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Formulation and Design for Food Structure and Stability (SolidFood)

Key external stakeholders:

Dairy and beverage industry
Academic and research institutes

Practical implications for stakeholders:

The Irish dairy and food industry can benefit from improved capacity resulting from better, science-based understanding of formulation of food solids. The aim was to provide solutions to the Irish food industry for processing and stabilisation of ingredients for future foods. The knowledge outcome of our research will allow the food industry to respond to the needs of the increasing elderly population and consumer trends looking for foods with healthy choices by providing dairy and food ingredients with appropriate composition and secured nutrient delivery. Our research data will also contribute to commercial applications and regulations on uses of novel delivery systems. Our research outputs have immediate usefulness in industrial spray drying and dehydration processes and manufacturing of food ingredients. Improved stabilisation of food ingredients with reduced losses of nutrients, less degradation of bioactive components and lower levels of oxidation will provide high quality ingredients for foods following the needs of modern consumers with possible new technologies.

Main results:

- We developed the new structural strength concept definition and applications were presented using trehalose-WPI (Whey Protein Isolate), lactose-WPI systems as a basic carbohydrate-protein model.
- Structural strength of pure water (6.0 °C) and pure WPI at different water contents were also predicted using viscosity data.
- The strength parameters for several carbohydrate and protein mixes as well as dehydrated emulsions with lipids were determined. We found that the approach was suitable for characterization of miscible solids, such as sugars and maltodextrins, and segregated solids, such as sugars and proteins.
- We also used the lipid-carbohydrate-protein matrices and found similar type protection for encapsulated lipid soluble carotenoids. Model food ingredients have been used in carotenoids encapsulation and monitored for the effects of ratios of protein/lactose and types of proteins on water sorption and strength properties of spray- dried model dairy formulations.
- Studies on the post-dehydration processing protocols were extended to fluid bed granulation processing conditions to find properties of WPI/MPI model systems, and to develop approaches to evaluate functionality of model systems. We have also contributed to crystallization studies including precrystallization of lactose in dairy powder manufacturing to benefit stabilization and structuring of dehydrated food solids.
- The present project provided information on post-dehydration processes as useful technologies to modify structural and physical characteristics of dairy protein powders.

Opportunity / Benefit:

The project outcomes provide important new strategies for understanding the importance of materials selection in food formulation. The strength concept will reduce losses of materials resulting from failures in process operations. The studies of encapsulation and bioactives protection provide data which can be used to select wall materials in dehydration or appropriate product packaging and storage conditions for maximising food shelf life. The overall benefits of the research include reduced energy use in manufacturing which reduces national environmental responsibilities. The concept developed may also be used to select less valued raw materials for foods or use more healthy ingredients in products with reduced sugar or increased fiber contents. Such modifications can be possible by selecting ingredients to obtain similar or better processing characteristics while improving nutritional benefits of the products.

Collaborating Institutions:

University College Cork

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1. Project background:

Manufacturing of dairy and food ingredients is often based on dehydration of solids using empirical knowledge of dryer operation. The common problems are solids accumulation on dryer surfaces, poor dehydration and low stability of products because of water uptake leading to stickiness and caking problems and component crystallization. Similar problems are typical of dairy powders, including infant formulas. The modern food industry is facing needs to manufacture dairy and food ingredients with more complex formulations to respond to particular needs of various consumer groups and the increasing number of elderly consumers. The challenges for the food industry are (i) to increase capability of using existing processes to manufacture more complex ingredients; (ii) to incorporate bioactive components to common ingredients, such as dairy powders; (iii) to predict processability of materials with various carbohydrate-protein-lipids compositions; and (iv) to ensure stability and shelf life of dairy and food ingredients at global, highly varying shipping and storage conditions. The Irish dairy and food industry can benefit from improved capacity resulting from better, science-based understanding of formulation of food solids. These include infant formulas, foods for the elderly, medical foods, and sports supplements, as common examples. The aim was to provide solutions to the Irish food industry for processing and stabilisation of ingredients for future foods. Ultimately, the consumers are the main beneficiaries of the research through improved quality of products and nutrient delivery satisfying nutritional needs of the consumer. On the other hand, the knowledge outcome of our research will allow the food industry to respond to the needs of the increasing elderly population and consumer trends looking for foods with healthy choices by providing dairy and food ingredients with appropriate composition and secured nutrient delivery.

