bio-coal can be used as a substitute for fossil coal during co-firing (Agar and Wihersaari, 2012) but has a much more positive environmental footprint (Vega Biofuels, 2014) due to its fossil-free origins and creates a re-use possibility for a material which could be considered a waste.
Biochar is a highly absorbent, specially designed, charcoal-type product primarily used as a soil enhancement for the agricultural industry to significantly increase crop yields. The production of biochar for carbon sequestration in soil is a carbon-negative process and has been used for thousands of years: early civilisations cut up plant materials before burning and burying them, allowing them to smoulder which eventually produced a char material (Vega Biofuels, 2014). This process resulted in the restoration of the degraded soil to extremely rich and fertile humus. Nowadays biochar is produced by pyrolysis, a process in which biomass is heated in an oxygen-deprived environment to break it down into simpler substances (Vega Biofuels, 2014). Producing bio-coal or biochar from wood processing by-products offers the potential to generate an additional revenue stream for processors while also potentially avoiding disposal costs.

2.4.4 Marine Sector

Once landed, the addition of value to fish, shellfish, and algae products through processing represents an important source of economic activity in Ireland, providing employment in many coastal areas and generating substantial export earnings (DAFM, 2014i). In this instance the processing of seafood products includes for human consumption as well as emerging opportunities to extract bioactive compounds for use in the food, feed, pharmaceutical, and cosmeceutical industries. Ireland’s natural 7,500 km coastline, rich in aquatic life, adds to the potential and realisation of such opportunities (Bord Bia, 2015a).

According to DAFM (2015b), Ireland’s processing share of the 1.2 million tonnes of fish caught in the productive waters around Ireland equates to approximately 315,000 tonnes or

Table 16: Applications of nanocellulose currently in development or in use (after Turbak (2011))

<table>
<thead>
<tr>
<th>Engineering and technology applications</th>
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<tbody>
<tr>
<td>• Making 10% lighter auto components, improving fuel economy figures by 10%</td>
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<tr>
<td>• Improving diaper, non-woven, and catamenial fluid retention</td>
</tr>
<tr>
<td>• Making non-settling sand, coal, and other pumpable solids suspensions</td>
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<tr>
<td>• Making strong, translucent films</td>
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<table>
<thead>
<tr>
<th>Health and beauty applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Making low calorie bread and baked goods with 300% extended shelf life</td>
</tr>
<tr>
<td>• Making healthier, low calorie desserts, gravies, and salad dressings</td>
</tr>
<tr>
<td>• Making high quality cosmetics to minimise or prevent skin wrinkles</td>
</tr>
<tr>
<td>• Stabilising foams of all types, edible and non-edible</td>
</tr>
<tr>
<td>• Relieving arthritis joint pain</td>
</tr>
<tr>
<td>• Making artificial body parts</td>
</tr>
<tr>
<td>• Making nanochitosan used for instant blood clotting of severed arms and legs</td>
</tr>
</tbody>
</table>
approximately 25% of total allowable catches. This does not include output from the valuable inshore fisheries operating in the country (including for example, whelk and lobster) (DAFM, 2014i).

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2.4.5 Bioenergy Products

2.4.5.1. Solid Fuels

Solid renewable fuels are generally derived from wood material although some feedstocks are purpose-grown energy crops. The material is generally used in one of three forms: logs, pellets, and chips. Wood pellets are manufactured from saw dust, shavings, bark, or chips and are produced by drying and compressing with steam (SEAI, 2012b). Wood pellets have the advantage of being compact, easy to transport and store, and have a small carbon footprint associated with their production (approximately 2% of the energy content of the fuel itself) (SEAI, 2012b). Wood pellets also have a higher energy density than wood chips which means less fuel material is needed to generate the same amount of heat or electricity (SEAI, 2012b). Wood chips tend to be used in non-domestic boilers as a larger storage facility is required due to the larger chip size. During production the size of the chip is controlled by the positioning of the blades in a wood chipper and is determined by the end user’s requirements (SEAI, 2012b). Wood chips are usually produced from residues from sawmills, from forestry thinnings, and from purpose-grown short rotation coppice biomass.

Logs or briquettes are produced from forestry by-products and have been used in domestic heating in Ireland for generations. Burning firewood in an open fireplace has very low efficiency (approximately 30%) so their use in a boiler is more preferential, however log burners have the disadvantage of requiring manual loading whereas pellet and chip boilers can be fed automatically (SEAI, 2012b). Where forestry material provides the source for
solid fuels, the biomass used is the lowest value material remaining after the higher value chains have been fulfilled. The highest quality and highest value output from the forestry sector is derived from the production of sawlogs; it is this output that sawmills turn into high quality boards or planks that ultimately end up in the construction industry. Market requirements for construction materials dictate that this material should come from larger, straight growing trees with a diameter of at least 14 cm (Clancy et al., 2012). Achieving these criteria requires a forest management regime of thinning which will result in the output of large, clean, straight trees. The thinning process also yields smaller trees which are not sawlog-grade; this material is known as pulpwood or small roundwood and is channelled into the paper and pulp manufacturing sectors and is also used in the production of panelboards (Clancy et al., 2012). This material is also suitable for bioenergy use however the availability is dependent initially on demand from other sectors (Clancy et al., 2012). Although there are a number of sawmills and wood processing facilities in Ireland pellets and chips for energy use are not produced in all of these facilities. Most recent information available indicates that less than 100,000 tonnes of wood pellets are currently produced annually in Ireland for energy use. While wood chips are listed as an output from this industry this material is utilised for MDF and/or paper production (GP Wood, 2016); although this material could also be used for energy generation it is instead used to fulfil higher value product chains.

2.4.5.2. Liquid Fuels

Liquid biofuels can be produced from a number of source materials including crop biomass, recovered waste oils, and fats, among others. Bioethanol, the biological alternative to petrol, is generally produced from crop biomass and is widely used throughout Ireland as a result of the blending of road transport fuels with biological additives implemented by the Biofuels Obligation Scheme; none of the bioethanol consumed in Ireland is produced in Ireland, however (Dineen et al., 2014).

Ireland does currently have an indigenous biofuel industry but its contribution to total final consumption of the transport industry is almost negligible: biofuels in total, both produced in Ireland and imported, held just 2.4% of the market share in 2013 (Dineen et al., 2014). The indigenous biodiesel sector accounted for just 16% of the this small volume of biofuels consumed by the transport sector in 2013 (Dineen et al., 2015). This biodiesel is produced from used cooking oil recovered from the catering industry and from sterilised tallow which arises during rendering and is unsuitable for human consumption. So-called second
generation fuels are considered to be a more sustainable option for the production of biofuels as they do not compete with food for feedstock and they diversify the potential feedstocks for biofuel production (Dineen et al., 2014).

To support the use of renewable energy in the transport industry and to initiate the process of achieving the 10% mandatory target outlined by the Renewable Energy Directive, the Biofuels Mineral Oil Tax Relief scheme was introduced which provided an exemption for biofuel producers from excise, giving biofuels a competitive advantage over fossil fuels. A total of 18 facilities were awarded this exemption and the biofuels industry peaked at 2.4% penetration of biofuels into the transport market (Dineen et al., 2014). This scheme expired in 2010 and was replaced by the Biofuels Obligation Scheme which requires all transport fuel manufacturers to ensure a minimum volume of biofuels are placed on the market alongside fossil fuel.

Currently the weighted penetration of biofuels into the transport market as a result of this obligation is 4.9% although the actual volume of biofuels consumed is just 2.8% of total demand (Dineen et al., 2015). The vast majority of the biofuels consumed in Ireland are produced abroad and imported; just 16% of the biodiesel consumed in Ireland is indigenous, the pure plant oil which is produced and consumed in Ireland is negligible, and there is no indigenous production of bioethanol (Dineen et al., 2015). Dineen et al. (2015) report that the volume of biofuels consumed in Ireland declined between 2011 and 2012 and attribute this to the higher weighting given by the Biofuels Obligation Scheme to biofuels produced from waste materials, allowing a smaller volume of biofuels to be placed on the market while still achieving the same proportion of penetration. Although these measures were intended to support the establishment of an indigenous biofuels market which would provide security of supply and local employment, in reality a small number of large enterprises instead import fuels which have been mixed prior to shipping and which therefore satisfy the criteria of the obligation without creating any indigenous jobs or producing any indigenous transport fuels (Anon, 2012). Most recent information indicates that only one enterprise has survived the changeover from relief scheme to obligation scheme and is currently producing biofuels for consumption in Ireland, though it is believed that all of this transport fuel is currently exported.
2.4.5.3. Gaseous Fuels

Biogas, that is, the gas produced during the biological decomposition of organic material, can be used as an alternative to natural gas for the generation of heat and/or electrical energy. Biogas is formed naturally during digestion processes which occur in the absence of oxygen, such as during digestion in the ruminant system and in bogs and other anoxic environments. Currently in Ireland biogas is used to generate thermal or electrical energy both in on-site facilities whereby the material digested arises at the same location where the energy is then consumed, and in four merchant-scale facilities (EPA, 2014) and five landfill recovery facilities (SEAI, 2015c). As methane has 23 times the global warming potential of carbon dioxide (Holm-Nielsen et al., 2009), capturing and using this gas to generate valuable heat and electrical energy can greatly reduce the carbon footprint associated with power generation and can significantly reduce the use of fossil fuels for energy in Ireland. Landfill gas has a much greater contribution to biogas-associated heat and/or electricity generation: in 2013 landfill gas was associated with the generation of 158 GWh of electricity while anaerobic digestion was responsible for just 4.5 GWh of electricity (Dineen et al., 2015).

