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Abstract

Like any other product containing water and organic or inorganic substances, cosmetic and food products can be contaminated during storage and transit process leading to product spoilage, alter organoleptic characteristics and finally cause adverse effects to the consumer. The preservation of food and cosmetics is one of the most important issues facing the industry today. During the last couple of decades, nanotechnology has proven its competence in a variety of applications offering materials and structures within the nano scale, with unique properties. Cosmetics and food industries are among the first industries that nanomaterials are used. Most of the applications refer to the delivery of precious active ingredients into the target tissues being skin and gut with a variety of products claiming anti-ageing or nutritional functions. The use of nanotechnology in food and cosmetics for preservation purposes offered the possibility to boost the activity of antimicrobial agents or promote their safer distribution into the end product when incorporated into packaging or film constructions. In this review, current preservation strategies were discussed and the most recent studies in nanostructures being preservative systems were categorized and analyzed in a way that provides the most promising strategies for the use of their results for the improvement of product safety and self-life extension. Packaging materials were included since the container plays a major role in such products preservation. Conclusions revealed that most of the applications refer to the nanocomposites as part of the packaging mainly due to the various possibilities that nanoscience offers to this field. Apart from that, the route of exposure being skin or gastrointestinal system involves safety concerns and since migration of nanoparticles from their container can be measured concerns are minimized.

1. Introduction

According to the National Technology Initiative, nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers [(1)]. The concept nanotechnology began with a talk called “There’s Plenty of Room at the Bottom”, given by the physicist Richard Feynman in 1059 and the term nanotechnology was established in 1981 with the development of the scanning tunneling microscope. Since then, nanotechnology and nanoscience are combined among others with the fields of materials science, biology, biotechnology, chemistry and engineering. Consequently, nanomaterials are utilized in various industries including food and cosmetics industry.

In 2011, the European Commission defined nanomaterial as "A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm – 100 nm. This extremely small size combined with the high surface to volume area, leads to unique properties, able to provide solutions concerning the safety, functionality, aesthetics, effectiveness or the quality of a final product.

Ranging from oral, sun and hair care to intimate, body and face care, cosmetic and personal care products play an essential role in everyday life supporting aesthetic, hygiene and emotional functions. Cosmetics industry is predicted to exceed $716B by 2025 [(2)] , driven by consumers and science and counts the higher percentage in organic, natural or clean products consumer preference from all other products. Since science drives this market, large investments are made in research and development department and scientists investigate new biochemical pathways, consumer behavior, innovative technologies and sustainable sources to provide innovative raw materials and new products with high effectiveness, smart textures and emotional characteristics.

Cosmetics industry is among the first industries that nanomaterials are used. Twelve percent of cosmetic products are advertised to have Silver and TiO_2 nanoparticles[(3)]. The last updated catalogue of nanomaterials registered in Europe that are in use in cosmetics, consists of 29 ingredients. Both inorganic and organic nanomaterials are used in cosmetics. Tris-Biphenyl Triazine (nano) and Methylene bis-benzotriazolyl tetramethylbutylphenol (nano) are broad spectrum organic UV filters commonly used in suncare and antiageing products. Inorganic nanoparticles synthesized from inorganic elements such as Zn or Ti are widely used in sunscreens because they have UVA and UVB absorption capabilities, providing higher sun protection factor (SPF) along with a nice cosmetic result due to their transparency. For natural sunscreens, titanium dioxide and zinc oxide are used to absorb UVA and UVB light and since both inorganic filters are white in color, being in nanoscale turn them transparent and less greasy. Nano Silica, is used as anti-caking agent helping the distribution of pigments in color cosmetics, or for its ability to absorb oil and improve the texture of creams that contain high percentages of oils or for products that are intended to be used in oily skin. Nanohydroxyapatite, is used in oral care products replacing sometimes fluoride and liposomes protect sensitive ingredients such as vitamins from degradation, deliver them into the skin while at the same time have moisturizing properties [(4)]. Silver and gold nanoparticles have antibacterial and antifungal properties and are used in deodorants and cleansers.

According to the regulation in Europe, a nanomaterial is "an insoluble or bio-persistent and intentionally manufactured material with one or more external dimensions, or an internal structure, on the scale from 1 to 100 nm" [(5)] .Cosmetics that contain nanomaterials should be notified to the Commission six months prior to being placed in the market and by this way, a list with all the nanomaterials that are in use in cosmetic products is available and the last updated catalogue consists of 29 nanomaterials[(6)]. Current reported uses of nanotechnology in cosmetics, include materials for UVB or UVA protection for suncare products, substances with unique optical properties in color cosmetics and nanoparticles such as liposomes, dendrimers, niosomes and carbon nanotubes for the delivery of active compounds. Nanomaterials used in cosmetics, have excellent dispersibility and transparency, can alter the optical properties of the product or can boost the performance of some molecules either by protecting their integrity from light and oxygen or by ensuring their delivery into the skin where the target exists.