2. Questions addressed by the project:

This project will investigate structure formation in dairy and food ingredients with effects on formulation needs and stability, protection of sensitive components and shelf life. Characterisation and modification of glass forming properties of solids are based on fluidness characterisation of typical carbohydrate and protein components to improve ingredient manufacturing processes and product stability. Fluidness characterisation is based on changes in relaxation times of structure-forming components in formulations and interaction of dispersed and continuous phases. There will also be investigations on structure formation in nanoscale particles to obtain dispersed particles for transparent food liquids. The project involves fundamental investigations and specific research on industrial relevance for the support of the Irish dairy and food ingredient and infant formula manufacturers for using knowledge-based materials science data in process control and product formulation.

3. The experimental studies:

- The present research was designed to characterise dairy and food materials using structural relaxation times data to provide concepts for the use of “strength” properties of food materials in process control and dairy and food ingredient formulation. That is to understand systematically softening properties of food materials at various temperatures and water contents for the reduction of failures is dehydration and end-product storage. Our research used novel approaches beyond the existing state-of-the-art to provide data on food materials structure forming properties with industrial importance and applications. That is, for example, the establishment of strength parameters for dairy and food materials to relate such parameters to structure formation in processes, stabilization of bioactive components and shelf life. Our contribution to science-based formulation of dairy and food ingredients is providing a tool to design robust encapsulant formulations for the stabilisation and delivery of sensitive components, such as bioactive components (fatty acids, peptides, minerals and vitamins), required for the development of ingredients and foods for targeted consumer groups.
- The overall approach included research to provide data on characteristics of carbohydrate, protein and lipid components and their mixtures in formation of structures for improved food ingredient manufacturing processes and shelf life control; to facilitate improvements of formulation of dairy-based food solids using controlled structure formation, and data on physicochemical properties and structural factors affecting capability of food matrices to protect encapsulated components and sensitive and bioactive food ingredients; to introduce materials science approaches for description and quantification of capability of food solids components to form protective encapsulant matrices and food systems with

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enhanced processability, storage stability and release characteristics; and to enhance industrial uses of knowledge-based approaches in food processing and product formulation.

- Food materials typically exist in noncrystalline, i.e., amorphous, solid structures as a result of rapid water removal and cooling associated with dehydration. The variation of typical dairy and food formulation properties as affected by temperature and water content could be studied by analysing water sorption and using thermal analytical methods to determine specific state transition temperatures. Materials with known thermal properties were used to include sensitive food ingredients and active components, such as beta-carotene. Shelf life studies employing chromatographic (HPLC) and spectrophotometric methods were used to show effects of structure formation in dehydration on stability of bioactive components, loss (reaction) kinetics of such sensitive components and thereby shelf life. Industrial relevance of food materials characterisation using the same methodology was tested using dehydrated materials and their post- dehydration processing with reconstitution to examine industrially relevant powder characteristics. Our approach used polymer science relationships of water and food components to develop the strength characterisation for their glass forming properties.

