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

Food Institutional Research Measure

Final Report

Manufacture, application and assessment of smart packaging concepts consisting of novel nanoparticles technologies (metal- and non-metal based) in conventional food packaging systems (SMARTPACK2)

DAFM Project Reference No: 11/F/038

Start date: 01/03/2013

End Date: 31/03/2017

Principal Coordinator and Institution: Dr Malco Cruz-Romero; [1]Food Packaging Group, School of Food & Nutritional Sciences, University College Cork, Cork.
Email: m.cruz@ucc.ie

Collaborating Research Institutions and Researchers: Prof. Joe Kerry, Food Packaging Group, School of Food & Nutritional Sciences, University College Cork, Cork; Prof. Enda Cummins, UCD School of Biosystems and Food Engineering, Agriculture and Food Science Centre, Belfield, Dublin 4; Prof. Michael Morris, Advanced Materials and Bioengineering Research (AMBER) and School of Chemistry, Trinity College Dublin, College Green, Dublin 2.

Please place *one* "x" below in the appropriate area on the research continuum where you feel this project fits

Basic/Fundamental → Applied → Pre Commercial

1	2	3	4X	5	6	7

Please specify priority area(s) of research this project relates to from the National Prioritisation Research Exercise* (NRPE) report.

Priority Area (s)	**I Sustainable Food Production and Processing; L Manufacturing Competitiveness; M Processing Technologies and Novel Materials**

Key words: *Nanomaterials, Smart packaging, antimicrobial active packaging, metal- and food-derived nanoparticles*

1. Rationale for Undertaking the Research

Antimicrobial active packaging is a promising form of smart packaging especially for food products. Since microbial contamination of most food products occurs primarily at the surface, due to post-process handling, attempts have been made to improve safety and to delay spoilage by the use of antibacterial sprays or dips. Limitations of such antibacterials include neutralisation of compounds on contact with the food surface or diffusion of compounds from the surface into the food product mass. Incorporation of bactericidal agents into food products, such as meat for example, may result in partial inactivation of the active compounds by meat constituents and therefore, exert a limited effect on surface microflora. To confer antimicrobial activity to packaging materials, antimicrobial agents may be coated, incorporated, immobilised, or surface modified onto package materials.

Interestingly, while many substances have been identified as antimicrobials and their potential use in packaging materials championed, very few of these substances have been researched in any significant way to ascertain their true potential and consequently, have received very little commercial attention. The same can be said of NP application to packaging materials. Clearly, scientific attention needs to focus on exploring the full potential that NP technology and its application has to offer in terms of improving food quality, sensory evaluation, safety and shelf-life during packed storage. The inclusion of novel antimicrobial nanoparticles into- or onto-food packaging materials have also the potential to reduce food waste.

While the development of novel antimicrobial packaging materials containing NPs possess enormous potential, it needs to be scrutinised in terms of health and safety issues. Concerns around metal-toxicity, NP migration, source and form all need to be carefully and adequately addressed. Additionally, use of NPs in packaging must not only be sufficiently safe and active for optimised function, but must also be commercially viable.

When issues of active functionality, safety and commercial viability have been ultimately addressed, development of antimicrobial active packaging materials containing NPs derived from numerous sources (food and non-food) will assist in the delivery of safer consumer foods, possessing extended shelf-lives. Additionally, the use of such materials will enhance production processes and provide food companies with a competitive advantage when it comes to moving product through the distribution chain, especially to overseas markets, where transport and storage conditions can be challenging and food products experience both handling and temperature abuse.

The application of novel nanotechnologies in the food industry has the potential to improve many aspects of the farm-to-fork lifecycle. In particular food packaging containing antimicrobial nanocoatings have the potential to reduce microbial spoilage and prolong the shelf life of food. The nanocoatings ability to extend food shelf life would allow the food to be sold into new markets. In addition, extending food shelf life would reduce food waste which could benefit the consumer by improving the security of the world's food supply, while also reducing associated environmental impacts. SMARTPACK2 investigated the possibility of producing novel forms of NPs created from food ingredients possessing antimicrobial properties. SMARTPACK2 also assessed NP-treated packaging materials (both metal-based- and non-metal-based-NPs) for application to both internal/external surfaces of packaging materials and these assessed for antimicrobial potential. Additionally, all developed nanocomposite films were assessed in terms of their effects on food quality preservation, shelf-life extension and toxicology. As the uptake of these novel technologies is dependent on the elucidation of uncertainties regarding the potentially enhanced mobility of nanoparticles within packaging and the human body, bioaccumulation and heightened toxicity caused by their physicochemical properties. Therefore, SMARTPACK2 also investigated experimental and modelling strategies for the migration and human exposure assessment of nanoparticles released from antimicrobial nanocoatings into food.