Food industry is a more complicated field where different areas are included in the term, including farming, livestock, agrochemicals, food processing, packaging and labelling. Three are the main components of food industry, agriculture, food processing and food distribution. Agriculture includes crop farming, fish farming and livestock raising, food processing makes seasonal food available all year-round including packaging and distribution brings food to the market and the consumer. All three components are regulated by responsible authorities in order to ensure the quality and safety of the goods.

From crop farming to storing, modern food industry, uses a large variety of innovative technologies to increase productivity, produce high quality and safe products and finally manage to influence consumer behavior and choices. Nanotechnology is a technology of emerging interest that has already opened new possibilities not only in foods but also around food products via active, smart or improving packaging. Nanotechnology in food industry comprises anticaking agents to improve the consistency of the product or nanoencapsulation methods to protect and increase the bioavailability of the active ingredients in functional food. Inorganic nanoparticles are widely used for processing, packaging and nutritional purposes [(7)]. Titanium Dioxide is the main whitening or anti-caking agent in chewing gums, dairy, processed food, beverages and seeds [(8)]. Silicon dioxide, is used in food and food supplements for its free-flowing properties and as anticaking agent and it can easily carry flavors [(8)] .

Furthermore, nanotechnology has major advantages when used in packaging and is already applied for the development of either active packaging using nanoparticles as preservation agents to protect the product, or smart packaging using nanosensors to detect microbial or chemical contamination or to ensure authenticity of the food product [(9)]. Nanotechnology, increases bioavailability, improves solubility, facilitate controlled release, ensures safety and high quality during the processing and storage of food products. Furthermore, nanotechnology offers the possibility for more sustainable techniques or products. For example, nanozymes, artificial enzyme mimetic nanomaterials are an excellent tool for the detection of major agri-food analytes [(10)].

The preservation of food and cosmetics is one of the most important issues facing the industry today. On the one hand, the protection of the consumer to avoid contamination by pathogenic microorganisms and on the other hand discussions about his safety in terms of exposure to a number of preservatives bring to the surface the need to find solutions to improve both food and cosmetics quality and safety. Furthermore, there is a great demand for a sustainable live by minimizing waste and the extension of the shelf life of products. The evolution of nanotechnology has improved many areas of science and technology by offering materials with a wide range of possibilities and improve both consumer safety and quality of life with respect to the environment.

In this review, current applications of nanotechnology for the preservation of cosmetics and food, are discussed. The most recent studies in this field are categorized and analyzed in a way that provides the most promising strategies for the use of their results for the improvement of product safety and self-life extension. Data collection was based on using PubMed and Science Direct databases. Databases were queried relevant keywords and build the search string using Boolean operators and quotation marks. Example was "nanotechnology AND cosmetics AND preservative". Our selecting criteria were filtered based on the date of publication, preferentially published during the last 10-15 years, the type of the article etc. review or in vivo trial as well as materials used. The cosmetics industry has always extracted ingredients and technology from the food industry and vice versa. As a result, one can find common trends and technologies in food and cosmetic products. Nanotechnology has found application in both disciplines giving ideas from one sector to another while evolving both sectors in parallel. For this reason, the applications of technology for the preservation of cosmetics and food are examined in simultaneously.

1.1. Preservation and preservatives in cosmetics and food industries

Like any other product containing water and organic or inorganic substances, cosmetic and food products can be contaminated during storage and transit process leading to product spoilage, alter organoleptic characteristics and finally cause adverse effects to the consumer. Preservation is a way of processing goods in order to avoid spoilage, alteration of their functionality and extend their shelf life and it is mainly achieved following three ways: protect from microbial contamination, protect from oxidation and prevent enzymatic or non-enzymatic browning. Ancient people first introduced the importance of preservation while storing their food in cold and dark places. Preservation can be direct to the bulk product, for example, with the addition of a preservative or indirect by the use of the appropriate packaging.

1.1.1. Current preservation strategies in cosmetics industry

According to the European regulation for cosmetics, a preservative is a natural or synthetic ingredient that is added to products to prevent them from spoiling. The availability of a wide and safe range of preservatives is one of the key challenges to the cosmetics sector' (11). Furthermore, Commission has a guidance role for the national authorities in order to help them by checking safety of products already in the European market and encourages scientific research to develop new, safe and innovative preservatives for cosmetics (12) .The application of good manufacturing practices (GMPs), the control of raw materials, and the verification of the preservative effect by suitable methodologies, including the challenge test, are used currently to validate preservative systems (13) .The European Commission ensures an updated list of scientifically evaluated safe preservatives for cosmetic products marketed in European Union and guides national authorities to monitor products on the EU market. This list sets limits for the maximum concentration, any special labeling requirements outlining conditions of use and warnings as well as other restrictions. The list updated in the 25th of May, 2021 contained 176 substances/entries (14).

