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One of the main functions of food product packaging is to maintain the integrity, quality and safety of the product. From a microbiological viewpoint, packaging has the function of protecting from environmental contamination as well as extending the shelf life of the product by preventing or controlling the growth of spoilage organisms or pathogens.

One approach to enhance packaging for prevention of microbiological proliferation is by the application of antimicrobial packaging films (active packaging). The use and authorization of active and intelligent materials and articles intended to come into contact with food is regulated under Commission Regulation (EC) No 450/2009. The regulation also establishes an EU-wide list of substances that can be used in the manufacture of these materials: substances may only be added to the list once their safety has been evaluated by EFSA. Previously, these have been prepared by blending agents with antimicrobial properties. These agents can include but are not limited to: organic acids, bacteriocins, enzymes, essential oils and phenolic compounds (Sung et al., 2013). For these reasons, much recent research has addressed the development composite films for food packaging (Marra et al., 2016).

Priyadarshi and co-workers proposed a chitosan film enhanced with apricot kernel essential oil. The antimicrobial properties of the film were assessed against *Bacillus subtilis* and *Escherichia coli in vitro*. In addition, the antifungal properties of the film were tested on samples of bread over a 10-day shelf life. The proposed film showed promising results to maintain the safety of bread over its shelf life (Priyadarshi et al., 2018). The possibility of extending shelf life requires further investigation as well as the applicability of the material for large scale production.

A novel melanin-stabilised zinc oxide nanoparticle (ZnONP) biopolymer-based nanocomposite film has been described based on carrageen (Roy et al., 2019). In their work, the authors describe the preparation of their material through treatment of squid ink and its subsequent incorporation into the zinc acetate and potassium hydroxide synthesised materials. Carrageenan, a linear sulfated polysaccharide extracted from marine red algae, was mixed with water, glycerol and the melanin-stabilised ZnONPs. The products were analysed for their antimicrobial properties against *E. coli*, *Listeria monocytogenes* and total viable count. The results indicated a decreased viability of all organisms analysed over a 12-hour period. The study suggests that the proposed bio-based packaging could present a viable alternative to some plastic based compositions in the food industry.

Prabhawathi and colleagues proposed the use of a polycaprolactam, biodegradable polymer, which was covalently linked to papain, a protease from the papaya fruit with antimicrobial properties towards *E. coli*. The study used the proposed wrap on processed cottage cheese samples and found that the long-term antimicrobial effect of the polycaprolactam / papain film had significantly reduced the microbial activity of *E. coli* within the cheese over the period of one month when stored at 4°C. In addition, papain is already widely used within the food industry as part of the cheese ripening process and its food safety has previously been established not to cause unwanted by-products (Prabhawathi et al., 2014).

A study by Correa et al. investigated the effectiveness of nisin-PHB / PCL separating films on extending the shelf life of packaged cooked ham. The proposed material was composed of PHB, a renewable thermoplastic material, PCL, organo-clays nanofillers and nisin (a commercially available bacteriocin which has approval for food application). The data demonstrated that the packaging reduced the microbiological load of the ham and extended its regular 7 day shelf-life to one month (Correa et al., 2017). However, due to potential concerns over the safety of nanoclays when in direct contact with a food product further investigation is required to understand safe levels of nanomaterials in packaging.

A cellulose film covalently bonded with nisin was investigated in 2018 by Wu et al. and its antimicrobial activity over a three month period was evaluated (Wu et al., 2018). The proposed

material was a cotton linter cellulose was formed into a membrane and nisin was bonded to the material and tested against *Alicyclobacillus acidoterrestris in vitro* over prolonged storage of the material. Analysis showed the material retained its antimicrobial activity over a three-month period. Further investigation into the applicability and safety of the material are required.

Valerini and co-workers described a coating based on treating PLA films, a linear aliphatic nature-derived polyester approved for food safety, with nanostructured aluminium-doped zinc oxide. Antimicrobial properties were investigated against *E. coli* (Valerini et al., 2018). The proposed coating and film demonstrated the ability to inhibit *E. coli* growth over a 48-hour period *in vitro*. However, simultaneous analysis of the degradation of the coating over a three-week period demonstrated some release of the materials on films not coated uniformly. The effect as a packaging migrant on the safety of the product remains to be investigated as well as its applicability to large scale productions.