2. Research Approach

Our approach was to take state-of-the-art NPs research evolving from the work conducted in the FIRM funded SMARTPACK project for the synthesis and characterisation of NPs and combine with standard polymer film technologies to create new antimicrobial active packaging materials. The SMARTPACK2 project investigated new approaches to attaching metal- and food-derived NPs to commercially available polymer film packaging materials using various chemical approaches. The novel antimicrobial active packaging materials were then characterized on the basis of their antimicrobial properties and their effects on the mechanical and barrier properties of the active packaging materials. Additionally, this proposal looked at the possibility of creating active NPs from food ingredients naturally possessing antimicrobial properties (chitosan and plant derived essential oils). The created NPs materials were attached to packaging film materials after chemical surface modification of the films. Throughout the project, all packaging materials were continuously improved through cycles of testing and synthesis. The developed packaging materials were used in vivo to extend the shelf life of muscle-based food products. The potential migration of the coated NPs were quantified and characterised from a range of nanocoatings (spin, layer-by-layer, spray and direct coatings) on a number of polymer packaging materials (low density polyethylene, polyester and polystyrene). Both experimental methods and simulation techniques were used to gain an understanding of the mechanisms governing migration and to evaluate human exposure to migrant nanoparticles. Migration studies were performed on the nanocoated packaging under aggressive testing conditions according to EU Regulation No. 10/2011 and under real use conditions (i.e. when used in the hypothetical scenario as milk packaging). Due to a shortfall in analytical methodologies for the quantification and characterisation of nanoparticle migration, operating procedures for novel techniques such as cryogenic transmission electron microscopy and nanoparticle tracking analysis were developed to enable migration assessment. In addition, a suite of complementary techniques such as scanning electron microscopy with energy dispersive x-rays and inductively coupled plasma-atomic emission spectroscopy were also used. To evaluate nanoparticle migration, novel simulation techniques such as empirical desorption models and artificial neural networks were developed to gain an understanding of factors that influence migration and predict how nanoparticles interact with the food and food packaging. Using the migration study results, predictive human exposure models were developed to evaluate the human exposure to nanoparticles migrating from the antimicrobial nanocoatings. Toxicity testing for materials containing NPs was also carried out.

3. Research Achievements/Results

Metal- (Silver (Ag), copper (Cu) and zinc oxide (ZnO)) and food-derived (chitosan and essential oil) nanoparticles (NPs) were successfully synthesized and their antimicrobial activity assessed. From the antimicrobial test, Ag NPs showed the best antimicrobial effects against a wide range of test microorganisms: *Staphylococcus aureus, Bacillus cereus, Escherichia coli* and *Pseudomonas fluorescens* as well as microflora isolated from raw chicken breast fillets (CBF), raw beef and cooked ham. Therefore, further investigation into the development of antimicrobial Ag NPs were then employed to manufacture antimicrobial films *via* solvent casting, extrusion or coating techniques. Subsequently, the resulting films were assessed in terms of their mechanical, thermal, barrier and antimicrobial properties.

Commercial polymer films such as low density polyethylene (LDPE), composite LDPE with 4% ethylene vinyl acetate (LDPE-EVA) or polypropylene (PP)) are hydrophobic in nature and chemically inert, thereby making such films unreponsive to the attachment of antimicrobials onto the surface of the films. Therefore, surface modification of the polymer films using strong oxidising solutions (piranha solutions) or UV/ozone treatment was carried out to increase wettability and attachment of Ag. In general, the mechanical and thermal properties of the active films were dependent upon the type of polymer and method employed to incorporate Ag NPs. The manufactured Ag- active films were then tested on CBF and results showed that, regardless of the method used (solvent casting, extrusion or coating), the shelf-life of CBF was significantly extended. UV/ozone treatment increased the wettability of commercial polymer films compared to piranha solutions as shown by toluidine blue O (TBO) assay and FTIR analysis. Furthermore, antimicrobial activity of the Ag-coated LDPE films increased with increased exposure time to UV/ozone.

Novel methods to manufacture Ag- coated films were developed using self-assembled polystyrene-*b*-polyethylene (PS-*b*-PEO) block copolymer (BCP) and layer-by-layer (LbL) application. *In vitro* antimicrobial testing showed that Ag-active films had good antimicrobial activity against Gram-positive and Gram-negative bacteria. However, these coating methods were not easy to scale-up for shelf-life testing purposes. For this reason, a simple process for producing robust Ag-coated films was developed that allowed surface-modification of commercial LDPE films so that a well-defined antimicrobial surface could be prepared using Pluronic™ surfactant and PS-*b*-PEO BCP. The Pluronic™ surfactant provide a surface that is more readily functionalised, whilst BCP provides a reactive interface which is important in providing a route to Ag NPs that are well adhered to the film surfaces. Because of the simplicity of the methods developed, this technique did not have a film size limitation. The resulting active films showed good antimicrobial activity, but results obtained were dependent upon the initial concentration of Ag precursor used and the number of Ag coatings applied. Generally, Gram-negative bacteria were more susceptible to Ag NPs compared to Gram-positive bacteria and that pure culture bacteria were more susceptible than microflora isolated from meat products. The Ag-active films developed in this thesis have the potential to be used as antimicrobial packaging in food packaging applications.

