An Roinn Talmhaíochta,
Bia agus Mara
Department of Agriculture,
Food and the Marine

15F679 – Developing the next generation of protein-enriched spray dried dairy powders with enhanced hydration properties (DAIRYDRY)

Final Report

This project was funded under the Department of Agriculture, Food and the Marine Competitive Funding Programme.

SUMMARY

This project was a major research collaboration bringing together Ireland's leading research centres in the areas of dairy science, ingredient and process dehydration technology, photonics, and imaging expertise. The project came about due to a significant issue regarding the solubility and hydration of high protein ingredients. The objectives of the project were as follows; to develop new analytical tools and baseline knowledge to understand the scientific basis of powder formation and hydration properties and key formulation-process conditions, to integrate and optimise formulation-process conditions for manufacturing through new sensor-based process control, to evaluate new mixing/dispersion process technology for powder processing, to develop a new platform of protein-enriched base powders with enhanced stability and hydration properties. The objectives of the project were divided under seven experimental tasks across five research institutes. Results from the project have led to significant findings in terms of improving powder hydration by making slight changes to their formulation or changing particle morphology. Secondly, significant steps were taken to assess powder functionality using photonics, microscopy, spectroscopy and dynamic mechanical analysis. DairyDry had a major impact on both academia and industry. Dissemination of results from the project took the form of eighteen peer-reviewed publications, meetings, industry engagement and public forums (e.g., Teagasc Gateways). An industry partner of the project also ran commercial plant trials in-line with some of the work performed in DairyDry. In terms of personnel development, the training of PhD students and post-doctoral researchers in dairy chemistry, spectroscopy and novel imaging techniques have been significant, with all personnel associated with the project finding employment since the completion of the DairyDry project.

KEYWORDS

High protein dairy ingredients; Solubility; In-line photonics

ACRONYM	DAIRYDRY
PROJECT COORDINATOR, INSTITUTION	Dr Noel McCarthy, Teagasc
EMAIL	noel.mccarthy@teagasc.ie
COLLABORATORS, INSTITUTION	Dr Seamus O'Mahony, University College Cork Dr Barry O'Hagan, University of Ulster Dr Ramesh Raghavendra, Waterford Institute of Technology Dr Tomasz Ochalski, CAPPA Cork Institute of Technology
PUBLICATION DATE	February 2024

Section 1 - Research Approach & Results

Start Date

01 December 2016

End Date

31 July 2022

Research Programme

Food Institutional Research Measure

TRL Scale

TRL 3: Experimental Proof of Concept

NRPE Priority area

Sustainable Food Production and Processing

Total DAFM Award

€2,192,740.00

Total Project Expenditure

€2,424,734.45

Rationale for undertaking the Research

To compete internationally, the Irish dairy industry needed the highest quality and depth of science to underpin product R&D, specifically for powdered dairy ingredients intended for export. High protein powders such as micellar casein are particularly difficult to hydrate, requiring extensive mixing/heating over long time periods. Heat-induced protein denaturation is another serious problem, particularly in complex infant milk formulation (IMF) process lines with multiple temperature ramps or where UHT treatment is required for export and increased shelf stability (e.g. age gelation). These issues are becoming more common with increasing complexity of product formulations and demand for higher protein levels and product stability. There was an urgent need to develop highly dispersible protein powdered ingredients that can be incorporated into nutritional food and beverage products targeted at key markets such as early-stage life (IMF). This required a deep understanding of the complex interplay between composition, processing and hydration behaviour, requiring new research tools and an integrated approach. This project specifically addressed the needs of Irish dairy processors by providing new knowledge on powder hydration. The project delivered new strategies to both improve the quality of existing dried milk products and to drive innovation through microstructural design of novel protein-enriched powder formulation/process strategies.

Methodology

Physico-chemical properties were characterized at the molecular, nano- and microscales in real-time using advanced spectroscopy, microscopy and high speed imaging. Prototype photonics-based sensor devices including off-line flow cells and in-line infra-red sensors were developed to measure the pattern of dispersion and dissolution of specific constituents such as lactose, proteins and milk salts using infra-red and Raman spectroscopy. New tools were developed to characterise and measure hydration of individual powder particles for the first time. The production of powders were split across Tasks 2 and 3 where high protein ingredients were

produced at laboratory, pilot and semi-commercial scale. Powders were subsequently distributed among the other institutes where X-ray microtomography in WIT was utilized to examine the internal structure of the novel powder particles to identify pores, cracks and voids within the particles and distinguish between samples and to visualize the absorption of water with powder particles. An environmental scanning electron microscope allowed us to visualize the adsorption of water in to powder particles for the first time and also observe in-real time the lactose crystallization phenomena. The use of Raman spectroscopy and infra-red imaging at CIT(MTU) - CAPPA allowed for the determination of milk powder reconstitution characterized using spectroscopic methods. Probably one of the most important aspects of the project, was that DairyDry identified methodology that was effective, and in other instances clearly acknowledged and highlighted methods that were not successful.