2.5. Ongoing Development of the Irish Bioeconomy

2.5.1 Education and Training

Ireland has a number of third level colleges, institutes of technology, and universities located throughout the Republic; in the 2014-2015 academic year some 170,000 students were enrolled in full-time third level education with an additional 38,000 students in part-time education and 5,000 enrolled in distance learning programmes. The range of subjects and topics offered at a third level is significant and varied and a number apply directly or indirectly to the Irish bioeconomy (Higher Education Authority, 2016). A small sample of these courses is listed in Table 17 to illustrate the range of educational opportunities offered at tertiary level.

The programmes listed above are not the only educational opportunities associated with the development of the Irish bioeconomy. Education and Training Boards Ireland, for example, offers a range of preliminary education and training programmes aimed at early school leavers and returning to education as well as adult literacy programmes. These programmes focus on a range of topics which, while not directly related to the Irish bioeconomy in that they do not provide training on bio-chemical production, for example, provide an opportunity
to upskill and potentially diversify into processes and products associated with the bioeconomy. Advancing the education and training of those employed in the bioeconomy, such as through improving computer literacy, may lead to improved efficiencies within the supply chain.

2.5.2 Research

Ireland has a significant number of institutions which are actively involved in researching and developing such opportunities from the point of view of technical, environmental, modelling, marketing, and process optimisation, including others. The number of projects currently involved either directly or indirectly in the Irish bioeconomy is substantial, numbering the hundreds on a national basis. To illustrate the variety of topics and institutions currently associated with the Irish bioeconomy, the titles and funding body of projects which were awarded funding in 2014 and 2015 are listed in Appendix I. This list is not exhaustive and does not include research projects completed which have been awarded funding prior to this time frame, but it does serve to illustrate the wide range of research currently ongoing in Ireland for the expansion of the bio-based economy.

Table 17: A sample of the tertiary education programmes related to the bioeconomy currently offered in Ireland (this list is representative of the programmes offered)

<table>
<thead>
<tr>
<th>Name of programme and host institution(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture: CIT, ITT, LIT, UCD</td>
</tr>
<tr>
<td>Horticulture: CIT, DCU, ITB, UCD, WIT</td>
</tr>
<tr>
<td>Forestry: UCD, WIT</td>
</tr>
<tr>
<td>Crop and Livestock Production: CIT, DKIT, GMIT, UCD, WIT</td>
</tr>
<tr>
<td>Food Processing: DIT, DKIT, STA, UCC, UL</td>
</tr>
<tr>
<td>Environmental Sciences: CIT, DCU, DIT, DKIT, GMIT, ITT, ITL, ITL, NUIG, UCC, UCD, UL, WIT</td>
</tr>
<tr>
<td>Natural Environments and Wildlife: ITT</td>
</tr>
<tr>
<td>Environmental Protection Technology: AIT, ITS</td>
</tr>
</tbody>
</table>

AIT: Athlone Institute of Technology  ITT: Institute of Technology Tralee
CIT: Cork Institute of Technology    LIT: Letterkenny Institute of Technology
DCU: Dublin City University          NUIG: National University of Ireland, Galway
DIT: Dublin Institute of Technology   STA: St Angela’s College, Sligo
DKIT: Dundalk Institute of Technology UCC: University College Cork
GMIT: Galway-Mayo Institute of Technology UCD: University College Dublin
ITB: Institute of Technology Blanchardstown UL: University of Limerick
ITL: Limerick Institute of Technology WIT: Waterford Institute of Technology
### 2.5.3 Innovation

Research, development, demonstration, and innovation are important aspects of exploring and extrapolating new opportunities for the Irish bioeconomy. In December 2015 the Irish Government launched a new policy document, Innovation 2020, which has the aim of increasing spending on research and development in Ireland as a whole to 2.5% of gross national product by 2020, an increase from the current level of 2.05% (DJEI, 2015a), indicating the commitment to advancing Irish society through the use and application of research. A further initiative, Enterprise 2025, outlines an ambition to increase the number of commercial entities considered to be active in research, development, and innovation (DJEI, 2015b), recognising the importance of collaboration between research organisations and commercial enterprises to realise the outcomes of exploration initiatives.

The extent of innovation in the global bioeconomy is evident in the number of patents filed in recent years. During a review of the intellectual property (IP) space associated with the bioeconomy a division between invention and innovation became apparent. To this end, the follow definition and understanding has been adopted:

- **Invention** refers to the conversion of new knowledge into a new product, process or service, and
- **Innovation** refers to the process of putting this new product to work (this can be more complex to accurately define).

Various types of IP exist including patent, know-how/trade secret, copyright, and trademark. Of these a patent is the most complex and costly to obtain as it is a ‘legal monopoly’ granted to an inventor or owner. It is a registerable form of IP filed at a patent office and grants the holder exclusive rights to exploitation for a limited time. Due to the associated costs and complexity, licensing agreements can be a simpler option for the development of a technology or idea from lab-scale or prototype stage to a commercial product.

Within the European registered area, companies can file a patent application with the European Patent Office both for direct European applications and also for international applications that cover European and global regions. The results of an assessment of the applications filed within the most likely bio-economy areas in 2015 are presented in Table 18.
Within the general area of biotechnology, the applications cover a wide range of topics such as environmental technology (waste water treatment, air purification, etc), chemical engineering processes and techniques, food chemistry processes and techniques, and organic chemistry. Within Europe Germany was the leading country with the most biotechnology registered patents (306 in 2015); internationally the two top companies in 2015 for biotechnology patents were Japan (307) and United States (977). Examination of this data shows strong correlation between the number of biotechnology applications and countries with strong chemical and pharmaceutical industries.

Within the general bioeconomy space there are many examples of how materials from one value chain can feed into the development of a new value-added chain. The EU AgroCycle project outlines some of these possible pathways (Figure 26). From reviewing the types of patent applications and research organisations involved it can be seen that a number of international licenses in the areas of nutritional wastewaters from juice processing, wineries, and olive oil industries are being undertaken by research organisations and commercial companies. These wastewaters have high simple sugars and polysaccharides contents and can be used as a substrate for the production of single-cell protein to be used as a high nutritional value supplement for livestock forage.

As a separate aspect of the overall AgroCycle project, but intricately linked with other aspects of the project, effluents from livestock production systems are being assessed for potential nutrient recovery through a valorisation process. An integrated modular two-stage anaerobic digestion process coupled with an anoxic/aerobic membrane bioreactor is being developed by a number of organisations in Belgium and Denmark in order to achieve high efficiencies and lower energy consumption in effluent wastewater recycling. Higher efficiency and lower energy consumption is also being investigated within Ireland through the development of a pilot scale demonstration plant by a combination of research organisations, private companies, and EU Interreg funding. The main focus of this innovation

Table 18: Patent applications in the bioeconomy space filed with the European Patent Office in 2015

<table>
<thead>
<tr>
<th>Area of technology</th>
<th>Number of applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic fine chemistry</td>
<td>6414</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>5884</td>
</tr>
<tr>
<td>Biotechnology</td>
<td>6048</td>
</tr>
</tbody>
</table>
is the demonstration of gasification and pyrolysis: the BioBase4SME project will centralise and integrate existing pre-commercial, pre-pilot scale facilities at a site in Thurles, Co Tipperary and will enable companies to bench test gasification and pyrolysis techniques on a range of bio-materials with a view to assessing the feasibility of applying these technologies to their product prior to full scale investment.

The importance of commercial involvement in the developmental stage of innovation is also evident from work being done in Fraunhofer University in Germany as part of the overall AgroCycle project: in conjunction with a number of SMEs a research consortium is looking at aqueous, solvent, and supercritical extraction from fruit and vegetable residues for bio-compounds, proteins, and natural fibre factions. Some of the extracted bio-compounds have been shown to have potential for processing packaging and for use as an additive in the polymer matrix in active packaging in order to prevent migration into the food. Other companies in the consortium are looking at using the extractable proteins, fibres, and biopolymers for bulk packaging materials.

There are a number of examples of innovations and associated IP within the Irish bioeconomy. Within the plastic recycling area, for example, Trifol treats end of life waste plastics using a pyrolysis and contactor recovery and distillation system to create value added

Figure 26: Potential innovations in the agricultural production chain (after AgroCycle Consortium (2015))
waxes, oils, and lubricants using a patented technology. The patents held by Trifol are split between the various products based on the configuration of the system, allowing the optimisation of the plant for different investments. The pilot scale/semi industrial scale plant is outlined in Figure 27.

Another example of an activity related to the Irish bioeconomy is the wastewater treatment system developed by NVP research. NVP Energy was founded in 2013 after 15 years of academic research at the National University of Ireland, during which time the technology’s feasibility on various waste streams including municipal, dairy, brewing, malting and distilling, and meat processing was validated. R&D funding worth over €6.5M has been spent to date with 40 research articles in peer-reviewed journals published. The technology has been proven at a pilot scale, with over 2 years of successful on-site trials at several dairy sites which have displayed excellent wastewater treatment efficiencies that corroborate the lab research. The business is now moving into full-scale deployment.