The developed FDNPs have been shown to exhibit antimicrobial activity against common food borne pathogens and have potential to be incorporated into antimicrobial active packaging systems which in turn could be used to reduce microbial contamination of perishable food products extending shelf life beyond current maximum dates and maintaining freshness. The coating techniques employed herein show that these may be commercially viable and could be used on an industrial level, while retaining the barrier properties of commercially available material.

Toxicity of NPs was analyzed using a multi-parametric cell energy budget (CEB) approach for assessing the roles of different factors in cell bioenergetics. The tests identify metabolic abnormalities associated with a particular protein, gene mutation, drug treatment or disease state. Results indicated that NP have negligible cytotoxicity (including mitochondrial toxicity) in the range of 0-8 µg/ml. In cells loaded with 8 µg / ml NP, it was observed only minor decrease in protein and ATP levels (upon FCCP treatment), and a minor increase in the ratio between L-ECA in mock and FCCP-treated cells (from 0.57 to 0.61). Cell viability dramatically decreased in the samples treated with 24 µg / ml NP. This caused strong reduction of cell biomass (including massive decrease in cell number), ATP levels and the rate of lactate extrusion. Based on this test, we can conclude that Ag NP may be used for loading of HCT116 cells in the range of 0-8 µg/ml for 24 h. The MARA toxicity test system was also used to determine the Microbial Toxic Concentration (MTC) measure the growth inhibitory concentration of the nanomaterial.

The uptake of novel antimicrobial nanocoatings for food packaging applications by the food industry, the consumer and regulatory authorities is obstructed by uncertainties which surround nanoparticle behaviour in food packaging and the human body. This project investigated the potential migration of nanoparticles from nanocoated food packaging and subsequent human exposure with an aim to alleviate some of these uncertainties. The use of mathematical models in conjunction with experimental migration studies outlined environmental factors such as time, pH and temperature that could influence nanoparticle migration. In addition, these models outlined nanocoating factors such as surface treatments that could be used to reduce nanoparticle migration. The experimental procedures and mathematical models developed in this project provide the food industry with tools for the development and safety assessment of nanoparticle food packaging. The mathematical models developed for the desorption of nanoparticles from surface coatings are the first of their kind and provide useful tools for industry, academia and regulatory authorities. The experimental techniques which include, cryogenic transmission electron microscopy and nanoparticle tracking analysis, have not previously been used for migration testing and adds to the limited number of analytical techniques available.

The human exposure scenarios documented in this project, which includes total dissolution of the nanoparticles before human consumption and stability of nanoparticles prior to consumption, provide regulatory authorities with case studies in support of recent guidance documents on the risk assessment of nanotechnologies use in food. Furthermore, the evaluations performed for human exposure to nanosilver and nanocopper in food originating from nanocoatings may aid regulatory authorities when developing migration limits for nanoparticle release from food packaging, for which there are currently none available. Given the fundamental nature of the research conducted, this project may help to alleviate certain concerns experienced by consumers related to potential nanoparticle migration and outlines scenarios were human exposure presents low levels of concern. It therefore provides the consumer with valuable information and may assist them when making an informed decision on its use.

4. Impact of the Research

In present times, factors such as rising concerns towards food wastage and growing consumer awareness about health-related issues are demonstrating an increased demand towards antimicrobial active packaging. The Food & Agriculture Organisation (FAO) reported that in recent years, progress has been made globally in establishing sustainable food production systems aimed at improving food and nutrition security and the judicial use of natural resources. However, all of those efforts are in vain when the food produced in those systems is lost or wasted and never consumed. As food wastage increases in parallel with production increases, it becomes even more important to recognise that reducing food wastage must be part of any effort aimed at sustainable production and food security (FAO, 2014). In addition to this,