Project Results

The results of the DairyDry project can be assigned to methods of improving powder solubility and methods of assessing these changes using novel techniques. UCC examined the role of formulation strategies to increase solubility in high protein ingredients. Addition of a milk peptide known as glycomacropeptide to micellar casein streams prior to spray drying resulted in increased solubility of the powders. Increasing the pH of ultrafiltration retentate and thereby increasing casein micelle size and reducing the ionic calcium level in the milk improved hydration; however there was even further improvement when the system was re-neutralized. This study also developed a fundamental understanding of WPI powder obtained from nanoparticulated whey proteins, which could be applied for the development of functional whey-based ingredients in food formulations, such as nanospacers to modulate protein–protein interactions in dairy concentrates. Nanoparticulation of whey protein can be seen as a costly process but by creating nanoparticulated whey and re-adding to standard commercial whey proteins streams, it makes the process significantly more economical. At Teagasc, the addition of compressed gas into a high protein liquid stream prior to drying facilitated the creation of novel functional high protein powder ingredients. The process was highly successful and unlike previous products using ion exchange to reduce calcium this process causes no change to the formulation but simply creates voids and pores in the particles for water penetration and dissolution. Therefore, injection of compressed gas has real potential for increasing the solubility of these powders. Vacuum-assisted microwave drying was also performed but does not appear suitable for the drying of liquid milk protein concentrate intended to be rehydrated. However, this technology has potential in the development of high-protein snacks. Another outcome of the project suggests that heat treatment at or above 100°C for 30s can present processing challenges and should not be performed on liquid MPC prior to spray drying if rehydration performance is considered an essential quality attribute by the end-user. The x-ray diffraction technique at WIT gave excellent internal structural detail of powders and its use in the food industry has real benefits, in fact it has led Teagasc to purchase a similar instrument this year. The real-time visualization of swelling and dissolution of powder particles using the environmental electron microscope could be used for samples beyond high protein powders but also for nutritional formulations, particularly for examining in-situ observations of infant formula, such as onset of lactose crystallization. Atomic-force-microscopy proved an excellent tool to observe the surface structure of powder particles and could define surface properties such as roughness, elasticity all of which are important for powder flowability and particle-particle interactions. Similarly, the use of fluorescent microscopy in conjunction with functional nano-diamonds to increase photostability were employed. Dynamic-mechanical-analyser at Teagasc proved extremely valuable in assessing the physical properties of the powders particularly for the gas injected powders where fracturing and powder breakdown may be an issue. The project published 18 peer-reviewed papers and made significant advances in powder solubility, even to sectors outside the field of food research.

Section 2 - Research Outputs

Summary of Project Findings

The results generated from the DairyDry project can be divided into those of direct impact on the industry and those furthering our knowledge on milk protein chemistry. High-protein powder solubility can be significantly improved by altering particle morphology using compressed gas during spray drying. This has real impact on the industry but there are disadvantages to this process with a decrease in bulk density unavoidable, but it can be mitigated depending on the level of gas incorporation. This process does not affect product nutritional quality or cause any changes to the product composition. That heat treatment ≥100°C causes a drastic decrease in solubility of micellar casein containing powders and the industry should avoid if possible. Adjustments to pH during the production of micellar casein can significantly improve subsequent powder hydration properties when applied during the filtration of skim milk. With 18 peer-reviewed publications, Dairy Dry has significantly contributed to the field of powder hydration within the scientific community. The techniques developed to identify and quantify powder hydration and solubility are not only relevant to protein powders but are highly applicable to the pharmaceutical industry. Prior to DairyDry, no individual method was available to assess high protein powder hydration and solubility, but this project highlighted the best methods and developed techniques that could be used across the project and are now used regularly in Teagasc when assessing commercial powder samples. It must also be noted that prior to DairyDry there were essentially only 2 research groups applying microscopy to assess real-time hydration of food products but over the last 2 years the field has expanded drastically with a whole host of research centres now studying food constituents using techniques introduced by DairyDry. Another benefit of the project was the training and career development of PhD students and post-doctoral researchers.