4. Main results:

- This project developed a new approach to describe food solids properties for evaluation of their suitability to dehydration and post dehydration processing. That approach uses new structural relaxation times data and WLF relationship as key outcomes of our research. The Strength parameters provided can be used to show how glass transition of solids components affects flowability, food processing and food product stability. This project has determined strength parameters for several carbohydrate and protein mixes as well as dehydrated emulsions with lipids.
- Our research was divided to seven tasks which covered areas from basic underlying principles with publicly published earlier knowledge. Further research included the use of known carbohydrate, protein and lipids materials to investigate their properties and capability to form protective dehydrated structures and potential for post drying modifications. A series of studies were carried out to investigate bioactives stability during storage of powders with known materials properties.
- Task 1: Fluidness of noncrystalline structures
  - Literature data of relaxation times of various food components (carbohydrates, lipids and proteins) were collected. These data were included in the evaluation of suitability of various potential components in food formulations for improved dehydration or stability characteristics.
  - During data analysis and comparison of available mathematical models we have adapted the use of the Williams-Landel-Ferry (WLF) relationship to describe relaxation times in noncrystalline food solids. Instead of "fluidness" we have concluded from our experimental data that food systems can be characterized for their properties using measured relaxation times with the WLF modeling. We developed a new approach which uses the "strength" parameter, S, which shows the maximum allowable temperature increase above the glass transition temperature, Tg, of noncrystalline food solids. The S values are simple numbers indicating the temperature difference to a measured glass transition temperature at which the solids show a loss of stiffness that leads to dehydration and powder flow problems. Materials with increasing S values are easier to handle in industrial food processing equipment.
  - Experiments were carried out using trehalose-WPI and lactose-WPI systems and the S values were derived from experimental data. The methodology appears valuable to food and pharmaceutical formulations and their characterization.
- Task 2: Formulation and water
  - Trehalose-maltodextrin systems with a different ratio of components were used as an example of miscible carbohydrate systems. Several carbohydrate-protein systems such as trehalose-WPI and lactose-WPI were also under investigation. Partially crystalline trehalose with different ratios of amorphous and crystalline components was used as a precrystallized system. Trehalose-WPI-sunf lower oil systems with different ratios of lipids were used to investigate the effect of lipids on strength parameter in encapsulant systems.
  - Water sorption analysis, Differential Scanning Calorimetry (DSC), Dynamic Mechanical Analysis (DMA), DiElectric Analysis (DEA) and rheology were the main methods in this study. Optical light, confocal laser scanning and scanning electron microscopes were used to characterise powders microstructure. The glass transition temperature was obtained by DSC and it was in agreement with lipids-free materials results. Structural relaxation times were measured by DMA, DEA and rheology and combined to cover a broad range for strength assessment.
  - The results obtained from task 2 are useful in understanding and predicting thermodynamic and kinetic behaviour of complex food systems over a wide temperature range including the Tg region that is important to food stability and safety. For all systems, a known strength value for pure substances allows calculation of a strength estimate also for mixtures of such components at various water contents. These possibilities make structural strength concept a powerful tool in analyses and prediction of properties of amorphous carbohydrates, carbohydrate-protein, precrystal l ized and carbohydrate-protein-lipid systems in foods.

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Several examples include dairy powders, infant formulae, confectionary products, cheese products, supplements, high protein foods, etc. The outcomes of current research can be applied in different areas such as food, nutritional, pharmaceutical, polymer and material sciences areas to develop stability and quality control criteria for processing and storage of amorphous materials. The strength concept has a wide range of applications, therefore in the future strength analysis our results can be applied in studies of kinetics of diffusion phenomena, browning and Maillard reactions and oxidations in various food materials.

- It was shown, that for all different types of food systems the new strength concept was highly valuable. For all systems, S shows linear dependence on component concentration in a mixture and it was significantly decreasing with increasing water content. A new relationship, which allows calculation of strength values at various water contents, was established. Structural strength of pure water (6.0 °C) and pure WPI at different water content were predicted using rheometry data. Hence, new structural strength approach demonstrated a wide area of practical applications for adaptation to processing and characterisation of various food materials as well as in quality and stability control during food manufacturing and storage.