there also are environmental repercussions, including all of the natural resources used and greenhouse gases emitted during the production or disposal of food that is not consumed (FAO, 2014). Approximately 1/3 or over 1.3 billion metric tons of all edible food produced for human consumption is lost annually throughout the supply chain (FAO, 2011). The application of nanotechnologies in food packaging materials has the potential to tackle current food industry issues such as shelf life extension, increased safety and food waste reduction while also reducing associated environmental impacts.
This project synthesised metal and food grade antimicrobial nanoparticles and used different attachment methods to developed antimicrobial nanocomposite materials with good antimicrobial activity and when the developed antimicrobial nanocomposite packaging films were used for packaging food products it extended significantly the shelf life of the food products which can help to reduce food waste and enhance sustainability of food production. Despite these benefits of the antimicrobial nanoparticles, for the uptake by the food industry of these novel antimicrobial nanocomposite materials for food packaging applications, consumer and regulatory authorities' uncertainties regarding health and safety issues needs to be elucidated as nanoparticle behaviour in food packaging and the human body is unknown. This project investigated the potential migration of nanoparticles from nanocoated food packaging films and subsequent human exposure with an aim to understand the nanoparticle behaviour in food packaging applications and alleviate some of these uncertainties and concerns. Mathematical models in conjunction with experimental migration studies to assess the influence of environmental factors such as time, pH and temperature on the antimicrobial nanoparticle migration were developed. In addition, these models also included other factors such as surface treatments used for attachment of the antimicrobial nanoparticles that could be used to reduce nanoparticle migration. The experimental procedures and mathematical models developed in this project for the desorption of antimicrobial nanoparticles from surface coatings are the first of their kind and provide useful tools for the food industry, academia and regulatory authorities for safety assessment of nanocoated antimicrobial food packaging. Experimental techniques used in this project which include, cryogenic transmission electron microscopy and nanoparticle tracking analysis, have not previously been used for migration testing and adds to the limited number of analytical techniques available for assessing migration of nanoparticle materials.
The human exposure scenarios documented in this project, which includes total dissolution of the nanoparticles before human consumption and stability of nanoparticles prior to consumption, provide regulatory authorities with case studies in support of recent guidance documents on the risk assessment of nanomaterials used in food applications and the data generated in this project may alleviate certain concerns experienced by consumers related to potential nanoparticle migration and outlines scenarios were human exposure presents low levels of concern providing consumers with valuable information which may assist in making an informed decision on its use.

4(a) Summary of Research Outcomes

(i) Collaborative links developed during this research

During the lifespan of this research project, collaborative links with AMBER research centre, Trinity College Dublin and Versatile Packaging Ltd were developed and this collaboration is ongoing.

(ii) Outcomes where new products, technologies and processes were developed and/or adopted

Given the number of publications that cite antimicrobial food packaging as one of the main applications for nanotechnology and nanomaterials in the agriculture, feed and food sectors, it is then rather surprising to find that the number of publications which report the application of antimicrobial nanocomposite materials for the purposes of extending the shelf-life or improving the safety of actual packaged food components, especially for muscle-based food products, is surprisingly small. The data generated in the SMARTPACK2 project add to the publications on novel coating technologies and the application of these antimicrobial coated materials to extend the shelf life of food products.
The outcomes of the research documented in this study are fundamental in nature and forms a foundation for the food industry, regulatory authorities and the scientific community to develop and assess the safety of novel nanoparticle coatings for food packaging applications. The project developed experimental procedures and modelling techniques which are useful tools for the safety assessment of these novel

nanomaterials. The study also demonstrates modelling methodologies that can be used to engineer the nanocoatings for potential commercial applications through the use of surface treatments. The proposed modelling techniques in conjunction with experimental methodologies have the potential to reduce the burden associated with the European Commission's case-by-case testing strategy for nanomaterials and could reduce costs incurred by the food industry associated with the development of these novel materials.

(iii) Outcomes with economic potential

Shelf life extension of food products is required throughout the food cold chain. Extended shelf life of food products would make a very big difference to food producers, give competitive advantage for the internal and export market. The results generated in this project prove that metal based and food grade antimicrobials can extend significantly the shelf life of food products. As we wanted to test and show that the technology developed work on a most challenging situations; therefore, chicken meat was used for some of the experimental trials with meat products owing to its high microbial burden and relatively short shelf-life. While significant shelf life increase was obtained wit Ag-LDPE nanocomposite active packaging films, a lot of work needs to be carried out to demonstrate that Ag antimicrobial active packaging is safe to be used and comply with the food regulation framework. However, for food grade nanoparticles there is huge potential for immediate application as there are not many safety issues with the regulation framework as it is for metal-based active antimicrobial packaging. On application to chicken and cheese, dipping solutions and films containing food grade nanoparticles have demonstrated efficacy against fungal growth, Gram-negative and Gram-positive bacteria and extended the shelf life and safety of food products. Antimicrobial active packaging technology within the food sector has been shown to be both necessary and consumer acceptable, provide a range of functionalities specifically applicable and beneficial to food products, proven successful in *in vitro* operations and validated in application to food products. The use of antimicrobial nanocomposite packaging films have the potential to be used as one element in the hurdle technology approach with the specific aim to reduce spoilage microorganism or risk of pathogenic microorganism and increase the shelf-life of food products, especially on the highly perishable food such as chicken breast fillets. The developed antimicrobial active packaging look promising, potentially it can gain wide use in the food packaging industry and hence it is considered of high relevance and of significant utility.