Summary of Staff Outputs

Research Output	Male	Female	Total Number
PhD Students	2	1	3
Post Doctorates	4	2	6
Research Technicians/Assistants	1	0	1
MSc Students	1	0	1

Summary of Academic Outputs

Research Outputs	Total Number	Details
Publications in Peer Reviewed Scientific Journals	18	1. Maidannyk V., Lim A., Auty M., Roos Y. Effects of lipids on the water sorption, glass transition and structural strength of carbohydrate-protein systems (https://doi.org/10.1016/j.foodres.2018.10.008) Food Research International 116(2019); 1212-1222. 2. V. Maidannyk, E. Lutjes, S. Montgomery, N.A. McCathy, M.A.E. Auty Measurement of effective diffusion coefficients in dairy powders by confocal microscopy and sorption kinetic profiles

https://doi.org/10.1016/j.foostr.2019.100108 Food Structure, 20, 100108.
3. V. A. Maidannyk, D. J. McSweeney, S. A. Hogan, S. Miao, S. Montgomery, M. A. E. Auty, N. A. McCarthy Water sorption and hydration in spray-dried milk protein powders: Selected physicochemical properties https://doi.org/10.1016/j.foodchem.2019.125418 Food Chemistry, 304, 125418.
4. V. A. Maidannyk, N.A. McCarthy, M.A.E. Auty Microscopy Techniques for Characterization of Hydration in Dairy Powders https://doi:10.1017/S1431927619004331 Microscopy and Microanalysis, 25(S2), 720-721.
5. McSweeney, D.J., Maidannyk, V., Montgomery, S., O'Mahony, J.A., and McCarthy, N.A.. The Influence of Composition and Manufacturing Approach on the Physical and Rehydration Properties of Milk Protein Concentrate Powders. https://doi.org/10.3390/foods9020236. Foods, 9, 236.
6. D. J McSweeney, V. Maidannyk, J. A O'Mahony, N. A McCarthy Influence of nitrogen gas injection and agglomeration during spray drying on the physical and bulk handling properties of milk protein concentrate powders (https://doi.org/10.1016/j.jfoodeng.2020.110399) Journal of Food Engineering, 293, 110399.
7. O. M Power, V. Maidannyk, D. J McSweeney, M. A Fenelon, J. A O'Mahony, N. A McCarthy Water sorption and hydration properties of high protein milk powders are influenced by enzymatic crosslinking and calcium chelation Powder Technology, 364, 680-688.
8. Cenini, V., Gallagher, L., McKerr, G., McCarthy, N., McSweeney, D., Auty, M. & O'Hagan, B. A novel approach for dynamic in-situ surface characterisation of milk protein concentrate hydration and reconstitution using an environmental scanning electron microscope." 30 Nov 2020, In: Food Hydrocolloids. 108, 13 p., 105881.
9. R.R. Panthi, F. Bot, S.N. Shibu, D. Saladukha, T.J. Ochalski, J.A. O'Mahony Influence of pH adjustment on physicochemical properties of microfiltration retentates of skim milk and rehydration properties of resulting powders. https://doi.org/10.1016/j.idairyj.2020.104953 International Dairy Journal, 2021, 116, 104953.
10. Ram R. Panthi, Francesca Bot and James A. O'Mahony Influence of Glycomacropeptide on Rehydration Characteristics of Micellar Casein Concentrate Powder https://www.mdpi.com/2304-8158/10/8/1960 MDPI Foods, 2021, 10, 1960.
11. Jacob R Guralnick, Ram R Panthi, Francesca Bot,Valeria L Cenini, Barry MG O'Hagan, Shane V Crowley,James A

O’Mahony Pilot-scale production and physicochemical characterisation of spray-dried nanoparticulated whey protein powders https://doi.org/10.1111/1471-0307.12797 International Journal of Dairy Technology, 2021, 74, 581-591.