These case studies are just two of a substantial number of success stories associated with innovation in the Irish bioeconomy space. Initial research and development stages have effectively shown the feasibility and potential of these technologies and they have advanced from ideas to innovations which are actively employing skilled labour, are generating value-added materials from what would otherwise be considered waste, and are contributing to the sustainability of the Irish economy as a whole. These developments and others in the bioeconomy space have set a high standard for the current innovation initiative, Innovation

Figure 27: The end-of-life plastics recovery and value-addition system
2020, to continue.
3. Situational Analysis of the Irish Bioeconomy
The initial sections of this report have detailed the current status of the Irish bioeconomy, that is, what the bioeconomy currently is, its inputs, outputs, key players, resource availability, etc. A large number of interacting factors have contributed to this current status, including policy measures introduced by various governmental and organisational bodies, increases/decreases in consumer demand for products, development of new markets and of new products, environmental pressures, etc. Further developing the sub-sectors which comprise the bioeconomy will require an in-depth analysis and discussion of the opportunities which exist or which may exist, including considering any possible threats to expansion such as competing use of resources and environmental concerns. The first step in such an analysis is to determine what strengths and weaknesses lie within each sub-sector, what opportunities are in place that could be advanced to expand the sub-sector, and what threats may be encountered during such an expansion. To this end, an analysis of the strengths, weaknesses, opportunities, and threats analysis was conducted for each sub-sector, the results of which are presented in Tables 19-24. This information will be used as context in determining whether an opportunity identified as having potential for value-added expansion has realisable significance in the Irish bioeconomy.

Table 19 provides a summary of the strengths, weakness, opportunities, and threats applicable to the agriculture industry in Ireland and its potential expansion. Table 20 provides a summary of the strengths, weakness, opportunities, and threats applicable to the food industry in Ireland and its potential expansion. Table 21 provides a summary of the strengths, weakness, opportunities, and threats applicable to the marine industry in Ireland and its potential expansion. Table 22 provides a summary of the strengths, weakness, opportunities, and threats applicable to the forestry industry in Ireland and its potential expansion. Table 23 provides a summary of the strengths, weakness, opportunities, and threats applicable to the bioenergy industry in Ireland and its potential expansion. Table 24 provides a summary of the strengths, weakness, opportunities, and threats applicable to the by-products industry in Ireland and its potential expansion.
### Table 19: SWOT analysis of the agriculture industry

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Comparative advantage for grass-based, sustainable systems (lower carbon intensity)</td>
<td>• Seasonality of production</td>
</tr>
<tr>
<td>• Access to domestic, EU and international markets with strong export performance across agricultural categories</td>
<td>• Cost competitiveness, particularly the ability to compete with cheap international imports</td>
</tr>
<tr>
<td>• Excellent research base with significant government investment in research infrastructure</td>
<td>• High cost base for some inputs (e.g. high energy and import feed costs)</td>
</tr>
<tr>
<td>• Favourable animal health and welfare status bolstered by organisations such as the Irish Cattle Breeding Federation and Animal Health Ireland</td>
<td>• Variability in the absorptive capacity of farmers</td>
</tr>
<tr>
<td>• Strong genetics capability in animals and crops</td>
<td>• Need for more scientific evidence and backing of the environmental credentials of Irish food and assurance schemes</td>
</tr>
<tr>
<td>• Well-educated, young and adaptable workforce</td>
<td>• Access to finance (widespread)</td>
</tr>
<tr>
<td>• Family farm ownership bolstering traditional image of Irish food</td>
<td>• Access to land and low levels of land mobility</td>
</tr>
<tr>
<td>• Publically funded advisory services and supports for farmers</td>
<td>• Low profitability on farms outside of dairy; net margins thin for many</td>
</tr>
<tr>
<td>• Commitment at a national level to the agricultural sector; recognised as one of the most important indigenous industries</td>
<td>• High dependence on farming subsidies</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ireland’s testbed potential for sustainable agricultural methods</td>
</tr>
<tr>
<td>• Collaborative farming arrangements to aid succession management, improve land mobility and encourage optimum use of land (e.g. farm partnerships, contract rearing, or share farming)</td>
</tr>
<tr>
<td>• Longer term land leasing for greater investment in the land.</td>
</tr>
<tr>
<td>• New partnerships between farming sub-sectors to harness optimal use of resources and outputs (e.g. between tillage and livestock sectors)</td>
</tr>
<tr>
<td>• Broaden the Origin Green sustainability campaign to include a wider range of sustainability credentials</td>
</tr>
<tr>
<td>• Increased protein demand with growing global populations and rising middle class- grass-based livestock production, development of Irish</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Continued environmental impact of agriculture (e.g. GHG emissions, reduced water quality) threatens clean, green image and growth potential</td>
</tr>
<tr>
<td>• International obligations and government commitment to reduce GHG emissions may curb ambitious agricultural growth plans</td>
</tr>
<tr>
<td>• Climate change impacts on growing season in Ireland through changing rainfall patterns and increasing extreme weather events</td>
</tr>
<tr>
<td>• Price and income volatility for Irish farmers</td>
</tr>
<tr>
<td>• Lack of markets for increased/diversified farm output</td>
</tr>
<tr>
<td>• Continued and further meat and dairy production only possible if the sustainability of Irish production is verified</td>
</tr>
<tr>
<td>• Future CAP reforms and international trading agreements</td>
</tr>
</tbody>
</table>
seafood outputs and new protein crops to meet this demand

- Dairy production expansion on abolition of milk quotas with potential knock on positive effects for tillage sector due to increased feed demand
- Agriculture as the basis for the future bioeconomy and development of bio-based goods and services using outputs and waste streams
- Increased demand for malting barley and wheat by an expanding beverage industry
- Agro-forestry - increasing afforestation on-farm
- Export Ireland’s expertise in relation to sustainable food production
- Contribution to ecosystem services and public good
- Agri-food tourism joint branding initiative

determining stability and volatility of Irish farming

- Geopolitical instability: market access issues (e.g. potential UK exit from the EU, Russian embargo)
- Increasing power of retailers impacting price paid to farmers
- Supply chain disruption due to food risk or disease outbreak risks
- Increasing input costs (e.g. energy and imported feed)
- Changing land use: food vs fuel vs fibre debate
### Table 20: SWOT analysis of the food industry

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Clean, green image of Irish food</td>
<td>• High input costs (e.g. labour and energy)</td>
</tr>
<tr>
<td>• Business to business supply of food ingredients for further processing</td>
<td>• Business to consumer supply more limited; limited number of internationally recognised consumer brands</td>
</tr>
<tr>
<td>• Quality and integrity of food input ingredients</td>
<td>• Seasonality of production impacts capacity utilisation, adding to operating costs for Irish processors.</td>
</tr>
<tr>
<td>• Excellent natural resource base: productive lands and proximity to productive fishing grounds</td>
<td>• Need for more scientific evidence regarding the sustainability credentials of Irish food</td>
</tr>
<tr>
<td>• Access to affluent domestic, EU and international markets with strong export performance across food categories</td>
<td>• Access to finance (investment community not focused on food industry; difficult to obtain a loan as an early stage food company)</td>
</tr>
<tr>
<td>• Strong food quality and safety reputation, fostered by high regulatory standards</td>
<td>• Difficulties attracting new and relevant skills to the food industry</td>
</tr>
<tr>
<td>• Full traceability for Irish foods</td>
<td>• Fragmented industry and smaller in scale than international competitors; high proportion of SMEs</td>
</tr>
<tr>
<td>• Quality and sustainability assurance schemes (e.g. Bord Bia Quality Mark, Origin Green)</td>
<td>• Lack of investment in innovation and research: spend on R&amp;D below international best practice</td>
</tr>
<tr>
<td>• Well-educated, young and adaptable workforce</td>
<td>• Poor absorptive capacity of scientific and academic research</td>
</tr>
<tr>
<td>• Low levels of corporation tax</td>
<td>• Small domestic market</td>
</tr>
<tr>
<td>• Presence of multi-national corporations in Irish food landscape</td>
<td>• Booming artisan food industry not translating into scalable, export-led companies</td>
</tr>
<tr>
<td>• A number of exemplar companies and organisations with a proven track record and international credibility e.g. Kerry, Glanbia and ABP</td>
<td>• Commodity pricing system not closely aligned to consumer requirements (e.g. EUROP meat grading scheme)</td>
</tr>
<tr>
<td>• A strong foundation in science based innovation and product development</td>
<td>• Lack of incubation space for New Product Development (NPD)</td>
</tr>
<tr>
<td>• State/enterprise support institutions and schemes e.g. DAFM, Bord Bia, Teagasc, FSAI, IBEC and Enterprise Ireland</td>
<td></td>
</tr>
<tr>
<td>• R&amp;D clusters for food innovation and development (e.g. the ‘Golden Triangle’ involving the dairy industry, Teagasc and UCC in Cork)</td>
<td></td>
</tr>
<tr>
<td>• Industry driven research agenda feeding into the development of funding strategies and dedicated technology centres (e.g. meat and dairy)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Meet upper market consumer demand with traceable, high quality</td>
<td>• Competition from cheaper imports in domestic and main</td>
</tr>
</tbody>
</table>
Irish food, targeting different life-stage requirements and lifestyle choices
- Dairy production expansion posing opportunity to harness new milk for value-added products and ingredients
- Potential for new Foreign Direct Investment with strong food production reputation and expansion of dairy
- Functional food and nutraceutical opportunities offering distinct nutritional and health benefits
- Development of bio-based goods, materials and chemicals through extraction of novel proteins, elements and polymers from food ingredients
- Fifth quarter and meat by-products
- Ireland as a testbed for new and sustainable food and beverage technologies
- Extend existing quality promotion campaigns to further develop brand Ireland (e.g. Origin Green, Bord Bia Quality Mark)
- Value-added capabilities through innovation, NPD, use of by-products and waste streams
- Employment growth potential in labour intensive food supply chain
- Increased importance of, and access to, third country markets
- Consolidation and collaboration opportunities across processing sectors
- Import substitution potential, particularly in prepared consumer foods and horticulture sectors

international markets
- Environmental impact of some agricultural production and continued antibiotic use in the supply chain threatening clean, green image
- Regulatory and fiscal burden out of line with competitors
- Time taken to obtain authorisation for health claims in the food industry adds to the already lengthy process of NPD
- Patent system in EU more expensive than USA
- Over-reliance on the UK market for many Irish food exports: vulnerable to foreign exchange fluctuations
- Geopolitical instability and embargoes create market access issues
- Developing scale without losing craft characteristics that drove initial competitiveness
- Need to develop markets for any increased/diversified output
- Further meat and dairy production only possible if the sustainability of Irish production is verified and takes over from intensive methods elsewhere in the world
- Continued international trade liberalisation means Irish goods increasingly compete for market share with other food exporting countries: small scale relative to buyers
- Growth of output from developing economies substituting Irish output
- Supply chain disruption due to food risk or disease outbreak risks
- Unpredictable consumer perceptions and acceptance of products
- Increasing input costs (e.g. energy and labour)
- Limited access to finance and funding to invest in processing plant infrastructure
Table 21: SWOT analysis of the marine industry