Novel methods of coating and insertion of nanomaterials onto/into packaging film have been developed in this project, and these coating methods can easily scaled-up and open potential commercial application of the developed antimicrobial packaging materials. The findings of this research will add to the scientific understanding the effects of coating metal or food grade antimicrobial nanoparticles on the film properties and their effects on shelf life extension. The data generated in this project are of interest for the scientific community, food packagers and packaging producers.

(iv) Outcomes with national/ policy/social/environmental potential

The food industry is looking for to reduce manufacturing waste and to adopt a more sustainable manufacturing approach. The developments of technologies which can assist food manufacturers to address these demands are important. Antimicrobial active packaging is one such approach that might enable packaged food products to have extended shelf-life and/or improve microbial food safety. The SMARTPACK2 project developed antimicrobial active packaging materials which are novel and offer a broad range of applications to increase shelf life and safety of food products in a cost-effective manner. As most of the contamination of food products occurs on the surface of the food due to the post-process handling; therefore, the use of the developed antimicrobial active packaging films to package food products could delay or inactivate the microorganisms present on food surfaces; thereby leading to prolonged product shelf life and reduced food waste. Food packaging materials containing antimicrobial nanocoatings developed in this project have the potential to reduce microbial spoilage and prolong the shelf life of foods; hence, reducing food waste and improving sustainability of food production. Nanotechnology is seen as one possible way to increase the antimicrobial properties of packaging materials. Through shelf-life extension of food products, a reduction in retailer supply chain wastage of these products can be achieved, improving sustainability. The outcomes of the SMARTPACK project have strong strategic impact on: 1) Food Packaging industry, 2) Antimicrobial packaging, 3) sustainability, 4) packaging technology development, 5) food safety and public health, 6) Food waste reduction, 6) society, 7) education and training of young scientists, and obviously 8) Science.

4 (b) Summary of Research Outputs

(i) Peer-reviewed publications, International Journal/Book chapters.

Rodríguez-Calleja, J.M., Cruz-Romero, M.C., García-López, M.L. and Kerry J.P. (2014). Antimicrobial and antioxidant activities of commercially available essential oils and their oleoresins. Research & Reviews: Journal of Herbal Science 3(3), 1-11.

Azlin-Hasim, S., Cruz-Romero, M., Ghoshal, T., Morris, M., Cummins, E. and Kerry J.P. (2015) Application of silver nanodots for potential use in antimicrobial packaging applications. Innovative Food Science and Emerging Technologies 27, 136-143.

Azlin-Hasim, S., Cruz-Romero, M., Morris, M., Cummins, E. and Kerry J.P. (2015) Effects of a combination of antimicrobial silver low density polyethylene nanocomposite films and modified atmosphere packaging on the shelf life of chicken breast fillets. Food Packaging and Shelf Life 4, 26-35.

Hannon, J.C., Kerry, J., Cruz-Romero, M., Morris, M. and Cummins, E. (2015). Advances and challenges for the use of engineered nanoparticles in food contact materials. Trends in Food Science and Technology 43, 43-62.

Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. (2016) Assessment of the migration potential of nanosilver from nanoparticle-coated low-density polyethylene food packaging into food simulants. Food additives and contaminants: Part A 33(1),167-178.

Azlin-Hasim, S., Cruz-Romero, M., Morris, M., Cummins, E. and Kerry J.P. (2016) The potential use of a layer-by-layer strategy to develop LDPE antimicrobial films coated with silver nanoparticles for packaging applications. Journal of Colloid and Interface Science 461, 239-248.

O'Callaghan, K. A. M. and Kerry, J. P. (2016) Preparation of low and medium molecular weight chitosan nanoparticles and their antimicrobial evaluation against various microorganisms including cheese-derived cultures. Food Control 69, 256-261.

Azlin-Hasim, S., Cruz-Romero, M., Morris, M.A., Padmanabhan, S.C., Cummins, E. and Kerry J.P. (2016). The potential application of antimicrobial silver polyvinyl chloride nanocomposite films to extend the shelf-life of chicken breast fillets. Food and Bioprocess Technology 9, 1661-1673.

Hannon, J.C., Kerry, J.P., Cruz-Romero, M., Azlin-Hasim, S., Morris, M. and Cummins, E. 2016. Human exposure assessment of silver and copper migrating from an antimicrobial nanocoated packaging material into an acidic food simulant. Food and Chemical Toxicology 95, 128-136.

Cruz-Romero, M. and Kerry, J. 2017. Packaging systems and materials used for meat products with particular emphasis on the use of oxygen scavenging systems. In Enda Cummins and James Lyng (Eds), Emerging technologies in meat processing (pp. 233-263). Oxford: Wiley-Blackwell.