12. Jacob R. Guralnick, Ram R. Panthi, Valeria L. Cenini, Vinay S. N. Mishra, Barry M. G. O’Hagan, Shane V. Crowley, James A. O’Mahony "Rehydration Properties of Whey Protein Isolate Powders Containing Nanoparticulated Proteins https://www.mdpi.com/2624-862X/2/4/47" MDPI Dairy,2021, 2, 602 – 616.
13. D. J. McSweeney, V. Maidannyk, J. A. O'Mahony, N. A. McCarthy Rehydration properties of regular and agglomerated milk protein concentrate powders produced using nitrogen gas injection prior to spray drying https://doi.org/10.1016/j.jfoodeng.2021.110597 Journal of Food Engineering, 305, 110597.
14. D. J. McSweeney, J. A. O'Mahony, N. A. McCarthy Strategies to enhance the rehydration performance of micellar casein-dominant dairy powders (https://doi.org/10.1016/j.idairyj.2021.105116) International Dairy Journal, 122, 105116.
15. Vinay S.N.Mishra, Tomasz J.Ochalski, Noel McCarthy, André Brodkorb, Brian J.Rodriguez, Sean A.Hogan Topographical changes in high-protein milk powders as a function of moisture sorption using amplitude-modulation atomic force microscopy. (https://doi.org/10.1016/j.foodhyd.2022.107504) Food Hydrocolloids (January 2022, 107504)
16. V. Maidannyk; D. J. McSweeney; S. Montgomery; V. L. Cenini; B. M.G. O'Hagan; L. Gallagher; S. Miao; N. McCarthy The effect of high protein powder structure on hydration, glass transition, water sorption and thermomechanical properties. (https://doi.org/10.3390/foods11030292) Foods (ISSN 2304-8158).
17. David J McSweeney, Tugce Aydogdu, Yonas Hailu, James A O'Mahony, Noel A McCarthy. Heat treatment of liquid ultrafiltration concentrate influences the physical and functional properties of milk protein concentrate powders International Dairy Journal. Volume 133, October 2022, 105403.
18. Ram Raj Panthi, Sini Nanadath Shibu, T. J. Ochalski, James A. O’Mahony. Raman spectra of micellar casein powders prepared with wet blending of glycomacropeptide and micellar casein concentrate. International Journal of Dairy Technology, doi.org/10.1111/1471-0307.12920.

PhD Theses	3	1. David Mc Sweeney (Thesis submitted) 2. Sini Nanadath Shibu (Thesis submitted) 3. Vinay Mishra (Thesis to be submitted Q1 2024)
Masters Theses	1	1. Jacob Guralnick (2 papers published)
Other	36	National and international conferences where DairyDry results were presented.

Summary of other Project Outputs

Project Outputs	Details	Total Number
New Processes	A number of processes were developed: Effects of pH adjustment on physicochemical properties of microfiltration retentates of skim milk and rehydration of resulting micellar casein concentrate (MCC) powders were investigated. Aliquots of retentate (pH 6.9) were adjusted to pH 7.3, 7.6 or 7.6 followed by readjustment to pH 6.9 (6.9R) prior to powder preparation. The retentates with pH 6.9, 7.3, and 7.6 had casein micelle size of 179, 189 and 197 nm, respectively, while sample 6.9R had size of 183 nm, similar to retentate at pH 6.9. Higher retentate pH resulted in lower ionic calcium and higher conductivity, with sample 6.9R having higher values for both parameters than the pH 6.9 sample. The MCC powders displayed poorer wettability and enhanced dispersibility with increasing retentate pH. Interestingly, the 6.9R powder had the best wettability and dispersibility. This study demonstrated that pH-mediated modifications of the physicochemical properties of retentates improve the rehydration properties of resultant MCC powders. Glycomacropeptide (GMP) shows potential for enhancing the rehydration properties of high-protein dairy powders due to its hydrophilic nature. This study involved formulating micellar casein concentrate (MCC) solutions (8.6% final protein content) with 0, 10, and 20% GMP as a percentage of total protein, and investigated the physicochemical and rehydration properties of the resultant freeze-dried powders (P-MCC-0G, P-MCC-10G, and P-MCC-20G, respectively). The surface charges of caseins in the control MCC and 10 or 20% GMP blended solutions were −25.8, −29.6, and −31.5 mV, respectively. Tablets prepared from P-MCC-10G or P-MCC-20G powders displayed enhanced wettability with contact angle values of 80.6° and 79.5°, respectively, compared with 85.5° for P-MCC-0G. Moreover, blending of GMP with MCC resulted in faster disintegration of powder particles during rehydration	3

(i.e., dispersibility) compared to P-MCC-0G. Faster and more extensive release of caseins from powder particles into solution was evident with the increasing proportion of GMP, with the majority of GMP released within the first 15 min of rehydration. The results of this study will contribute to further development of formulation science for achieving enhanced solubility characteristics of high-protein dairy powder ingredients, such as MCC.