A study by Woraprayote and colleagues described a polylactic acid/sawdust particle biocomposite film coated with Bacteriocin 7293, a bacteriocin obtained from *Weissella hellenica*. The film was tested as a packaging for *Pangasius sp.* fish fillets for its ability to inhibit the growth of *E. coli*, *L. monocytogenes*, *Salmonella typhimurium*, *Staphylococcus aureus*, *Aeromonas hydrophila* B1 and *Pseudomonas aeruginosa* under refrigerated conditions. The analysis conducted on inoculated fish samples with the above cocktails showed an antimicrobial effect of the proposed packaging film over a 7-day shelf life. In the same study, the authors analysed the migration of the packaging film components into the fish. The results indicated that migration was occurring over the 7-day storage time due to changes in the packaging structure but the overall migration in mg/dm<sup>2</sup> was below the migration limit set out in EU standards. The analysis of the novel film suggests it may be suitable for use as a food packaging material (Woraprayote et al., 2018).

Chitosan and gelatin were combined with silver NPs in a nanocomposite film for the packaging of fresh red grapes and was investigated by Kumar et al. The grapes were wrapped directly in the film and stored over a 14-day period. In this study, film composition was analysed and the microbiological quality was assessed visually. Compared to the controls, which included standard plastic wrapping, there was no putrefaction or change in appearance of the grapes when wrapped in the biopolymer film (Kumar et al., 2018). Although the study showed promising results for the application in food, further investigations into the migration of nanomaterials and life cycle behaviour are required.

Salari et al., (2018) examined a chitosan-based nanocomposite film, with bacterial cellulose nanocrystals and silver nanoparticles for use as an antimicrobial packaging film. The *in vitro* analysis demonstrated growth inhibition for *S. aureus*, *B. cereus*, *E. coli* O157, *P. aeruginosa* and fungi.

A packaging film based on cassava starch and pumpkin peel obtained from industry waste was reported by dos Santos Caetano et al. Oregano essential oil was added to the film to promote antimicrobial activity. The *in vitro* analysis of the film demonstrated an antimicrobial effect against *E. coli*, *S. aureus* and *L. monocytogenes* (dos Santos Caetano et al., 2018). However, further investigation into the durability of the material is required, as well as its ability to retain its antimicrobial functionality when applied to different food matrices.

A novel packaging film based on cassava starch and blueberry pomace, both obtained from waste by-products from the food manufacturing industry, was reported by Luchese et al. The material was assessed for its physiochemical properties as well as ability to extend food shelf life by providing an effective UV barrier for water rich food products *in vitro* (Luchese et al., 2018). The results showed that the material had desired properties, however further optimization of the material is required.

ZnONPs are of particular interest due to their antifungal and mycotoxin syntheses inhibition abilities (Sun, Q. et al., 2018). The European Food Safety Authority (EFSA Panel on Food Contact



Materials, Enzymes & Processing Aids, 2016) concluded that ZnONPs in their current analysis are safe to use in a food contact material.

Edible coatings or films are of great interest due to their ability to create additional barriers directly on the surface of the food product to support quality, safety and shelf life (Dehghani et al., 2018). For example, protein/chitosan edible films have been investigated for their antimicrobial properties and to coat packaging or food products. A quinoa flour/chitosan film has been described by Medina et al. and its antimicrobial activity *in vitro* was discussed. In their work, the authors described how the preparation of a quinoa flour/ NP thymol chitosan composition exhibited antimicrobial activity against *S. aureus*, *S. typhimurium* and *Listeria innocua in vitro*. The results obtained indicated that the NP with thymol had significant antimicrobial properties in comparison to controls (Medina et al., 2019). Whilst use as an edible film is outside the scope of this report, the authors also proposed using this nanocomposite material as a coating for plastic-based containers to reduce the water loss of fresh produce (blueberries and cherry tomatoes). In addition, the proposed coating could be applied to other bio-based or even non-bio-based packaging materials to enhance their antimicrobial properties to extend shelf life.

Antimicrobial substances are prevalent in current research for the enhancement of novel packaging materials due to their ability to potentially support food safety and shelf life of food products. However, the proposed substances in combination with the materials require further investigation into their properties and a risk assessment before considering their use on a larger scale. Particularly, when considering the increasingly observed antimicrobial resistance of microorganism in food and non-food (Pellerito et al., 2018).

Applications of nanomaterials in the food systems are of great interest due to their antimicrobial properties and abilities to enhance packaging materials food safety and shelf life. It has been reported that some nanomaterials (especially 'hard' or 'engineered' nanomaterials) may pose a potential risk to the consumer, either via direct contact or through secondary contact as a result of migration into food (Huang et al., 2018).