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Significant ocean resources currently underdeveloped, both organic and non-organic</td>
<td></td>
</tr>
<tr>
<td>• Government initiatives and strategies for marine sector development (e.g. <em>Harnessing Our Ocean Wealth</em>, <em>National Strategic Plan for Sustainable Aquaculture Development</em>)</td>
<td></td>
</tr>
<tr>
<td>• Research and government agencies dedicated to the development of the sector (e.g. Marine Institute, Bord Iascaigh Mhara)</td>
<td></td>
</tr>
<tr>
<td>• Current trends of increased demand in export-driven markets</td>
<td></td>
</tr>
<tr>
<td>• Recent collaborations between Irish fish processing industry and foreign trawlers; potential for similar schemes with other enterprises</td>
<td></td>
</tr>
<tr>
<td>• Recent tourism initiative identifying the western seaboard as a destination</td>
<td></td>
</tr>
<tr>
<td>• Limited SME base with low levels of R&amp;D engagement</td>
<td></td>
</tr>
<tr>
<td>• Catch quotas regime and frequent revisions of allowable catch potentially unsuited to significant development of the sector</td>
<td></td>
</tr>
<tr>
<td>• Little investment interest from venture capitalists</td>
<td></td>
</tr>
<tr>
<td>• Missing link between research and commercialisation (e.g. no marine equivalent of Teagasc)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Major growth potential in new and emerging areas including offshore renewable energy, green technology, marine biotechnology, etc</td>
<td></td>
</tr>
<tr>
<td>• Renewed opportunities in traditional marine sub-sectors of fish landings/ aquaculture/ seafood processing, seaweed, water-based tourism and leisure/ cruise, marine transport and commerce</td>
<td></td>
</tr>
<tr>
<td>• Anticipated growth in global demand for seafood to 2030</td>
<td></td>
</tr>
<tr>
<td>• Potential of marine natural resources in non-food applications e.g. biopharmaceuticals, cosmetics</td>
<td></td>
</tr>
<tr>
<td>• Reactive versus proactive approach to the development of the sector</td>
<td></td>
</tr>
<tr>
<td>• Degradation of coastal water quality will impact on clean/green reputation</td>
<td></td>
</tr>
<tr>
<td>• Fragmentation of support agencies</td>
<td></td>
</tr>
<tr>
<td>• Sustainability of fish stocks and continuous re-assessment of catch quotas</td>
<td></td>
</tr>
<tr>
<td>• Limited level of innovation and product development-related investment</td>
<td></td>
</tr>
<tr>
<td>• Highly regulated and legislated environment may restrict development potential</td>
<td></td>
</tr>
</tbody>
</table>
Table 22: SWOT analysis of forestry industry

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Biomass growth rates more than double those achievable in some European countries for some species</td>
<td>• Current low level of forest cover limits resource availability</td>
</tr>
<tr>
<td>• Government policy to increase rates of forestation will make available resources both for commercial production and renewable energy</td>
<td>• Long growth cycles mean resource availability may prove an obstacle in the short-term before additional material becomes available</td>
</tr>
<tr>
<td>• A variety of grant and premium schemes in places to encourage forestry establishment both for commercial timber production and for energy</td>
<td>• Long lag period before a return on investment is realised; may prohibit new investors from becoming involved</td>
</tr>
<tr>
<td>• Demand for wood-based products has increased in the past years with exports showing strong growth in particular</td>
<td>• Much of the private plantings from 1980s and 1990s reaching first and second thinnings, but poor infrastructure and access restrictions may prevent thinning and harvesting</td>
</tr>
<tr>
<td>• A variety of R&amp;D projects both ongoing and recently completed strengthen the knowledge base on a wide range of forestry aspects</td>
<td>• Fragmented nature of forestry industry reduces the likelihood of profitability due to haulage distances to end user</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Growing demand for resources for sawnwood and panelboard industries</td>
<td>• Vulnerability to fluctuations in demand on a global scale as predominantly export-driven industry</td>
</tr>
<tr>
<td>• Growing exports of finished product: export volume has increased year-on-year since 2010; potential to continue growth in export market</td>
<td>• Growing demand from Asian markets potentially endangers Latvian-derived wood imports</td>
</tr>
<tr>
<td>• “Green shoots” recovery will help construction sector to revive, increasing demand for materials</td>
<td>• Recent outbreak of disease in ash stands have highlighted vulnerability to disease, particularly as national forest is dominated by one species (Sitka spruce)</td>
</tr>
<tr>
<td>• Agroforestry allows farmers to diversify into forestry while maintaining traditional farming practices</td>
<td>• Biomass to energy industry has been practically stagnant in the last five years due to lack of investment for renewable heat; delays in delivering a renewable heat incentive scheme have contributed to uncertainty</td>
</tr>
</tbody>
</table>

• Fluctuating (and currently very low) oil price makes biomass the expensive option
Table 23: SWOT analysis of the bioenergy industry

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Inherent environment and climate supports growth of energy crops</td>
<td>• Legislation is creating a huge hurdle for the AD industry regardless of feedstock or intended end use</td>
</tr>
<tr>
<td>• Significant quantities of organic wastes of varying nutritional composition potentially available for AD with methane capture</td>
<td>• Small foothold of oil crops in Ireland (with existing and established supply chains) are unlikely to have an impact on renewable transport targets; 1 in 5 rotation limits the amount of oilseed rape likely to be produced annually</td>
</tr>
<tr>
<td>• EU Landfill Directive prevents disposal of biodegradable waste to landfill, requiring an alternative management option for vast quantities of waste</td>
<td>• Existing supply chains for tallow and recovered vegetable oil make indigenous processing into second generation biofuels unlikely</td>
</tr>
<tr>
<td>• R&amp;D has been extensive in recent years in many aspects of renewable energy with funding coming from a variety of public and private sources</td>
<td>• Aging farmer population unlikely to see benefits of moving from traditional agriculture to energy crop production</td>
</tr>
<tr>
<td>• Long-standing agricultural traditions of arable production can easily divert into energy crop production</td>
<td>• Delay in confirming RHI format has hindered establishment of forestry/energy crops without a defined end use market</td>
</tr>
<tr>
<td>• Arable infrastructure largely suitable for energy crop production</td>
<td>• Current low uptake of energy crop production so limited biomass resource</td>
</tr>
<tr>
<td>• Waste cooking oil has been banned for use as an animal feed, thereby potentially making it available for conversion into biofuels. Estimates by SEAI suggest 8,000 tonnes could be available annually for conversion without significant intervention. The same study estimates that 7,500 tonnes of tallow could be available for conversion into biofuels.</td>
<td>• Low REFIT price for AD: indicates that Government policymakers do not see any value in the treatment of manure despite the associated environmental benefits of electricity generation, reduced GHG emissions, and safer fertiliser for land application</td>
</tr>
<tr>
<td>• Significant quantities of grass available as a feedstock for AD for biomethane production</td>
<td>• EU Landfill Directive prevents disposal of biodegradable wastes to landfill, thereby reducing the future contribution of landfill gas to renewable electricity</td>
</tr>
<tr>
<td>• Newly published energy white paper strengthens the case for renewable energy</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• R&amp;D is on-going into the feasibility of applying sludge/organic materials to willow for remediation without risking the food chain (legislation/policy prevents this action currently)</td>
<td></td>
</tr>
<tr>
<td>• Government policy supporting increase of forestation will make available woody biomass for renewable heat</td>
<td></td>
</tr>
<tr>
<td>• Double weighting of second generation fuels for 2020 target more favourable than energy crops for biofuels; waste vegetable oils and</td>
<td></td>
</tr>
</tbody>
</table>

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| tallow could be converted into biofuels using existing technology already in operation in Ireland |
| Restructuring of sugar industry offers potential to re-establish sugar beet in Ireland for bioethanol production |

- Lack of expertise in a variety of renewable energy areas including AD, biofuel production
- Biomass to energy industry has been practically stagnant in the last five years due to lack of investment for renewable heat; delays in delivering a renewable heat incentive scheme have contributed to uncertainty
Table 24: SWOT analysis of the by-products industry