The rehydration properties of original whey protein isolate (WPIC) powder and spraydried WPI prepared from either unheated (WPIUH) or nanoparticulated WPI solutions were investigated. Nanoparticulation of whey proteins was achieved by subjecting reconstituted WPIC solutions (10% protein, w/w, pH 7.0) to heat treatment at 90 °C for 30 s with no added calcium (WPIH) or with 2.5 mM added calcium (WPIHCa). Powder surface nanostructure and elemental composition were investigated using atomic force microscopy and X-ray photoelectron spectroscopy, followed by dynamic visualisation of wetting and dissolution characteristics using environmental scanning electron microscopy. The surface of powder particles for both WPIUH and WPIC samples generally appeared smooth, while WPIH and WPIHCa displayed micro-wrinkles with more significant deposition of nitrogen and calcium elements. WPIH and WPIHCa exhibited lower wettability and solubility performance than WPIUH and WPIC during microscopic observation. This study demonstrated that heat-induced aggregation of whey proteins, in the presence or absence of added calcium, before drying increases aggregate size, alters the powder surface properties, consequently impairing their wetting characteristics. This study also developed a fundamental understanding of WPI powder obtained from nanoparticulated whey proteins, which could be applied for the development of functional whey-based ingredients in food formulations, such as nanospacers to modulate protein– protein interactions in dairy concentrates.

The physical, bulk handling and rehydration properties of regular and agglomerated milk protein concentrate (MPC) powders, prepared using nitrogen (N2) gas injection as part of the spray drying process, were analysed following milling. Powder loose and tapped bulk density increased, while air content and powder particle size decreased, following milling. Differences in surface composition were observed, in particular a lower proportion of fat and a higher proportion of lactose at the surface of powder particles produced using N2 injection, with the reverse trend apparent for regular MPC powder particles. Scanning electron microscopy images

	showed breakage and fragmentation of powders into fine and coarse particles. No change in conductivity was recorded following milling, as regular and agglomerated powders released minerals into solution at a higher rate than the corresponding powders produced using N2 injection. The dispersion and solubilisation of all MPC powders were generally lower following the milling process, but still remained higher for those manufactured using N2 injection directly prior to atomisation.	
New Technology	1. Using commercial Matlab software a method was developed to analyse large data sets of information from microscopy images to determine particle rehydration rates, with significant application for commercial samples, even for outside the high protein powder arena. This work is currently submitted for publication. Existing techniques that were tailored for assessing powder functionality: 2. Atomic force microscopy 3. Dynamic mechanical analysis 4. Raman spectroscopy	4
New Industry Collaborations Developed	Abbott nutrition commenced a collaborative research project based on developing high protein ingredients. An EI funded industry project commenced last year with an Irish dairy company and a second project is under evaluation	2

Potential Impact related to Policy, Practice and Other Impacts

Impact	Details
Industry	The methodology developed during DairyDry is now used routinely at Teagasc for assessing commercial powder solubility.
Socio-Economic	This project has furthered the career of PhD graduate Dr. David McSweeney, who has taken up full-time employment with Tirlán (formerly Glanbia) who were one of the partners in the steering committee of DairyDry. Sini Nanadath Shibu took up employment in the Tyndall institute in Cork, while the expertise that Vinay Mishra obtained on atomic force microscopy led him to a position at the University of Southern Denmark. Post-doctoral researcher Valentyn Maidannyk took up employment after DairyDry with Mead Johnson and is currently working with Nestlé.

Dissemination Activities

Activity	Details
Workshops at which results were presented	Tomasz Ochalski International Symposium on Diamonds Films and Functional Devices, November 3-5, 2017, Hangzhou, China Optical characterization of natural and CVD diamonds ad fluorescent nanodiamonds 03/11/17.

Maidannyk V., Roos Y., Auty M Universitas Padjadjaran, Indonesia Strength analysis for understanding structural relaxation in different food systems. CLSM as a method to visualize real-time powder hydration 21st March 2018.

Maidannyk V The 12th European PhD Workshop on Food Engineering and Technology. Berlin, Germany Structural “Strength” concept of various food systems 17-18 April 2018.

Maidannyk V Microscopy/microanalysis Summer School 2018, Liquid Crystal Institute 12-17 July 2018, OH. U.S.A.

Maidannyk V MIAP Zeiss OAD Workshop. , Life Imaging Center, Albert-Ludwigs University Freiburg, Freinburg im Breisgau, Germany. 15-17 October 2018.

Tomasz Ochalski 3rd Workshop Diamond-based nanomaterials and nanostructures for advanced electronic and photonic applications, Leicester, UK The development of nanodiamonf biomarkers - optical properties of CVD diamonds 09/07/18.

Tomasz Ochalski 25th Congress of International Federation for Heat Treatment and Surface Engeenering Invited talk: "Influence of nitrogen implantation on optical properties of CVD bulk diamond and diamond film" 12/09/18.

Agnieszka Furmanâ ITC Carlow at South East Research Sparks event. Developing protein-enriched spray dry dairy powders with optimised hydration properties 12/03/19.