Chitosan-based films are amongst the most promising candidates to provide the base for novel packaging materials. Whilst *in vitro* and small-scale studies focusing on physiochemical properties and antimicrobial properties have produced promising results further intensive investigations are required to assess the suitability of the proposed composites to a variety of food products and the possibility of combining several technologies as well as their applicability to mass production. Additionally, toxicity studies are required to investigate the food safety of the chitosan composites as well as the realistic environmental impact of their production and degradation (Wang et al., 2018).

Although BBFCMs have been suggested as being useful for long shelf life food products (Peelman et al., 2016), one of the biggest potential hurdles is their ability to be deployed on a large scale. The majority of BBFCMs having undergone only limited analysis under laboratory conditions with respect to their ability to provide effective packaging solutions for specific types of food commodities or *in vitro* studies. Whilst these materials prove to be efficient in reducing microbiological activity and thereby supporting an extended shelf life, it remains unknown whether these attributes remain present in large scale packaging productions and on complex foods. Additionally, very limited information is available regarding the ability of the proposed packaging alternatives to behave under unexpected or adverse storage conditions, e.g. temperature abuse and whether under these conditions they could still maintain their properties. In addition, limited information is available on how the materials would behave over extended product shelf life. Depending on the type of proposed material and the required manufacturing methods it remains unclear if the cost of large scale production would be feasible or if the impact on the environment from the novel technologies such as the bioactive ingredients or nanomaterials would have an equal negative impact as the plastic manufacture from production point to the waste stream (Werner et al., 2017).

In case of complex food products or composite products, packaging may require a combination of several technologies to provide the desired functions of safety, quality and shelf life. It needs to be highlighted that most of the available analysis to date on proposed bio-based packaging materials have not been tested with multiple technologies and have focused on one composition and one food type or *in vitro* analysis. Additionally, investigations looking at negative impacts on the food during trial phases have not been considered (Vilela et al., 2018).

Key factors for the development of plastic alternative packaging need to take into consideration their intended use on the product and their capability to maintain their structure and properties during their entire cycle.

Thermoplastic starches which have been converted from agri-food by-products through casting, extrusion, compression or moulding into films or packaging material, are promising candidates for use as food contact materials. However, thermoplastic starch has been shown to have a limited shelf life as it is easily biodegraded. The lack of durability is a significant drawback and further work is required to develop a material composite which retains its quality for extended periods of time before degrading. Currently, the large scale production of this type of material is not economical and consumer reluctance due to its relatively higher cost outweighs the environmental benefit (Prabhu & Prashantha, 2018).

Biomaterials such as alginate and chitosan have been assessed for their suitability as coatings when applied to paper-based packaging products in a study by Kopacic et al., (2018). The results demonstrated a reduction of permeability, migration and transmission when compared to traditional paper-based packaging and control paper. These biopolymers have the potential to be a beneficial additive to existing packaging and enhance food material shelf life. Similarly, wrapping paper prepared from a carbohydrate blend of alginate, cellulose, carrageenan with the addition of grapefruit extract enhanced the antimicrobial properties when compared to traditional wrapping papers. The analysis showed activity against *L. monocytogenes* and *E. coli* over a shelf life of 9 days when wrapped around fish paste stored under refrigerated conditions (Shankar & Rhim, 2018).

Zhang et al discussed steps to achieve commercial production of novel BBFCM packaging materials (Zhang et al., 2018). In particular, techniques such as electrospinning of biopolymers were reviewed and difficulties in up-scaling were identified. Despite these issues, nanotechnologies were considered likely to have a positive impact on future food packaging, enhancing its performance and also food safety, quality and shelf-life (Mihindukulasuriya & Lim, 2014).

### 3.11 Kitchenware and tableware

Whilst much attention has been focussed on the use of BBFCMs for food packaging, the production of food service items such bowls, plates, cups and cutlery based on composites containing plant fibres has increased significantly. This is also perceived as a more sustainable solution, generating both lighter and stronger products. These materials are also promoted by industry as a more acceptable alternative to conventional plastic FCMs. In these items, the composites consist of a resin reinforced with lignocellulosic fibres and powders derived from crop by-products such as bamboo, banana, coir, peanut shells, bagasse or rice straw. The plant-derived fibres and/or powders are mixed with materials such as phenol-formaldehyde resins or polypropylene. Mechanical and chemical processing of the plant fibres to reduce the lignin content is frequently performed, in association with the addition of agents to the resin to enhance mixing, wetting and interfacial adhesion between the components. The composite mixture is subjected to a combination of high pressure and temperature for varying time periods to generate a thermoset plastic item of kitchenware or tableware (Abd-El Salam, 2014; Naik et al., 2015; Shah et al., 2016).