Cushen, M and Cummins, E.J. 2017. Smart Packaging solutions encompassing nanotechnology. In Enda Cummins and James Lyng (Eds), Emerging technologies in meat processing (pp. 265-284). Oxford: Wiley-Blackwell.

Morris, M.A., Padmanabhan, S.C., Cruz-Romero, M.C., Cummins, E. and Kerry J.P. (2017). Development of active, nanoparticle, antimicrobial technologies for muscle based packaging applications. *Meat Science* 132, 163-178.

Hannon, J., Kerry, J., Morris, M., Cruz-Romero, M., Azlin-Hasim, S., and Cummins, E. (2017) Kinetic desorption models for the release of nanosilver from an experimental nanosilver coating on polystyrene food packaging. *Innovative Food Science & Emerging Technologies 44, 149-158.*

Hannon, J., Kerry, J., Morris, M., Cruz-Romero, M., Azlin-Hasim, S., and Cummins, E. (2017) Migration assessment of silver from nanosilver spray coated low density polyethylene or polyester films into milk. Food Packaging and Shelf Life, 15, 144-150

Hannon, J., and Cummins, E. (2017) Nanotechnology in Food: from Farm to Fork. In Rai, V.R and Bai, J.A. (Eds), Trends in *Food Safety and Protection* (pp. 95-118). Boca Raton: CRC Press.

Clarke, D., Tyuftin, A.A., Cruz-Romero, M.C., Bolton, D., Fanning S., Pankaj S.K., Bueno-Ferrer, C., Cullen, P.J. and Kerry, J.P. (2017). Surface attachment of active antimicrobial coatings onto conventional plastic-based laminates and performance assessment of these materials on the storage life of vacuum packaged beef sub-primals. *Food Microbiology* 62, 196-201.

Sullivan, D., Cruz-Romero, M.C, Azlin-Hasim, S., Kerry, J.P and Morris, M.A. (2017). Natural antimicrobials for use in food packaging. In Atul Tiwari (Ed.), *Handbook of Antimicrobial coatings* (pp. 181-234). Oxford: Elsevier Inc.

Cruz-Romero, M.C. and Kerry, J.P (2017). Packaging systems and materials used for meat products with particular emphasis on the use of oxygen scavenging systems. In Enda Cummins and James Lyng (Eds), *Emerging technologies in meat processing* (pp. 229-259). Oxford: Wiley-Blackwell.
Garvey M, Padmanabhan SC, Pillai SC, Cruz-Romero, M., Kerry, J.P. and Morris, M. 2017. *In Vitro* Cytotoxicity of Water Soluble Silver (Ag) Nanoparticles on Hacat and A549 Cell Lines. *Journal of Toxicology and Pharmacology* 1:016.
Sullivan, D., Cruz-Romero, M.C, Kerry, J.P and Morris, M.A. 2018. Synthesis of monodisperse chitosan nanoparticles. *Food Hydrocolloids* 83, 355-364.
Azlin-Hasim, S., Cruz-Romero, M.C., Cummins, E., Kerry J.P. and Morris, M.A. 2018. Spray-coating application for the development of nanocoated antimicrobial LDPE films to increase the shelf-life of chicken breast fillets. *Food Science and Technology International* 24(8), 688-698.
Cruz-Romero, M.C., Kerry, J.P and Morris, M.A. 2018. Food Packaging: Surface Engineering and Commercialization. In Miguel Cerqueira, Antonio Vicente, Lorenzo Pastrana and Jose Maria Lagarón (Eds) *Nanomaterials for Food Packaging* (pp. 301-328). Oxford: Elsevier Inc.
Cruz-Romero, M.C., Kelly, C.A., Papkovsky, D. and Kerry, J.P. 2018. Applications of phosphorescent O_2 sensors in food and beverage packaging systems. In Dmitri B. Papkovsky and Ruslan I. Dmitriev (Eds) Quenched-phosphorescence detection of Molecular Oxygen (pp. 335-360). Cambridge: Royal Society of Chemistry.