Tomasz Ochalski Photonics West Confreence,San Fran,USA Carrier and refractive index dynamics in core-shell nanolasers grown on silicon during spontaneous and stimulated emission- https://doi.org/10.1117/12.2529494 12/09/19.

Dzianis Saladukha Food&Drink, Dublin 05/09/19.

Dzianis Saladukha, Sini Nanadathshibu , Tomasz J. Ochalski Workshop Birmingham, UK Fluorescence nanodiamonds 19/09/2019.

Dzianis Saladukha Radiate Ion Implamtation, Surey Diamond implantation with variable energy&profile. 20/09/19.

S. NanadathShibu, D. Saladukha, V. Maidannyk, C. M Li and T.J Ochalski IPIC Industry day-Poster presentation, UCC, Cork Raman Spectra of Milk Proteins Enhanced by Nano-Diamonds 05/03/20.

Sini Nanadath Shibu Presented a talk in Tyndall webinar, Tyndall National Institute, Cork Surface chemistry and surface topography studies of high concentration milk protein powders using optical spectroscopy and atomic force microscopy’ 28/05/2020.

Dzianis Saladukha, Sini Nanadathshibu, Tomasz J. Ochalski FIMMWAVE and FIMMPROP training course 28-29/05/20.

	Sini Nanadath Shibu, Dzianis Saladhuka, Nianhua Peng, ChengMing Li, Junjun Wei, Tomasz J. Ochlaski Presented a virtual poster in the UK National Ion Beam Centre -Virtual user day meeting, University of Surrey, UK Au-Ag Ion-implanted Diamond Platform for Surface Enhanced Raman Scattering 09/06/2020.
Seminars at which results were presented	Attendance at 36 national and international events • Oral Presentation/ International Whey Conference 2017. • Oral Presentation/ 2017 ADSA Annual meeting, Pittsburgh, June 25-28. • 46th Annual Food Research Conference, Oral Presentation/ 6-7 December 2017, Teagasc, Dublin, Ireland. • 46th Annual Food Research Conference, Poster Presentation/ 6-7 Dec 2017, Teagasc, Dublin. • 3rd Food Structure and Functionality Forum Symposium & the 3rd IDF Symposium on Microstructure of Dairy Products. Oral presentation/ 3-6 June 2018, Montreal, Canada. • Photonics Ireland 2018. Oral presentation/ 3-5 September, Cork, Ireland. • Euro Food Water 2018. Oral presentation/ 19-21 September. Prague. Czech Republic. • Euro Food Water Poster Presentation/ 2018. 19-21 September. Prague. Czech Republic.. • 2018 Baker Hughes GE X-ray forum, Cincinnati, OH, 16/5/18 • Photonics Ireland Poster Presentation/ 2018 3-5 September, Cork, Ireland. • Photonics Ireland Poster Presentation/ 2018 3-5 September, Cork, Ireland. • Photonics Ireland Poster Presentation/ 2018 3-5 September, Cork, Ireland. • 47th Institute of Food Science and Technology Ireland, Oral Presentation/ 2018 Dec 6-7, University College Cork, Cork, Ireland. • 47th Institute of Food Science and Technology Ireland, Poster Presentation/ 2018 Dec 6-7, University College Cork, Cork, Ireland. • SPIE-Photonics west international conference. Oral Presentation/ -2019, 2-7 February, San-Francisco, California, USA. • 8th International Symposium on Food Rheology and Structure, ETH Zurich, Switzerland, Oral Presentation/ June 17-20, 2019. • 8th International Symposium on Food Rheology and Structure, ETH Zurich, Switzerland, Oral Presentation/ June 17-20, 2019. • SPIE Nanoscience & Engineering Conference-118659) 2019. Oral Presentation/ Sept 12, San Diego, USA. • 2nd Food Chemistry Conference, Poster Presentation/ 2019 Sept. 17-19, Seville, Spain. • 16th Confocal Raman Imaging Symposium. International Conference for Chemical Characterization & Imaging. Ulm, Germany, Poster Presentation/ September 23-25, 2019. • Microscopy & Microanalysis 2019 meeting symposium. Oral Presentation/ August 4-8, 2019 Portland, OR, USA. • 11th NIZO Dairy Conference - Milk Protein Functionality, Poster Presentation/ 8-11th October 2019, The Netherlands. • 11th NIZO Dairy Conference - Milk Protein Functionality, Poster Presentation/ 8-11th October 2019, The Netherlands. • 11th NIZO Dairy Conference - Milk Protein Functionality, Oral and Poster Presentation/ 8-11th October 2019, The Netherlands. • MRS fall meeting -2019, Oral presentation, Dec 1-6, 2019, Boston, USA. • 48th Annual Food Science and Technology Conference, University of Limerick, Oral Presentation/ 16th December 2019.