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Significant quantities of various materials generated year-round</td>
<td>• Limited re-use currently</td>
</tr>
<tr>
<td>• Recent interest in production efficiency and sustainability <em>vis à vis</em></td>
<td>• Minimal infrastructure for value extraction (both physical and labour)</td>
</tr>
<tr>
<td>corporate sustainability responsibility and circular economy</td>
<td>• Economy of scale may restrict uptake of processing</td>
</tr>
<tr>
<td>• Strong growth in various by-product use markets; potential to expand</td>
<td></td>
</tr>
<tr>
<td>markets to include other by-products</td>
<td></td>
</tr>
<tr>
<td>• Various European legislative measures requiring separation and value</td>
<td></td>
</tr>
<tr>
<td>recovery from biological materials</td>
<td></td>
</tr>
<tr>
<td>• Established pharmaceutical manufacturing industry; potential to access</td>
<td></td>
</tr>
<tr>
<td>this industry via bio-based intermediates or to diversify educated</td>
<td></td>
</tr>
<tr>
<td>workforce into other processing facilities</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Opportunities</td>
<td>Threats</td>
</tr>
<tr>
<td>• Intended expansion of agri-food sector will increase the volume of</td>
<td>• Existing and mature current uses and markets for by-products</td>
</tr>
<tr>
<td>by-products generated, increasing feedstock supply for processing</td>
<td>• Price competition with non-biological origin equivalents (mass</td>
</tr>
<tr>
<td>• Production of biofuels from waste material, contributing to RES-T</td>
<td>produced, long history of production</td>
</tr>
<tr>
<td>targets</td>
<td>• Minimal investment or government support to develop this sector</td>
</tr>
<tr>
<td>• Production of platform products and intermediates to feed into</td>
<td>• Consumer negativity towards consumption of “waste” products</td>
</tr>
<tr>
<td>pharmaceutical, food and biochemicals industry</td>
<td></td>
</tr>
<tr>
<td>• National “green” image could be expanded beyond agri and food</td>
<td></td>
</tr>
<tr>
<td>production into new industries</td>
<td></td>
</tr>
<tr>
<td>• Expansion of “green” image opportunities for sustainability-</td>
<td></td>
</tr>
<tr>
<td>conscious companies</td>
<td></td>
</tr>
</tbody>
</table>
3.1. Identification of Opportunities to Develop the Irish Bioeconomy

Knowing the opportunities which have already been developed within the Irish bioeconomy and the strengths, weaknesses, opportunities, and threats which must be considered when investigating new development opportunities, the focus must now turn to the prospective value chains which could be developed for the advancement of the Irish bioeconomy. To conduct this examination a number of analytical techniques were used to obtain a comprehensive evaluation of each sub-sector of the bioeconomy and the variables which may influence its expansion. Examining the value chain as a whole provides the opportunity to examine all stages of production, processing, and supply to identify any opportunities arising at any stage rather than seeking specifically to identify new final outputs using existing value chains. This allowed a comprehensive review of all possible opportunities to be compiled without prejudice towards or against any possible overlaps between existing supply chains. Determining the feasibility of each opportunity will follow in subsequent tasks of this project; for now the primary aim is to identify where these opportunities lie.

The identification of new opportunities required two levels of analysis: (i) a review of secondary data relating to the inputs, outputs, and by-products of the Irish bioeconomy. These data were obtained from annual publications issued by relevant domestic and international bodies such as Bord Bia, CSO, DAFM, DCENR, EPA, EUROSTAT, FAO, SEAI, Teagasc, UNECE, etc and were considered as reliable and accurate sources of information relating to sub-sector value chains including input and output volumes, current markets, geographical spread of sub-sector, etc; and (ii) a series of interviews to collect primary data on the opportunities arising within each sub-sector. These interviews were conducted with key informants who are well-placed within the domestic and/or global bioeconomy with the aim of obtaining an expert insight into the opportunities that may exist within the Irish bioeconomy. This level of insight is not available by reviewing secondary data as the reports issued by the organisations listed above describe the current form and functioning of the relevant bioeconomy value chain and generally do not anticipate or forecast opportunities other than to suggest a continuance of a currently evidenced trend. The inclusion of key informants offered a chance to acquire an expert opinion of the opportunities which may exist to increase output of current value chains, to create linkages between value chains or to create new value chains within the Irish bioeconomy.
One drawback of conducting one-to-one interviews is the time-consuming nature of the data collection; this restricts the number of possible participants compared with group-based interviews however a group-based interview process was not deemed appropriate for this research, given the variety of backgrounds and expertise of the potential informants. Although performing one-to-one interviews limited the number of interviews which could be conducted due to time constraints, great care and attention was expressed in selecting the informants to ensure the candidates chosen for interview were the most appropriate candidates.

3.1.1 Selection of Key Informants

The key informants which were selected for interview include experts from within the indigenous bioeconomy industry as well as international experts from countries which have exhibited successful expansion and development of their national bioeconomy. Selecting domestic informants provided an opportunity to discuss the potential of the Irish bioeconomy with key players who have first-hand knowledge and experience of the industry by being involved in one of the sub-sectors of the bioeconomy; the international experts provided an insight into how their own bioeconomies became established, what opportunities were created and exploited, and what hurdles, if any, had to be overcome to reach their current position. This experience was combined with the indigenous insights to determine whether an opportunity could be realised in Ireland given the current circumstances of production, resource availability, demand, regulation, workforce availability, etc.

The process of selecting the key informants began with identifying organisations and institutes that were involved at some level in the key sub-sectors of the bioeconomy; these organisations and institutes include academia, research institutions, stakeholder groups, advisory groups, regulatory agencies, departments of national governments, etc. A unique aspect of the BioÉire project is its access to a panel of experts from within the Teagasc advisory body; as many members of this panel are actively involved in research as well as in the advisory role performed by Teagasc it was deemed that this group could provide an appropriate insight into ongoing research associated with the Irish bioeconomy. The availability of this group of experts meant that the selection of key informants could be concentrated on other aspects of the bioeconomy supply chains.

Preliminary identification of relevant organisations and institutes was conducted from the material included in the literature review: a number of publications reviewed during this
process were produced by government departments (e.g. DAFM, DCENR, DJEI), government advisory/regulatory bodies (e.g. CSO, EPA, SEAI, Teagasc), groups representing value chain stakeholders (e.g. Bord Bia, IFA, IrBEA), and funding bodies (e.g. Enterprise Ireland) as well as stakeholders with a private interest in the Irish bioeconomy (e.g. Bord na Móna, Coillte). This initial pool of organisations was expanded by performing an internet search using keywords relevant to each value chain to identify organisations which had been represented by speakers at conferences and/or workshops held in Ireland since 2010. The next stage in identifying potential key informants involved ascertaining the most relevant person(s) from within each of these organisations. A number of criteria was used to identify the most appropriate profile from within each institution; these criteria were used to ensure the informants identified could provide the most appropriate and informed insight into the bioeconomy. It was agreed that the potential informants should meet at least three of the following criteria to be considered for interview:

- Be informed/experienced in the bioeconomy. To meet this criterion the potential key informants were required to have a minimum of five years' experience in the bio-based industry;
- Be active and enthusiastic in the bio-based industry. To meet this criterion the potential key informant should have been invited to present at (not just attend) workshops/conferences, participate at committee level in stakeholder organisations (such as IFA), etc;
- Be working towards developing the bioeconomy. To meet this criterion the potential key informants were required to be in a position whereby they are working towards developing renewable and/or sustainable biological resources, whether this be via research, commercial, non-government organisation, policy, etc;
- Be in a senior role such that the interviewee can influence change. To meet this criterion the potential key informants were required to occupy a management level position, hold office on an organisation’s committee, have contributed to guidance or policy documents, etc;
- Have a recognisable profile within the bio-based industry. To meet this criterion the potential key informants should be or have recently been on the committee of an organisation working within the bioeconomy, have contributed to a strategy document influencing the development of the bioeconomy, be a keynote or invited speaker at an international conference focussing on the advancement of a specific
aspect of the bio-based industry, be a media contact point for an organisation working in the bio-based industry, etc.

A subsequent level of selection criteria was applied to ensure that the key informants provided a range of opinions from each level of the supply chain within the bioeconomy; the opinions of producer and processor stakeholders as well as regulators and policy makers, etc, were deemed equally important and thus were sought and included. The profiles of potential candidates were evaluated according to each of the above-listed criteria and subsequently considered to ensure an appropriate and relevant mix across bio-based supply chains was achieved. The profiles of the key informants who were ultimately selected for inclusion are included in Table 25.

A total of 12 key informants were interviewed for their insights into what development potential exists for the Irish bioeconomy. As shown in Table 25 these informants are from a variety of backgrounds with six being considered supply chain actors (e.g. commercial entities); three were members of stakeholder groups (e.g. representative/lobbyist bodies); and three had administrative, advisory or other roles. The intertwined supply chains of agriculture, food, and marine were represented in five interviews, bioenergy was represented in two interviews while forestry and biotechnology were the main focus of one interview. An international perspective was obtained in two interviews.

3.1.2 Key Informant Interviews

The expert interview method was used to obtain the opinions of the key informants. Of the interview types described by Flick (2009), namely the focused interview, the semi-standardised interview, the problem-centred interview, the expert interview, and the ethnographic interview, it was deemed most appropriate to use the expert interview to elucidate the opinions of informants as this method is based on the assumption that the interviewee is not the focus of interest, rather they are integrated as a representative of a group (Flick, 2009). Flick (2009) further described how where expert interviews are used, the targeted groups are mostly staff members of organisations with specific functions and professional experience and knowledge.
The interviews had a semi-structured format in that the interviewer had a prepared list of questions however the interview also allowed for freedom of discussion where a point of interest was made while answering a question. This allowed the informants to speak somewhat freely on a particular aspect of the bioeconomy without being confined by a strict set of questions. The questions asked of the informants are included in Appendix II of this report.