(ii) Popular non-scientific publications and abstracts including those presented at conferences
http://www.foodpackagingforum.org/news/review-on-engineered-nanoparticles-in-fcms
Hannon, J., Cruz-Romero, M., Morris, M., Kerry, J., Cummins, E. (Dec. 2014) Migration Assessment of Nanosilver Coated Low Density Polyethylene with Potential Application in the Food Industry. *43rd Annual Food Research Conference*, UCD, Dublin, *43, pp. 58-59* (Oral Presentation). Award for Best Oral Presentation in the thematic area of Food Safety awarded by SafeFood.
Hannon, J., Cummins, E. (2014) Metal and Non-metal Nanoparticle Migration Potential and Human Exposure Assessment. 2nd Food Integrity and Traceability Conference *ASSET'2014 Conference*, QUB, 8th-10th April 2014, Belfast: UK.
Padmanabhan, S.C., Azlin-Hasim, S., Cruz-Romero, M.C., Morris, A., Cummins, E. and Kerry, J.P. The modification of polyvinyl acetate (PVAc) substrates and their improved antimicrobial activity for use in antimicrobial active packaging applications. International Conference on Food Safety and Regulatory Measures. 17th – 19th August 2015. Birmingham, United Kingdom.
Sullivan, D., Cruz-Romero, M., Morris, M., Cummins, E. and Kerry J.P. Development of size controlled chitosan nanoparticles for anti-microbial food packaging applications. European Research Materials Society (E-MRS), 11th-15th June 2015. Lille, France.
Sullivan, D., Cruz-Romero, M., Morris, M., Cummins, E. and Kerry J.P. Development of size controlled chitosan nanoparticles for anti-microbial food packaging applications. 67th Irish Universities Chemistry Research Colloquium, 25th-26th June 2015. Maynooth, Ireland
Hannon, J., Kerry, J.P., Cruz-Romero, M., Morris, M and Cummins, E. Migration Assessment of Nanoparticulate Silver, Copper and Gallium from an Experimental Nanoparticle/PS-b-PEO Coated Food Packaging. 19th Annual Biosystems Engineering Research Seminar, University College Dublin, 12th March 2015, Dublin, Ireland.
Azlin-Hasim, S., Cruz-Romero, M., Morris, M., Cummins, E. and Kerry J.P. (2015). The potential use of layer-by-layer strategy to develop LDPE antimicrobial films coated with silver ion for food packaging applications. The 3rd International Meeting on Packaging Material / Bioproduct Interactions (MATBIM 2015), 17th-19th June 2015, Zaragoza, Spain.
Cruz-Romero, M., Morris, M., Rabe, J., Cummins, E. and Kerry J.P. (2015). Development of active antimicrobial and antioxidant nanocomposite gelatine films containing food grade nanosolubilisates for potential use in food applications. The 3rd International Meeting on Packaging Material / Bioproduct Interactions (MATBIM 2015), 17th-19th June 2015, Zaragoza, Spain.
Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. Characterisation and assessment of the migration of nanosilver from a nanoparticle coated low density polyethylene food packaging. Innovations in Food Packaging and Shelf Life, O4.4, 15-17th September 2015, Munich, Germany.

Cruz-Romero, M., Lechenet, H., Morris, M., Cushen, M., Cummins, E. and Kerry, J.P. 2013. Effects of particle size of silver nanoparticles on their antimicrobial properties. EUROFOODCHEM XVII. May 07-10, Istanbul, Turkey.

Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. Migration Assessment of Chitosan Nanoparticles from an Experimental Nanoparticle/Dip and Spin Coated Food Packaging Annual Biosystems Engineering Research Seminar 21, Dublin, Ireland, pp. 28-32, 12th March 2016.

Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. Artificial Neural Networks as a Tool to Predict the Migration of Silver from Antimicrobial Nano-coated LDPE Films FOODSIM'2016, Catholic University Louvain, Ghent, Belgium, pp. 38-43, 3-7th April 2016.

Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. 2016. Safety assessment of antimicrobial polystyrene coated with silver nanoparticles for potential packaging applications 18th World Congress of Food Science and Technology, IUFoST'2016, August 21st-25th, Dublin, Ireland.

Azlin-Hasim, S, Cruz-Romero, M.C., Morris, M.A., Cummins, E. and Kerry, J.P. 2016. Surface modification of commercial LDPE films to improve attachment of silver for the development of antimicrobially-active packaging. 18th World Congress of Food Science and Technology, IUFOST 2016. August 21st-25th, Dublin, Ireland.

Tiuftin, A.A., Clarke, D., Cruz-Romero, M.C., Bolton, D., Fanning S., Pankaj S.K., Bueno-Ferrer, C., Cullen, P.J. and Kerry, J.P. (2016). Potential use of gelatin as a carrier of active antimicrobials to develop antimicrobial coated conventional plastic-based laminates and their performance assessment on the storage life of vacuum packaged beef sub-primals. 18th World Congress of Food Science and Technology, IUFOST 2016. August 21st-25th, Dublin, Ireland.

Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. 2016. Migration and human exposure assessment of silver from an antimicrobial spray coated low density polyethylene nanocomposite material into milk. Food Chemistry and Hydrocolloids, Toronto, Canada, 28-30th August 2016.

Hannon, J., Kerry, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M. and Cummins, E. Migration assessment of chitosan nanoparticles from a spin coated antimicrobial packaging material 30th EFFoST'2016, Vienna, Austria, pp. 33, 28-30th November 2016.