	• 26th Australian Microscopy and Microanalysis Conference - February 2020, Canberra, AU. • Tyndall Talks/ 12th May 2020. • UKNIBC Virtual User Day/ 16th July 2020. • 4th Food Structure and Functionality Symposium, Cork, Ireland/ Oral Presentation/ 20th October 2020. • 4th Food Structure and Functionality Symposium, 19th to 20th October 2021, Ireland. • 4th Food Structure and Functionality Symposium, online/ 19-20 October 2021. • 4th Food Structure and Functionality Symposium, Cork, Ireland/ Oral Presentation/ 19-20th October 2021 35 EFFoST International Conference, 1-4 November 2021, Lausanne, Switzerland (oral presentation). • Poster presentation at the online Photonics Ireland Conference (14-16 June 2021) Food Science 2022 - Hybrid Edition (Online), Global Conference on food Science and Nutrition.
Media Events	Barry O'Hagan, Tara Moore Radio Ulster, Agri News Interview 07/12/17. Noel McCarthy Irish Food Magazine Dairy Powder Potential (http://www.irishfoodmagazine.com/images/pdf/2018/issue5_2018.pdf); page 40 issue 5 2018)

Knowledge Transfer Activities

Identify knowledge outputs generated during this project.	All the publications generated from DairyDry formed the basis for the knowledge outputs for industry. However, when presenting this data to our industry colleagues the application was emphasised and the benefits directly impacting them were highlighted. 1. Gas injection improves solubility and was very successful 2. Minor changes to ingredient formulation made significant improvements to powder hydration. 3. Polardry technology did not offer a solution for producing highly soluble powders 4. Vacuum-assisted microwave drying was not successful for the application of creating high soluble protein powder. The knowledge generated on these technologies was important to the industry, as a number of them requested us to assess their capability. 5. Atomic force microscopy can give exceptional details on powder particle surface imagery while x-ray microtomography gave a complete image of the internal structure of particles. These techniques showcased to the industry what is available to them during the project but also for their own samples. This was also the case for the environmental scanning electron microscope.
Identify any knowledge transfer activities executed within the project.	Over the course of the project there were numerous meetings with industry to discuss trials, methods and the future direction of the project. This is aside to the plethora of conferences attended. Industry Steering committee meetings 19th of May 2017 17th of May 2018

	27th of August 2019 27th of January 2022 (online) The meeting and presentations were recorded; however, the file is too large to attach, but is available upon request. Photonics Ireland 16-09-2019 Teagasc Gateways 20-11-2018
List any impacts resulting from the knowledge transferred during the project.	One of our partners on the steering committee has since funded 2 projects on aspects of the project with specific relevance for them: the first involving membrane filtration of protein streams and the second on powder solubility. Another partner carried out their own independent trials on gas injection in their commercial plant and assessed the subsequent powder functionality.

Section 3 - Leveraging, Future Strategies & Reference

Leveraging Metrics

Type of Funding Resource	Funding €	Summary
Other	€200,000.00	EI-Industry funding has been obtained for improving fat-filled milk powder solubility. The project is heavily based on the knowledge and methodology from the DairyDry project. Project commenced in 2022. There is also a second project submitted for funding in association with another dairy company. The project is gone through for evaluation. The project revolves around improving powder solubility.
Non-Exchequer National Funding	€136,924.00	A Sympatec Dynamic Image Analyser was secured through the Enterprise Ireland Capital Equipment Call 2020 (€136,924). The Dynamic Image Analyser instrument consists of a modular dispersion system which acts to disperse samples (wet and dry) into a measurement zone where a set of lenses allow an ultra-high-speed camera, supported by an appropriate light source, to capture digital images of every individual particle contained within the sample.

Future Strategies

The issue of powder solubility remains an on-going concern for nutritional dairy companies. As mentioned above there are a number of industry/Enterprise Ireland funded projects based on improving the solubility of nutritional milk powders. We have moved the findings from this project to other applications outside of the dairy industry, particularly to the area of plant protein powders and other novel protein fractions.

Project Publications

1. G. Greene, L. Koolman, P. Whyte, H. Lynch, A. Coffey, B. Lucey, J. Egan, L. O'Connor and D. Bolton (2020). An in vitro investigation of the survival and/or growth of Campylobacter jejuni in broiler digestate from different feed types. Letters in Applied Microbiology, 72 (1), 36-40.