- Task 3: Spray drying and microstructure
  - Materials characterised in the project were used as solids for spray drying and analysis of the resultant powder properties. The main emphasis was on the analyses of microstructure using microscopic and rheolog ical characterisation and physicochemical analysis using determination of thermal properties with emphasis on DMA and DSC.
  - Dairy solids with smaller size particles showed lower glass transition temperatures (Tg) after equilibration at 0.11-0.33 water activity (aw). The presence of less than 46.8% crystalline lactose in lactose/WPI mixtures had only a minor impact on water sorption behaviour at 0.11-0.44 aw, whereas samples with higher crystallinity had higher stable water content after lactose crystallization. Increasing the amount of crystalline lactose had no significant influence on the glass transition temperatures and the initial crystallization temperatures at 0.11-0.44 aw, but dairy powders with higher crystallinity had higher stiffness. Water plasticisation had a stronger effect on the structural relaxation of dairy powders with lower crystallinity.
  - In encapsulation applications, wall material consisting of lactose/WPI (4:1) mixture had significantly ($P < 0.05$) higher encapsulation efficiency. Increasing lactose content could increase the encapsulation efficiency of wall materials during spray drying. The addition of MD could increase stiffness and thus, reduce molecular mobility of encapsulation systems. Wall materials consisting of lactose/MD (13-17)/WPI (1:3:1) mixtures and lactose/MD (23- 27)/WPI mixtures had higher flavor retention than other wall materisls after equilibration at high water activity (⩾ 0.54 aw).
  - Understanding the effect of lactose/protein ratios on the physical and mechanical properties of dairy solids will help the industry to optimize their information and help to achieve better stability of their products. As pre-crystallisation of lactose is widely used in the production of dairy powders, the findings of pre-crystallised systems could be very useful in the whey production of dairy industry.
- Task 4: Post-dehydration processing and functionality
  - The post-dehydration technology has the potential for improving the functionalities of dairy powders, by controlling the key parameters affecting the formation of dairy powder structures. The various rehydration behaviours (wetting, dispersing and dissolving) of different high protein milk powders (milk protein isolate, MPI, whey protein isolate, WPI, micellar casein, MC, and sodium caseinate, SC) were assessed to find the suitable methods to quantify these dynamic processes. The agglomerated casein-dominant powders (MPI and MC) exhibited significantly better wettability by needing much shorter wetting time, being quickly penetrated by water droplets and absorbing more water by capillary forces. The small particle size and dense structures are believed to be the rate-limiting factors to control the dynamic wetting process of the casein-dominant powders. Thus, the increases of particle size and powder porosity caused by fluidised bed agglomeration play beneficial roles in the improving of wettability.
  - For the agglomerated MPI produced by fluidised bed (FB), the larger size was corresponding to more irregular shape properties, having lower circularity and convexity. The larger FB agglomerates with higher porosity are related to higher water uptake by capillary rise. Similar results were also observed for the large granules, which absorbed the greatest amount of water, had the least wetting time, as well as caused quickest disappearance of water droplets.
  - The addition of lecithin dramatically shortens the wetting time for WPI powder, especially when adding lecithin solution by fluidised bed agglomeration, WPI powder only requires several seconds to be completely wetted. WPI coated by lecithin solution appears to form weaker layers, where water more easily penetrates through and wets the particles. The fluidised bed granulator creates agglomerated MPI that is 2 to 4 times (100 mm - 200 mm) greater in particle size than that of the primary MPI powders. The formed agglomerated MPI powder is very irregular, showing less rounded shapes and rougher surfaces than non-agglomerated particles. MPI granules produced by hot steam, HS, can reach sizes of more than 1000 mm, which are ~20 times those of the primary powders. Binding bridges being comparatively weak in the agglomerates produced by fluidised bed; while the HS granules are consolidated by strong mechanical agitation, which leads to much

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stronger adhesive forces and thus tend to adhere more particles. Compared to agglomerated WPI, the coated WPI had no significant difference in bulk density and porosity values, though some of them may have bigger sizes based on their partial agglomeration. For the agglomerated MPI produced by fluidised bed, the larger size is corresponding to more irregular shape properties, having lower circularity and convexity. The high shear mixer agglomeration exhibits completely different behaviour in the granule growth process, as mechanical agitation tends to rapidly coalescence the MPI particles. The granules from HS and FB present different physical and structural characteristics.