(iii) National Report -N/A

(iv) Workshops/seminars at which results were presented

1. Hannon, J., Kerry, J., Cruz-Romero, M., Morris, M. & Cummins, E. (May 2014) Potential for Mathematical Nanoparticle Migration Predictive Models to be used for Compliance Purposes. *UCD Biosystems Engineering Research Review 19*, pp. 17-20. (http://hdl.handle.net/10197/5672).
2. Hannon, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M., Kerry, J., Cummins, E. (May 2015) Migration Assessment of Nanoparticulate Silver, Copper and Gallium from an Experimental Nanoparticle/PS-b-PEO Coated Food Packaging. *UCD Biosystems Engineering Research Review 20*, 25-28. (http://hdl.handle.net/10197/6758). Award for Best Oral Presentation PhD year 1-2.
3. Hannon, J., Azlin-Hasim, S., Cruz-Romero, M., Morris, M., Kerry, J., Cummins, E. (May 2016) Migration Assessment of Chitosan Nanoparticles from an Experimental Nanoparticle/Dip and Spin Coated Food Packaging. *UCD Biosystems Engineering Research Review 21*, pp. 21-25. (http://hdl.handle.net/10197/7671).

(v) Intellectual Property applications/licences/patents

1. Invention Disclosure at UCC: Morris, M., Kerry, J., Cruz-Romero, M., Cummins, E., Azlin-Hasim, S. Modification of conventional film surfaces to promote adhesion of antimicrobial substances. UCC-2014.
2. Invention Disclosure at UCC: Morris, M., Padmanabhan, S.C., Cruz-Romero, M., Kerry, J. A block copolymer based methodology for coating plastics for antimicrobial nanomaterials loading and applications thereof. UCC-2017.
3. Patent filing. Morris, M., Padmanabhan, S.C., Cruz-Romero, M., Kerry, J.) A coating composition comprising integrated functionality. European patent office. Application N°: 18179171.6-1102; 21/06/2018.

(vi) Other

5. Scientists trained by Project

Total Number of PhD theses: 4

1. Hannon, J. Migration and Human Exposure to Nanoparticle Food Contact Materials, PhD Thesis, University College Dublin, submitted on January 2017.
2. Azlin-Hasim, S. Manufacture of metal-based nanoparticles and their incorporation into plastic materials for the development of antimicrobial food packaging, PhD Thesis, University college Cork, Submitted on August 2016.
3. O'Callaghan, K. A. M. Assessment, Development and Optimisation of Packaging Systems for Cheese Products using Smart Packaging Technologies, PhD Thesis, University College Cork, submitted on January 2016 (Ms O'Callaghan was partly funded by this project).
4. Sullivan, D. Synthesis of food-grade antimicrobial nanoparticles for the development of antimicrobial active food packaging, PhD Thesis, University college Cork, Submitted on June 2019.

6. Permanent Researchers

Institution Name	Number of Permanent staff contributing to project	Total Time contribution (person years)
UCC	3	1.20
UCD	1	0.40
Total	**4**	**1.60**

7. Researchers Funded by DAFM

Type of Researcher	Number	Total Time contribution (person years)
Post Doctorates/Contract Researchers	1	1.99
PhD students	3	7.83
Masters students		
Temporary researchers		
Other		
Total	**4**	**9.82**

8. Involvement in Agri Food Graduate Development Programme

Name of Postgraduate / contract researcher	Names and Dates of modules attended
David Sullivan	Next Generation Food Formulation 22-24 March, 2017

9. Project Expenditure

Total expenditure of the project: € 492,316

Total Award by DAFM: € 499,978

Other sources of funding including benefit in kind and/or cash contribution(specify): € -

Breakdown of Total Expenditure

Category	UCC	UCD	Total
Contract staff	116,550	-	116,550
Temporary staff	-	-	-
Post doctorates	-	-	-
Postgraduates	102,551	73,390	175,941
Consumables	47,233	21,799	69,033
Travel and subsistence	8,975	5,730	14,705
Sub total	275,310	100,920	376,229
Durable equipment	1,593	1,778	3,321
Other	-	-	-
Overheads	82,490	30,276	112,766
Total	**359,392**	**132,924**	**492,316**

10. Leveraging

Additional staff. PhD scholarship from the Ministry of education Malaysia.
Enterprise Ireland, commercialisation fund: “Commercialization of antimicrobial food packaging (ANTIMIC-FOODPACK)”. SFI Industry fellowship to advance technology with Versatile Packaging.

11. Future Strategies

Food packaging containing antimicrobial nanocoatings have the potential to reduce microbial spoilage and prolong the shelf life of foods; hence, reducing food waste and improving sustainability of food production. Nanotechnology is seen as one possible way to increase the antimicrobial properties of packaging materials. The antimicrobial materials realized here have significant commercial potential and our major objective is to deliver these technologies for exploitation. The patent filed allowed us not only to publish papers but also provide some detail to potential partners on the development. However, we recognize that commercialization is complex and can be difficult and requires expert input.