Table 25: Profiles of key informants who contributed to the situational analysis

<table>
<thead>
<tr>
<th>Informant’s area of expertise</th>
<th>Key informant type</th>
<th>Position held/Career history, etc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Value chain actor</td>
<td>Non-executive director; 10+ years in government department with international trade experience</td>
</tr>
<tr>
<td>Food</td>
<td>Stakeholder representative body</td>
<td>Chairman; 30+ years’ experience in the food industry; has served on a number of national and international expert panels</td>
</tr>
<tr>
<td>Food</td>
<td>Value chain actor</td>
<td>Policy director; 10+ years’ experience in biomedical, food commercialisation, and nutrition areas</td>
</tr>
<tr>
<td>Marine</td>
<td>Value chain actor</td>
<td>CEO; 15+ years’ experience in various aspects of marine industry (stakeholder group, government advisory group)</td>
</tr>
<tr>
<td>Marine</td>
<td>Value chain actor</td>
<td>Joint CEO; 5+ years’ experience in marine industry; current and former board member of national and stakeholder boards</td>
</tr>
<tr>
<td>Forestry</td>
<td>Value chain actor</td>
<td>Business development manager; 10+ years’ experience in forestry sector</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>Administrative/advisory/investment</td>
<td>Head of a number of steering committees with the organisation; 10+ years’ experience in energy sector</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>Stakeholder representative body</td>
<td>Management/committee member for 5+ years; 10+ years’ experience in waste/energy sector</td>
</tr>
<tr>
<td>Biotechnology</td>
<td>Value chain actor</td>
<td>CTO of biotech company; 15+ years’ experience in academia and research in microbiology and biotechnology</td>
</tr>
<tr>
<td>International experience</td>
<td>Stakeholder representative body</td>
<td>Executive director; 10+ years’ experience in advisory/consulting roles for bio-based industry development</td>
</tr>
<tr>
<td>International experience</td>
<td>Administrative/advisory/investment</td>
<td>Chairperson of Bioeconomy Council; 15+ years’ experience in biotechnology/microbiology areas</td>
</tr>
<tr>
<td>Commercialisation</td>
<td>Administrative/advisory/investment</td>
<td>Partner; 10+ years’ experience in funding organisations focussing on commercialisation and intellectual property management</td>
</tr>
</tbody>
</table>
3.1.3 Value Chains Highlighted

Table 26 depicts the various options which exist which could be explored to expand the Irish bioeconomy. This list was compiled based on the value chains identified during the key informant interviews as well as some additions from the Teagasc Bioeconomy Working Group (TBWG). Each of the generalised value chains was discussed with the TBWG for its initial feasibility, i.e. whether a significant hurdle stands immediately in the way of the value chains such as legal, social or environmental concerns, for example.

Given the generalised nature of the value chains, none of the opportunities was deemed to be unfeasible in an Irish context, but the point was raised that the use of any of the resources for bioenergy purposes would represent the lowest level of value addition for that resource and that as such, higher levels of value addition should be prioritised. That being said, determining the best use of a resource takes into consideration a number of criteria including its environmental implications, current legal restrictions relating to materials handling, employment opportunities (particularly relevant in rural areas), the associated social perception of the value chain as well as the financial opportunity represented, therefore the use of any resource for bioenergy reasons should not be immediately discounted. The specifics of each value chain listed in Table 26 are discussed and evaluated later in the BioÉire project for their feasibility and applicability to the Irish bioeconomy.
Figure 28: Possible opportunities for value addition within the Irish bioeconomy
Table 26: New and underdeveloped value chains which present an opportunity to develop the Irish bioeconomy

<table>
<thead>
<tr>
<th>Input</th>
<th>Transformation Technology</th>
<th>Output</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underexploited agricultural resource</td>
<td>Existing</td>
<td>Bio-chemicals</td>
<td>e.g. use of grass for bio-chemical conversion</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td>Bioenergy</td>
<td>e.g. slurry from piggery sector as feedstock for anaerobic digesters</td>
</tr>
<tr>
<td></td>
<td>Existing/Novel</td>
<td>Cosmetics</td>
<td>e.g. animal by-products for cosmetics – ceramide</td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Bio-chemicals</td>
<td>e.g. organic acids from dairy whey, sugar beet</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td>Bioenergy</td>
<td>Animal manures, energy crops, grass for biomethane production</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Existing agricultural resource</td>
<td>Existing</td>
<td>Food</td>
<td>e.g. sustainable food branded products; obesity and ageing population</td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Food</td>
<td>targeted products</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td>Bioenergy</td>
<td>e.g. functional food ingredients; tailored nutrition responses;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>performance nutrition options away from dairy powder</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td>Pharmaceuticals</td>
<td>Cereal crops for biofuel production (biodiesel from oil crops, bioethanol</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>from wheat, etc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Phenolic compounds from cereals</td>
</tr>
<tr>
<td>Novel agricultural resource</td>
<td>Novel</td>
<td>Bio-chemicals</td>
<td>e.g. development of other grass varieties for extraction of higher value</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>products</td>
</tr>
<tr>
<td>Imported agricultural feedstock</td>
<td>Existing</td>
<td>Food</td>
<td>e.g. imported dairy streams for bio-refining and value addition</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td>Pharmaceuticals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Food</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Pharmaceuticals</td>
<td></td>
</tr>
<tr>
<td>Underexploited marine resource</td>
<td>Existing</td>
<td>Food</td>
<td>e.g. highly derivitised bioactive extracts from seaweeds for functional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pharmaceuticals</td>
<td>foods</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>e.g. highly functionised chitosan for the pharmaceutical industry;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>collagen from jellyfish for medical bandages</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bio-chemicals</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cosmetics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Food</td>
<td>e.g. algae potential for use in the food industry</td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Pharmaceuticals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Novel</td>
<td>Bio-chemicals</td>
<td></td>
</tr>
<tr>
<td>Resource Type</td>
<td>Existing</td>
<td>Novel</td>
<td>Benefits/Products</td>
</tr>
<tr>
<td>---------------------------------------------------</td>
<td>----------</td>
<td>-------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Existing marine resource</strong></td>
<td></td>
<td></td>
<td>e.g. health and nutritional supplements from seaweed</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td></td>
<td></td>
<td>e.g. Lactic acid, succinic acid; green solvents e.g. ethyl lactate</td>
</tr>
<tr>
<td>Bio-chemicals</td>
<td></td>
<td></td>
<td>Ethylene and propylene for polymer production</td>
</tr>
<tr>
<td>Cosmetics</td>
<td></td>
<td></td>
<td>Nutraceuticals e.g. omega-3 PUFA, Carotenoids</td>
</tr>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td>Functional foods e.g. rich source of vitamins A, B1, B2, B3, B9, E</td>
</tr>
<tr>
<td><strong>Marine algae</strong></td>
<td></td>
<td></td>
<td>Organic acids e.g. Lactic acid, succinic acid; green solvents e.g. ethyl lactate</td>
</tr>
<tr>
<td>Bi-chemicals</td>
<td></td>
<td></td>
<td>Ethylene and propylene for polymer production</td>
</tr>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td>Nutraceuticals e.g. omega-3 PUFA, Carotenoids</td>
</tr>
<tr>
<td><strong>Existing forestry resource</strong></td>
<td></td>
<td></td>
<td>Expansion of renewable heat in residential and commercial sectors using pellets &amp;</td>
</tr>
<tr>
<td>Bioenergy</td>
<td></td>
<td></td>
<td>chips</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td></td>
<td></td>
<td>e.g. extraction of taxols</td>
</tr>
<tr>
<td>Bio-materials</td>
<td></td>
<td></td>
<td>e.g. production of moulded wood elements</td>
</tr>
<tr>
<td>Bio-chemicals</td>
<td></td>
<td></td>
<td>e.g. planting of particular species for targeted compounds</td>
</tr>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td>e.g. Fish meal or Animal feed</td>
</tr>
<tr>
<td><strong>Underexploited marine processing</strong></td>
<td></td>
<td></td>
<td>Processing of fish processing to generate bioactive peptides - cardioprotective,</td>
</tr>
<tr>
<td>industry side-stream resource</td>
<td></td>
<td></td>
<td>anti-oxidant, anti-microbial applications</td>
</tr>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td>Carbohydrate-containing molecules (e.g. glycosaminoglycan and glycoprotein fractions) for pharmaceutical applications (possible cancer treatment)</td>
</tr>
<tr>
<td>Nutraceuticals</td>
<td></td>
<td></td>
<td>Fish oils, amino acids, omega-3</td>
</tr>
<tr>
<td>Cosmeceutical applications</td>
<td></td>
<td></td>
<td>Collagen fraction extracted from skin: currently used as a skin care product with moisture retaining functions, can be used in biomedical for implants, bone substitution and drug delivery</td>
</tr>
<tr>
<td><strong>Underexploited food processing</strong></td>
<td></td>
<td></td>
<td>e.g. protein substitute in sports nutrition</td>
</tr>
<tr>
<td>industry side-stream resource</td>
<td></td>
<td></td>
<td>e.g. increased used of dairy processing by-products; 5th quarter processed products</td>
</tr>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td>e.g. 5th quarter tallow in cement; tomato residuals for bio-plastics; cheese</td>
</tr>
<tr>
<td>Bio-materials</td>
<td></td>
<td></td>
<td>brine to de-ice roads</td>
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<tr>
<td>Energy</td>
<td></td>
<td></td>
<td>e.g. powder derivatives from meat processing streams; use of fat surplus</td>
</tr>
<tr>
<td>Category</td>
<td>Novel</td>
<td>Existing/Novel</td>
<td>Existing</td>
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<tr>
<td>Bio-materials</td>
<td>e.g. creation of bio-compostable packaging and bio-plastics</td>
<td></td>
<td></td>
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<tr>
<td>Bio-chemicals</td>
<td>Organic acids e.g. lactic acid (polymer, food &amp; beverage, personal care &amp; pharmaceutical), succinic acid (polymers, food, metals, pharmaceuticals, coatings, fibres, solvents, lubricating oils, diesel fuel oxygenates, and cosmetics)</td>
<td>Green solvents e.g. ethyl lactate</td>
<td></td>
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<tr>
<td>Bio-products</td>
<td>Bio-polymers e.g. polylactic acid, thermoplastic compound from sugar beet</td>
<td></td>
<td>Biogas/methane for electricity or transport fuel</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>Alcohols e.g. ethanol, butanol</td>
<td></td>
<td>Recovered vegetable oils for biofuel production</td>
</tr>
<tr>
<td>Bio-chemicals</td>
<td>Alcohols e.g. ethanol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-chemicals</td>
<td>Bio-polymers e.g. PHAs from butyrate</td>
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</tr>
<tr>
<td>Bioenergy</td>
<td>e.g. electricity or transport fuel</td>
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</table>
4. Conclusions
Ireland has a long and strong history of bio-based production and processing. Such is the importance of this industry to the overall economy that despite the recent recession the agri-food industry employs more than 8% of the total national work force, Irish agri-food exports have reached an all-time high, forestry products show strong export growth, and bioenergy use is at its highest. These levels of production, conversion, and consumption are due in part to various government strategies and policies which support the use of indigenous sources of organic materials. Although each of these sub-sectors is a part of the Irish bioeconomy there is no single strategy in place to support and develop the bioeconomy as a whole, taking into consideration the overlaps between sub-sectors which may provide opportunities for value addition and process efficiency.