  - The impact of liquid binders on the structural modifications of MPI agglomerates is not significant compared to the factors of processing types and granule growth. The small difference in the particle density was found for the agglomerated MPI using different liquid binders. Water binding agglomerates had comparatively less similarity of a circle and lower convexity due to higher binder liquid concentration resulted in the higher compactness of agglomerates. 5 % lecithin solution caused a slightly higher bulk density and lower porosity of WPI powders, as the higher concentration of liquid in the coating process results in the formation of thicker layers with high compactness.
  - The influence of agglomeration and coating processes on the dynamic rehydration processes, including wetting, dispersing and dissolving, have been investigated. According to the study, different processes, granule growth and different binders (coating materials) contribute differently to the rehydration behaviours of different milk protein powders. The MPI with densely packed structures made by high shear mixer granulator adsorbed least moisture and showed the slowest adsorption kinetics during storage at different relative humidities. The agglomerated MPI with loose and porous structures by FB exhibited no significant difference, compared to the non-agglomerated powder.
  - Large MPI granules have significantly better powder flow behaviours. Agglomeration processes can effectively reduce the minimum outlet diameters of hoppers for reliable flow from both mass-flow or core-flow hoppers. However, large wall friction angles caused by the HS granules (especially the smaller granules) may also require steeper hopper walls to discharge bulk solids and avoid them remaining at rest.
- Task 5: Fluidness and shelf life
  - Fluidness (strength) and shelf life studies used materials selected on the basis of the results of Tasks 1-3. Spray drying and freeze-drying were used for bioactives encapsulation. Bioactivers stability was analysed using High Performance Liquid Chromatography (HPLC) and loss kinetics were determined.
  - Ingredients were mixed and homogenised using high pressure homogenisation. We used structured emulsion interface, i.e., layer-by-layer emulsions were prepared. The glass transition of the powders was dependent on their composition and water content. Water activity, water content and temperature were varied to accelerate losses of active components.
  - Primary WPI layer of O/W emulsion had an effect on emulsion ζ-potential and ζ-average diameter but total solids content have minor effects. Deflocculation of Layer-By-Layer (LBL) system with sufficient primary layer was possible with individual particles still intact. High total solids Single Layer (SL) and LBL emulsions (45-50% w/w) with different wall material mixtures and lutein and all-trans-β-carotene as oil-soluble bioactives were obtained successfully from the spray drier. Powder characteristics of SL and LBL powders obtained from spray drying were comparable. Critical powder characteristics were affected and improved by LBL interfacial layer and wall materials. Tg and structural relaxation temperature, Tα of all systems reduced with increasing aw.
  - Spray drying was better in protecting encapsulated bioactives compared to freeze-drying. Studies showed that LBL interfacial structure reduced carotenoids loss rate. Carotenoids retention was higher in LBL systems upon long term storage with significance at higher storage temperature. Water and water-induced structural changes affected S and increase temperature and humidity sensitivity of the solids. Carbohydrate-carbohydrate glass formers systems exhibited higher S. LBL interfacial structure and increased S can increase stability of encapsulated bioactives.
- Task 6: Industry relevance
  - This task was designed to provide further data on the benefits of the use of fluidness (strength) characterisation in industrial dairy and food ingredient manufacturing. The experimental approach included powder and material testing with strength data comparisons.
  - Lactose/MPI mixtures with higher lactose contents showed better flowability at 0 and 44% relative humidity (RH), but they gave bigger friction angles after storage at 44% RH. For pre-crystallization systems, flow function tests indicated that dairy solid with 11.2% crystallinity was more easy-flowing than lactose/WPI mixtures with 1.0, 29.2 and 46.8% crystallinity after storage at 0 and 44% RH storage conditions. Dairy solids with higher crystallinity showed better resistance to develop cohesiveness when stored at high relative humidity conditions. Increasing lactose content could result in a higher rate of flavour release with increasing water content.
  - Wall material consisting of lactose/WPI (4:1) mixture had significantly higher encapsulation efficiency. The addition of maltodextrin in wall systems could increase the stiffness, and restrict the diffusion of flavour

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molecules during storage. Wall materials consisting of lactose/MD/WPI (1:3:1) mixtures had higher encapsulation efficiency compared to wall materials consisting of lactose/MD/WPI (3:1:1) mixtures.