This is analogous to the use of sizing agents in the production of glass fibre food contact materials as described in the Scientific Opinion of the EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (EFSA, 2015). Regulation (EU) No 10/2011 stipulates that IAS used in the manufacture of the composite food contact material must be listed in the Union List. Similarly, the IAS used to produce the food service items must comply with the positive list of chemicals permitted through regulations such as Commission Regulation (EU) No10/2011 for plastic materials and articles in contact with food. Any NIAS developed during processing of the materials also need to be identified to ensure safety. A frequently reported issue with the thermoset food service items based on phenol formaldehyde resins is the release of formaldehyde with potential for migration into food matrices. In response to the continuing rapid growth in demand by consumers for these 'sustainable' tableware and kitchenware items and the widening range of agri-food by-products used in their manufacture, greater surveillance of both IAS and NIAS chemical migrants may be required to ensure consumer protection.

## 4. Conclusions

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Based on the literature review, the following conclusions can be made:

1. Limited research into the development of BBFCMs derived from agri-food by-products, and the associated risks to the consumer, has been undertaken.
2. BBFCMs can exhibit barrier properties similar to traditional, fossil-based plastics enabling comparable shelf life performance and consumer protection.
3. Information on the presence of contaminants such as heavy metals, persistent organic contaminants and natural toxins in BBFCMs and their capacity to transfer from biomass-derived BBFCMs is required.
4. Polypeptide-based materials used for packaging include substances that are known allergens or are extracted from matrices that contain allergens. The effects of processing to produce packaging materials may alter allergenicity in unpredictable ways, depending on whether the allergenic epitopes are destroyed or revealed, for example due to conformational changes of the polypeptides. Very limited information is available on the allergenicity of BBFCMs as well as the potential for transfer of allergens to food.
5. Current analytical methods and risk assessment processes for establishing contaminant chemical transfer from fossil-based plastics to food are expected to be appropriate for BBFCMs.

Although the current analytical methods for determining the migration of IAS and NIAS from FCMs are expected to be applicable to BBFCMs, there is some scope for further method development e.g. high resolution mass spectrometry for allergen epitopes.

Migration studies have demonstrated that only a negligible amount of nanomaterial migrates from packaging into food simulants or foods, suggesting that consumer exposure to these nanomaterials would be low. However, the regulatory framework for nanomaterials in packaging is still underdeveloped even in major economies (Garcia et al., 2018).

The majority of BBFCMs are currently imported into the UK. Extended supply chains may present additional risks around integrity that might need to be addressed.

Overall, the results of this study indicate that in response to the ongoing innovation and growing use of BBFCMs as an alternative to fossil-based packaging, additional studies or actions may be required to help contribute towards ensuring future food safety and consumer protection.

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## Appendix 2: Regulations relevant to BBFCMs

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### UK National Regulations

The national regulations are The Materials and Articles in Contact with Food Regulations 2012.

Links to the regulations for England, Wales and Northern Ireland can be found at:

<https://www.food.gov.uk/business-guidance/food-contact-materials>

For Scotland, the Materials and Articles in Contact with Food (Scotland) Amendment Regulations 2019 can be found at:

<http://www.legislation.gov.uk/ssi/2019/32/contents/made>

### European Regulations, Directives and Recommendations

Copies of the Regulations are available online on the Eur-Lex website:

<https://eur-lex.europa.eu/homepage.html>

### General

Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety.

Regulation (EC) No 882/2004 of the European Parliament and of the Council of 29 April 2004 on official controls performed to ensure the verification of compliance with feed and food law, animal health and animal welfare rules.

Regulation (EU) 2017/625 of the European Parliament and of the Council of 15 March 2017 on official controls and other official activities performed to ensure the application of food and feed law, rules on animal health and welfare, plant health and plant protection products.

### Food Contact Materials

The regulations relating to food contact materials can be obtained from the European Commission at:

[https://ec.europa.eu/food/safety/chemical\\_safety/food\\_contact\\_materials/legislation\\_en](https://ec.europa.eu/food/safety/chemical_safety/food_contact_materials/legislation_en)

These include (but not limited to):

Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC.

Commission Regulation (EC) No 2023/2006 of 22 December 2006 on good manufacturing practice for materials and articles intended to come into contact with food.

Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food.