There is great scope beyond the current production and processing scenarios in place in the bio-processing industries to increase production, add value, and generate additional employment. A significant review and analysis of the sub-sectors associated with biological production and processing generated an update-to-date picture of the Irish bioeconomy in its current format, however did not provide an in-depth view of the gaps in the bioeconomy which could be developed to offer value addition opportunities with associated increases in employment, sustainability, and production efficiency. A number of interviews were subsequently conducted with a selection of key informants – stakeholders placed within the Irish or another national bioeconomy whose employment history and experience qualified them to provide an informed insider opinion of where the Irish bioeconomy holds promise for expansion. The aim of the interviews was to identify a number of areas which held potential for expansion and development, either from their current under-developed state or by creating new links between bioeconomy sub-sectors.

During the interviews a number of generalised value chains were identified which had potential for expansion in the context of the Irish bioeconomy. The value chains represent the full spectrum of the bioeconomy and include finding new uses for current processing inputs, creating new outputs from current processes, and establishing new processes to generate value from the by-products, side stream outputs, and wastes of various sub-sectors of the bioeconomy. These value chains underwent a preliminary evaluation to determine whether any faced immediate hurdles such as legal restriction, negative social opinion, feedstock shortages, environmental sustainability, etc. The next step in the BioÉire project is to subject the value chains which passed this initial round of assessment to further evaluation and strategic assessment. The ultimate aim of the BioÉire project is to identify up to eight value
chains which will be evaluated in terms of technical viability, economic viability, and sustainability thus informing development of integrated measures to overcome barriers and facilitate exploitation of commercial opportunities for the expansion of the Irish bioeconomy.
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6. Appendix I

Ongoing Research Projects Related to the Irish Bioeconomy
The following is a list of research projects which are related to the Irish bioeconomy organised by the source of funding and the year in which the funding was awarded. Due to the extensive nature of research within the realms of the Irish bioeconomy it is acknowledged that this list is representative of the research activities and that the possibility exists that a number of projects have been omitted. This omission is not intentional and projects which have not been included in this list do not necessarily lie outside the realm of the bioeconomy.

Irish Research Council-funded projects awarded in 2014

**Dublin City University**
- Bioactive and nutritional profiles of Irish honey and how they are affected by anthropogenic activity

**National University of Ireland, Galway**
- Public food consumption and the role of organisations in supporting sustainable regional food systems
- Harnessing triploid genetics for crop improvement
- *Tetanocera elata* (Diptera: Sciomyzidae): a novel biocontrol agent of pestiferous slugs in sustainable agricultural systems

**National University of Ireland, Maynooth**
- From commons to commoning: rethinking resource management through the Irish and European fisheries

**University College Cork**
- University College Cork *in collaboration with* GlaxoSmithKline R&D Cork
  New methods in green chemistry for pharmaceutical processes
- University College Cork *in collaboration with* FrieslandCampina Research
  Diversity and directed evolution of bacteriophages infecting lactic acid bacteria used for commercial dairy fermentations

**University College Dublin**
- University College Dublin *in collaboration with* Kerry Group Services International Limited
  Potential of food derived peptides to help in the management of blood glucose
- Assessing the potential for epigenetic gain in maize (*Zea mays*) hybrids through novel epiallele specific heterotic interactions

**The University of Dublin, Trinity College**
- Predicting the impact of environmental change on floral resources for pollinators at the national scale
- Development and application of a novel systemic approach to measuring resilience in ecosystems and economies

**University of Limerick**
- University of Limerick *in collaboration with* The Irish Equine Centre
  Analysis and characterisation of the nutritive value of forages
- Enhancement of direct production of ethanol by *Synechocystis* sp. through strain improvement and process intensification
Irish Research Council-funded projects awarded in 2015

Dublin City University
- Environmental Protection Agency Postgraduate Scholarship in partnership with the Environmental Protection Agency (EPA)
  Chemosynthetic pathways to increased carbon dioxide sequestration and improved productivity in soil

Institute of Technology Cork
- Engineering pharmabiotics for the targeted control of *Clostridium difficile* growth and toxin neutralisation

Institute of Technology Galway-Mayo in collaboration with Vet-Aqua International
- Bio-security risks associated with the use of lumpfish (*Cyclopterus lumpus*) as a cleaner fish species in salmonid polyculture systems in Ireland

Institute of Technology Limerick
- Production, extraction and detection systems for new marine phycotoxins in Europe

National University of Ireland, Galway
- The National University of Ireland, Galway in collaboration with Gas Networks Ireland
  Assessing the technical viability of thermal conversion of biomass for biomethane production

Teagasc
- Changes in perennial ryegrass allele frequencies under selection over time

University College Cork
- On-line bioaerosol sensing at a green waste management site in Ireland
- University College Cork in collaboration with Bio-marine Ingredients Ireland Ltd
  Optimisation of protein and lipid extraction from low-value fish sources and investigation of high-value applications

University College Dublin
- Multilateral governance of agri-food standards in international trade: a case study of Irish dairy exports to the Chinese market
- University College Dublin in collaboration with AnaBio Technologies Ltd
  Synthesis and in vivo evaluation of insulin-loaded microparticulates derived from food-grade materials in the streptozocin rat model of diabetes
- University College Dublin in collaboration with Nuritas
  Unravelling food derived bioactive peptides with dual functionality of antimicrobial and immunomodulating capabilities
- University College Dublin in collaboration with Origin Enterprises plc
  A study of the key agronomic and genetic factors affecting the production of *Avena sativa* specifically for milling market and to develop a universal practice model to ensure homogenous production of this crop on an annual basis.
- University College Dublin in collaboration with The Sustainable Energy Authority of Ireland
  The energy transition process in a rural area: becoming a sustainable energy community

University of Limerick
- Optimisation of carbon dioxide uptake systems in the ethanol producing
cyanobacterium *Synechocystis* sp. PCC 6803

Department of Agriculture, Food and the Marine-funded projects awarded in 2014

**Dublin Institute of Technology**
- Cold plasma treatment of waste water
- Innovative process technologies for the fresh produce industry
- Novel spectral and spatial process analytical tools for meat quality and safety assessment
- Fungal biofactories: improved delivery of natural selenium from the cultivated mushroom (*Agaricus bisporus*)

**Limerick Institute of Technology**
- Mushrooms and fungi functional and life enhancing reservoirs

**National University of Ireland, Galway**
- Enzymatic generation of sialylated lactose from waste whey using marine-derived sialytransferases
- Development of a water use and waste management framework for the dairy processing industry
- Profiling and optimising chemical composition of red Sea Vegetables for enhanced bioactive yields
- Impacts of forest clear-felling on Kerry Slug (*Geomalacus maculosus*) populations with the development of mitigation measures based on preferred diet of the species

**National University of Ireland, Maynooth**
- Developing budding yeast as a factory for production of the anti-oxidant ergothioneine