5. Opportunity/Benefit:

We developed the new structural strength concept definition and applications were presented using trehalose-WPI (Whey Protein Isolate), lactose-WPI systems as a basic carbohydrate-protein model. Systems with maltodextrins in place of WPI were also characterized. Lactose-WPI systems were used to create a new relationship, which allows determination of strength values over a wide water content range. Structural strength of pure water (6.0 °C) and pure WPI at different water contents were also predicted using viscosity data. Trehalose-maltodextrin systems, as an example of a miscible carbohydrate system, showed that our new concept can explain and predict miscible systems properties. Also, structural strength analysis showed good consistency taking into account the amorphous or crystalline contents in partially crystalline trehalose systems. Such data have a high applicability among manufacturers of dairy powders, as dairy-based solids often contain precrystallized lactose.
The effect of lipids was investigated using trehalose-WPI-sunf lower oil systems. Also strength parameters for several carbohydrate and protein mixes as well as dehydrated emulsions with lipids were determined. We found that the approach was suitable for characterization of miscible solids, such as sugars and maltodextrins, and segregated solids, such as sugars and proteins.
The work carried out has included studies of crystallization in lactose-protein systems, which represent numerous dairy-type materials. Such information would be important in controlling crystallization in dairy powders. Trehalose-maltodextrin as well as whey protein systems were further developed for encapsulation of oil with dissolved lutein and β-carotene as bioactive components. A layer-by-layer emulsion resisted dehydration and thermal stress and gave a higher retention of the bioactive components in a model food system also in spray dried solids. This system was further studied for carotenoids stabilization and strength analysis.
We also used the lipid-carbohydrate-protein matrices and found similar type protection for encapsulated lipid soluble carotenoids. Model food ingredients have been used in carotenoids encapsulation and monitored for the effects of ratios of protein/lactose and types of proteins on water sorption and strength properties of spray- dried model dairy formulations. Studies on the post-dehydration processing protocols were extended to fluid bed granulation processing conditions to find properties of WPI/MPI model systems, and to develop approaches to evaluate functionality of model systems.
We have also contributed to crystallization studies including precrystallization of lactose in dairy powder manufacturing to benefit stabilization and structuring of dehydrated food solids. The present project provided information on post-dehydration processes as useful technologies to modify structural and physical characteristics of dairy protein powders.
Our findings are helpful to enhance the wetting process during rehydration, control the water sorption behaviour and significantly improve powder flowability. There has been a wide dissemination of project results which has included a wide dissemination of the strength-concept as well as an industry targeted special workshops.

6. Dissemination:

The present project trained 4 students who completed a PhD thesis. In addition to scientific publications and conference papers, the project organised two specific, industry targeted workshops in 2012 and 2016.
The number of published peer reviewed Journal papers were 28. The project also produced 2 book chapters and 29 conference and other presentations.

Main publications:

1. Ji, J., Cronin, K., Fitzpatrick, K., Fenelon, M., Miao, S. 2015. Effects of fluid bed agglomeration on the structure modification and reconstitution behaviour of milk protein isolate powders. Journal of Food Engineering 167, 175–182.

2. Ji, J., Cronin, K., Fitzpatrick, J., Maguire, P., Zhang, H., Miao, S., 2016. The structural modification and rehydration behaviours of milk protein isolate powders: The effect of granule growth in the high shear granulation process. Journal of Food Engineering 189, 1-8.

3. Ji, J., Fitzpatrick, J., Cronin, K., Crean, A., Miao, S. 2016. Assessment of measurement characteristics for rehydration of milk. Food Hydrocolloids 54, 151-161.

4. Ji, J., Fitzpatrick, J., Cronin, K., Maguire, P., Zhang, H., Miao, S. 2016. Rehydration behaviours of high protein dairy powders: The influence of agglomeration on wettability, dispersibility and solubility. Food Hydrocolloids 58, 194-203.