2. G. Greene, L. Koolman, P. Whyte, H. Lynch, A. Coffey, B. Lucey, L. O'Connor and D. Bolton (2021). Testing barrier materials in the development of a biosecurity pen to protect broilers against Campylobacter. Food Control, 128, 108172. doi.org/10.1016/j.foodcont.2021.108172.
3. G. Greene, L. Koolman, P. Whyte, H. Lynch, A. Coffey, B. Lucey, J. Egan, L. O'Connor and D. Bolton (2021). Maximising productivity and eliminating Campylobacter in broilers by manipulating stocking density and population structure using 'biosecurity cubes'. Pathogens, 10, 492.https://doi.org/10.3390/pathogens10040492.
4. G. Greene, L. Koolman, P. Whyte, H. Lynch, A. Coffey, B. Lucey, J. Egan, L. O'Connor and D. Bolton (2021). The efficacy of organic acid, medium chain fatty acid, and essential oil based broiler treatments; in vitro anti-Campylobacter jejuni activity and the effect of these chemical-based treatments on broiler performance, Journal of Applied Microbiology, 132 (1), 687-695.
5. Lynch C, Hawkins K, Lynch H, Egan J, Bolton D, Coffey A, Lucey B. (2019). Investigation of molecular mechanisms underlying tetracycline resistance in thermophilic Campylobacter spp. suggests that previous reports of tet(A)-mediated resistance in these bacteria are premature. Gut Pathogens 2019;11(1):56; doihttp://dx.doi.org/10.1186/s13099-019-0338-1.
6. Caoimhe Lynch , Helen Lynch, John Egan, Paul Whyte , Declan Bolton , Aidan Coffey, Brigid Lucey (2019).Antimicrobial resistance of Campylobacter isolates recovered from broilers in Ireland in 2017 and 2018: an update. British Poultry Science, 15, 1-7.
7. Caoimhe T Lynch, Helen Lynch, Sarah Burke, Kayleigh Hawkins, Colin Buttimer, Conor Mc Carthy, John Egan, Paul Whyte, Declan Bolton, Aidan Coffey, Brigid Lucey (2020) Antimicrobial resistance determinants circulating among thermophilic Campylobacter isolates recovered from broilers in Ireland over a one-year period. Antibiotics 2020, 9, 308; doi:10.3390/antibiotics9060308.
8. Emanowicz, M., Meade, J., Bolton, D., Golden, O., Gutierrez, M., Byrne, W., Egan, J., Lynch, H., O'Connor, L., Coffey, A., Lucey, B., Whyte, P. (2020). The impact of key processing stages and flock variables on the prevalence and levels of Campylobacter on broiler carcasses. Food Microbiol. 2021 May;95:103688. doi:10.1016/j.fm.2020.103688. Epub 2020 Nov
9. Emanowicz, M., Meade, J., Burgess, C., Bolton, D., Egan, J., Lynch, H., O'Connor, L., Coffey, A., Lucey, B., Golden, O., Gutierrez, M., Byrne, W., Whyte, P. (2021). Antimicrobial resistance and genomic diversity of Campylobacter jejuni isolates from broiler caeca and neck skin samples collected at key stages during processing. Food Control, 135 108664. doi.org/10.1016/j.foodcont.2021.10866410. 2021.108664.
10. Lynch, C.T., Buttimer, C., Epping, L., O'Connor, J., Walsh, N., McCarthy, C., O'Brien, D., Vaughan C., Semmler, T., Bolton, D., Coffey, A., Lucey, B. (2022) Genomic comparison of two Campylobacter fetus isolates from a case of relapsed prosthetic valve endocarditis. Pathogens and Disease,;79(9):ftab055. doi:10.1093/femspd/ftab055.
11. Lynch, H., Franklin-Hayes, P., Koolman, L., Egan, J., Bolton, D., Reid, P., Coffey, A., Lucey, B., O'Connor, L., Unger, K., Whyte, P. (2022). Prevalence and levels of Campylobacter in broiler batches and carcasses in Ireland in 2017-2018. International Journal of Food Microbiology, 372, 2022, 109693, ISSN 0168-1605,https://doi.org/10.1016/j.ijfoodmicro.2022.109693.
12. Book chapter: Whyte, P., Bolton, D., Pedros-Garrido, S., Lynch, H., Emanowicz, M., Greene, G., Fanning, S., (2022). Campylobacter spp. In: McSweeney, P.L.H., McNamara, J.P. (Eds.), Encyclopedia of Dairy Sciences, vol. 4. Elsevier, Academic Press, pp. 419–430. https://dx.doi.org/10.1016/B978-0-08-100596-5.00984-7. ISBN: 9780128187661.