**Teagasc**
- Optimising annual output per sow by increasing the number of viable piglets born alive and minimising pre-weaning piglet mortality
- Measurement and abatement of ammonia emissions from agriculture
- Analysis of the functioning of Irish agricultural land markets
- Soil quality assessment and research
- High status waterbodies: managing and optimising nutrients
- Development, calibration and validation of feed intake methodology to rapidly screen dairy, beef and sheep for feed intake and efficiency
- Controlling *Septoria tritici* blotch through crop management
- An integrated multidisciplinary approach to improving the reproductive efficiency of seasonal calving beef cow herds in Ireland
- A multidisciplinary approach for the development of accurate biological markers of feed efficiency in cattle and pigs
- Genetic, nutritional and management approaches to improve fertility in lactating dairy cattle
- Nutritional composition, human health implications and marketing opportunities for beef from a grass-based production system
- Genomic strategies for animal and meat provenance, authenticity and traceability
- Intelligent/functional and medical foods for optimum brain health, targeting depression and cognition
- Nano-engineered dairy-based beverages with enhanced creaminess
• Beverage formulation/reformulation targeted at older population using *in vitro* assay to design whey protein structure for optimum glutathione (GSH) generation and increased anti-oxidant potential
• Shelf-life extension ingredient and processing technologies applied to fish
• Natural peptides to enhance food quality and safety
• Healthy-to-Bake: ready-to-bake mixes containing healthy flours generated from food processing by-products
• Detection of cephalosporins and quaternary ammonium compounds in food
• Reducing mycotoxin levels in plant derived foods and beverages
• Seaweeds as a source of non-digestible complex polysaccharide components for the development of novel prebiotic ingredients for the functional food industry
• Development of high protein bars as vehicles for functional ingredient delivery
• Data mining of existing consumer behaviour and attitudes databases to inform consumer led NPD

University College Cork
• Innovative control of fluke in Irish livestock leading to sustainable use of anthelmintics and reduced potential for anthelmintic resistance
• Development of risk assessment tools of package/product systems for a safe and sustainable food chain
• Beneficial effects of blackberry (*Rubus*) polyphenols on cardiovascular and metabolic health
• National nutrition databases for public health and new product development
• Avian diversity and afforestation planning tools

University College Dublin
• Effect of chicken mucin on *Campylobacter jejuni* global gene expression and colonization of poultry
• Early diagnosis of postpartum uterine disease for enhancement of reproduction and improved cow health
• European nutritional phenotype database sharing initiative within the Joint Programme Initiative
• Systems microbiology applied to the reduction and control of bacterial transmission in the powdered infant formula (PIF) production environment - towards scientifically validated improvements in food safety
• Development of online dietary assessment tool
• Food reformulation for consumers: Understanding barriers to consumer acceptance of reformulated food products
• The anti-inflammatory and microbial modulating effects of marine-derived laminarin and omega-3 fatty acids on inflammatory bowel disease in an experimental porcine model
• Adding value to ready to eat crustacean products by improving their quality, safety and shelf life enhanced conventional and novel processing methods
• Evaluation and refinement of timber forecasting tools using National Forest Inventory
• Developing a GIS-based agreed routes map for sustainable timber transport in Ireland and mobile app "Route Tagger"
• Biomass and renewable energy from short rotation forestry

University of Limerick
• Marine-sourced peptides for glycaemic management

Department of Agriculture, Food and the Marine-funded projects awarded in 2015

Dublin City University
• Mining marine materials for novel functional ingredients that modulate the immune response for benefit in inflammation and allergy

Dublin Institute of Technology
• Process analytical technologies for dairy and infant formula powder manufacture

Marine Institute
• Arsenic in marine macroalgae and implications for commercial uses

National University of Ireland, Galway
• Enhancing production and sustainability in Irish aquaculture

Teagasc
• Long-term sustainable breeding strategies for consistently superior health in cattle
• Strain specific pathogenicity of Staphylococcus aureus
• Multi-breed sheep genetic and genomic evaluations
• Strategies to protect and improve the welfare of dairy cows in Irish systems of milk production
• Virtual Irish centre for crop improvement
• Establishing a platform for IPM in Irish crops
• A genomic approach to understanding and improving mushroom compost utilisation
• Proofing relevant indicator data to evaluate the sustainability of Irish food
• Total factor productivity of Irish agriculture: measurement, sources and comparisons
• Measurement and understanding of the international competitiveness of Irish agriculture
• Foods solutions for replenishing disrupted microbiota in toddlers
• Development of spore analysis critical control point (SACCP) charts for application in dairy manufacturing processes
• Assuring the safety of mushrooms by the introduction of novel processes to reduce Listeria monocytogenes biofilms and environmental contamination in mushroom production facilities
• The comparative public and animal health risks associated with spreading anaerobic digestate, animal manure and slurry on land: science, policy and practice
• Improving timber forecasting
• Sensory food network Ireland

University College Cork
• Agri-Food Graduate Development Programme
• Reducing the impact of pathogens and disease in the Irish oyster industry to support the sustainability and growth of the sector
• Development of fortified blended foods using fermented buttermilk/cereal
• Dietary manipulation of microbiota diversity for controlling immune function
• Development of consumer optimised low carbohydrate Irish confectionary products
• Novel technological approaches for the development of low sugar - highly consumer accepted food and beverage products
University College Dublin
- Investigation of respiratory disease on Irish pig farms, associated risk factors & the relationship with performance, welfare & anti-microbial use
- Disaggregation of food consumption databases to raw agricultural commodity values for estimation of intakes of pesticide residues
- Novel nutritional solutions to combat chronic malnutrition in the elderly
- Application of novel food processing and microanalytical technologies to identify and control spores, in dried food ingredients, and of biofilms in food processing environments—a systems microbiology approach to ensuring quality and safety
- Developing a risk assessment framework for norovirus in Irish oyster production areas
- Windthrow risk modelling
- Assessing Ireland’s risk to airborne spread of ash dieback disease with Lagrangian stochastic models

University of Limerick
- Economic and environmental mapping of cascade use of wood

Waterford Institute of Technology
- Pre-commercial stump harvesting in Ireland

Science Foundation Ireland-funded projects awarded in 2014

Teagasc
- New weapons to fight old enemies - biocontrol of spoilage and pathogenic bacteria in the dairy industry with novel inhibitors of quorum sensing and biofilm formation
- Development of DNA-based biomarkers for compensatory growth in beef cattle
- Using precision technologies, technology platforms and computational biology to increase the economic and environmental sustainability of pasture based production systems
- The development of early non-invasive and reliable molecular biomarkers of pregnancy in dairy cattle.

University College Cork
- Examination of the cognitive enhancing potential of seaweed-derived mineral-rich nutraceuticals
- Seaweed-based Integrated Biorefinery in Ireland: A new approach for extraction of high-value products and biogas generation.
- Next generation diagnostic tools for problematic dairy bacteriophages

University College Dublin
- BIRDEYE - Thermal Imaging system to monitor poultry distribution and movement in poultry houses to form part of an overall process control system
- A method for enhancing plant immunity to multiple stressors
- Biobased polymers as a new generation of surfactants
- Monitoring of pathogenic bacteria using plasmonic enhancement methodology
- FOODBALL (The Food Biomarkers Alliance)

University of Limerick
- Realistic reaction kinetics models for the production of platform chemicals and designer fuels from biomass
Science Foundation Ireland-funded projects awarded in 2015

Dublin Institute of Technology
- Cold plasma decontamination of cereal grains

Marine Institute
- Creating the knowledge for precision fisheries management: spatially aware ‘nudging’ to achieve maximum sustainable yield using real-time fisheries incentives.

National University of Ireland, Galway
- i-PAD: Innovative biological phosphate (bioP) and anaerobic digestion (AD) technology for waste treatment, energy generation and phosphorus recovery

Teagasc
- Precision cattle breeding using precision genomics

University College Dublin
- Identifying disease resistance breeding targets in order to enhance the sustainability of cereal production and the security of food supply
- Application of new and emerging technologies to develop vaccines against Fasciola hepatica
- The macroalgal fibre initiative: ‘natural molecules naturally’

The University of Dublin, Trinity College
- Targeting microRNA to drive a successful host response to Mycobacterium tuberculosis - engineering a better vaccine
7. Appendix II

Key Informant Questions
The following is a list of questions asked of the key informants. The questions were designed to be open-ended and led to conversation and discussion based on the respondents’ answers.

Q1: What does the term ‘bioeconomy’ mean to you?

Q2: Based on your understanding of the bioeconomy and the definition used by the BioÉire project, do you see the bioeconomy as a promising growth area for Ireland?

Q3: Having worked in the bioeconomy space through your involvement with IrBEA, what do you think has been the most influential and important development, positive or negative, for the bioenergy industry in the last five years?

Q4: What do you see as being the next big thing for the bioenergy industry?
   Will this be achieved by 2020?; by 2025?

Q5: Based on the current status of the bioenergy industry and recent developments within this industry, is there a generally positive or negative opinion within the sector relating to the future of the sector?

Q6: The aim of this aspect of the BioÉire project is to identify a number of value chains which are currently either underdeveloped or which do not exist in the Irish bioeconomy. The BioÉire project considers a value chain to be the process by which a bio-based input is converted via a number of intermediary processes into a product of greater value. Based on what is currently happening within the bioenergy industry and where you envisage the industry going in the near-term, can you suggest some new value chains which could be developed to expand the bioenergy industry?
   To realise value chains three essential factors are necessary: resource availability, market demand, and expertise. Is this the case for each of the value chains you have suggested?
   Which one of these value chains do you think is the best option for the future development of bioenergy industry?

Q7: If there were no legal, environmental, technological, geographical or social restrictions, etc, limiting the expansion of the bioenergy industry what opportunities do you think could be achieved in Ireland?
   What is standing in the way of these opportunities?
Q8: From your experience working in the bioenergy industry, are there flagship examples either within the European Union or elsewhere that Ireland could look to for leadership or guidance?

Q9: I have no further questions; do you have any additional comments you would like to make, or is there anything else that you would like to discuss? Is there anything that you would like to ask me before we finish the interview?