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5. Ji, J., Fitzpatrick, J., Cronin, K., Fenelon, M., Miao, S. 2016. The effects of fluidised bed and high shear mixer granulation processes on water adsorption and flow properties of milk protein isolate powder. Journal of Food Engineering 192, 19-27.
6. Ji, J., Cronin, K., Fitzpartick, J., Miao, S. 2017. Enhanced wetting behaviour of whey protein isolate powder: the different effects of lecition addition by fludised bed agglomeration and coating processes. Food Hydrocolloids 71, 94-101.
7. Li, R., Roos, Y.H. and Miao, S. 2015. The effect of water plasticization and lactose content on flow properties of dairy model solids. Journal of Food Engineering 170, 50-57.
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11. Li, R., Roos, Y.H. and Miao, S. 2016. Roles of particle size on physical and mechanical properties of dairy model solids. Journal of Food Engineering 173, 69-75.
12. Li, R., Roos, Y.H. and Miao, S. 2017. Characterization of physical and mechanical properties of miscible lactose-sugars systems. Journal of Food Science 82: 2105-2112.
13. Li, R., Roos, Y. H. and Miao, S. 2017. Characterization of mechanical and encapsulation properties of lactose/maltodextrin/WPI matrix. Food Hydrocolloids, 63, 149-159.
14. Li, R., Lin, D., Roos, Y.H. and Miao, S. 2018. Glass transition, structural relaxation and stability of spray-dried amorphous food solids: A review. Drying Technology 37, 287-300.
15. Lim, A.S.L. and Roos, Y.H. 2015. Stability of flocculated particles in concentrated and high hydrophilic solid layer-by-layer (LBL) emulsions formed using whey proteins and gum Arabic. Food Research International 74: 160-167.
16. Lim, A.S.L. and Roos, Y.H. 2015. Spray drying of high hydrophilic solids emulsions with layered interface and trehalose-maltodextrin as glass former for carotenoids stabilization. Journal of Food Engineering 171, 174-184.
17. Lim, A.S.L. and Roos, Y.H. 2017. Carotenoids stability in spray dried high solids emulsions using layer-by-layer (LBL) interfacial structure and trehalose-high DE maltodextrin as glass former. Journal of Functional Foods 33, 32-39.
18. Lim, A.S.L. and Roos, Y.H. 2018. Amorphous wall materials properties and degradation of carotenoids in spray dried formulations. Journal of Food Engineering 223, 62-69.
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22. Maidannyk, V.A. and Roos, Y.H. 2017. Water sorption, glass transition and “strength” of lactose - whey protein systems. Food Hydrocolloids 70, 76-87.
23. Maidannyk, V.A., Nurhadi, B. and Roos, Y.H. 2017. Structural strength analysis of amorphous trehalose-maltodextrin systems. Food Research International 96, 121-131.
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25. Maidannyk, V.A., Lim, A.S.L., Auty, M.A.E. and Roos, Y.H. 2018. Effects of lipids on the water sorption, glass transition and structural strength of carbohydrate-protein systems. Food Research International 116, 1212-1222.
26. Nurhadi, B., Roos, Y.H. and Maidannyk, V. 2016. Physical properties of maltodextrin DE 10: Water sorption, water plasticization and enthalpy relaxation. Journal of Food Engineering 174, 68-74.

Popular publications:

Ji, J. 2017. The post-dehydration processing and the effects on the structural modifications and functionalities of milk protein powders. PhD Thesis, University College Cork.

Li, R. 2017. Studies on physical, mechanical, and industrially relevant properties of spray- dried dairy systems. PhD Thesis, University College Cork.

Lim, A. S. L. 2017. Design of high solids emulsions for dehydration and carotenoids stabilisation. PhD Thesis, University College Cork.

Maidannyk, V. 2017. Strength analysis for understanding structural relaxations in food materials. PhD Thesis, University College Cork.

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