Cosmetics can be contaminated either during the manufacturing process and packaging (primary contamination) or during their use by the consumer (secondary contamination). The fact that they are stored in the bathroom where humidity is very high, along with the high percentage of nutrients and water, influences microbes flourishing. A cosmetic product is not a sterile product, however authorities specify microbiological acceptance levels. In Europe, the Scientific Committee on Consumer Safety define cosmetic products in two categories. Category 1 includes products specifically intended for children under three years, to be used in the eye area and on mucous membranes and category 2 all the other products. For cosmetics classified in category 1 the total viable count for aerobic mesophyllic microorganisms should not exceed 10^2 CFU/g or 10^2 CFU/mL of the product, for cosmetics classified in Category 2, the total viable count for aerobic mesophyllic microorganisms should not exceed 10^3 CFU/g or 10^3 CFU/mL of the product. Pseudomonas aeruginosa, Staphylococcus aureus, and Candida albicans are considered the main potential pathogens in cosmetic products. These specific potential pathogens must *not be detectable in 1 g or 1 mL of a cosmetic product of Category 1 and in 0.1 g or 0.1 mL of a cosmetic product of Category 2*[15]. In the US, the Personal Care Products Council (PCPC) defines the limits for microbial contamination according to which, *should not be greater than 5x10^2 colony forming units (CFU)/g for products indented to be used around eyes and baby products, and should not be greater than 1000 CFU/g for all other products* [16]. According to the Japanese pharmacopeia, the total number of aerobic microorganisms in products for oromucosal, gingival, cutaneous, and nasal uses, *should not be greater than 10^2 CFU/g or CFU/mL and a total combined number of yeasts/molds should not be greater than 10^1 CFU/g or CFU/mL in the absence of Staphylococcus aureus and Pseudomonas aeruginosa in 1 g or 1 mL of the product* [17].

The ideal preservation system should protect the cosmetic product from microbial contamination both in its original packaging until it is consumed and in an open container, throughout its shelf life. Except for the main potential pathogens mentioned above, other miroorganisms can contaminate cosmetics being, Klebsiella oxytoca, Burkholderia cepacia, Escherichia coli, Enterobacter gergoviae, and Serratia marcescens Furthermore, other bacteria, fungi and yeasts can be found as well. The strategies used to preserve cosmetic products are divided in primary and secondary. Primary preservation is related to the manufacturing process and the application of Good Manufacturing Practices during the process. Secondary preservation is divided in physical, chemical and physicochemical preservation and its main scope is to preserve the product during storage and use [13]. Physical secondary preservation strategy is managed with the appropriate physical barrier and in the case of cosmetics that is packaging.

Physicochemical secondary preservation strategy concludes the use of low pH levels of the bulk, low water activity or the type of the emulsion. It is well known that the optimum pH for microbe's growth is between 5 and 8. That means that microorganisms cannot survive or proliferate in pH below 4 and higher than 9 and it turns out considering that cationic products such as hair conditioners or antiperspirants and alkaline soaps are not likely to be contaminated. Regarding water activity in cosmetic products, that can be reduced with the addition of specific substances concluding polyols, amino acids, sodium chloride and others. According to the European pharmacopeia, a product with a water activity under 0,75 does not require the addition of a preservative. In the list of the physicochemical ways to achieve secondary preservation belongs the type of an emulsion. Specifically, it is found that a water in oil emulsion is less prone to microbial spoilage than an emulsion where the continuous phase is water [18]. The size of the droplets and the composition of the oil phase - when it is the continuous phase - play a crucial role in product's antimicrobial ability[19, 20].

The chemical secondary preservation strategy refers to the addition of preservatives in the cosmetic synthesis. Those preservatives are substances that can be chemically synthesized or come from natural sources. In Europe, preservatives are regulated in Annex V where the positive and negative lists are included likewise concentration maximum limits. A preservative can be used alone or in a mixture with other preservatives. Mixtures are more effective offering broad spectrum antimicrobial activity, while minimizing the risk of toxicity that carry some preservative molecules when used in high concentrations [21]. Except for regulatory criteria, the selection of the appropriate preservative or preservative system depends on its efficiency, safety and compatibility with all other ingredients in the cosmetic synthesis. Furthermore, marketing orientation concerning natural, bio and other claims leads the preservative choice.

The preservative ingredients listed in Annex V of the Regulation (EC) No. 1223/2009, can be divided in eight categories according to their chemical composition and those are organic acids, formaldehyde releasers, isothiazolinones, biguanides, quaternary ammonium compounds, nitrogen compounds, heavy metal derivatives and inorganic compounds. Among organic acids, sorbic acid and benzoic acid are the most frequently used. The use of parabens has been cannibalized due to marketing reasons and formaldehyde donors are currently replaced from more safe alternatives. Biguanides are very efficient in micellar waters and wet wipes intended to be used on eyes.

The selection of the appropriate preservative depends on several factors. First of all, the actual use of the product and the route of the exposure directs the selection. The ideal preservative should be foremost, non-toxic and safe for the consumer. Products intended for use around the eyes, baby products or intimate care products have usually different restrictions regarding the preservatives they include. The restriction of a preservative is due to the reason that the continuation and the extend of use along with the route of exposure can have a significant impact on the toxicity of a compound. Even though preservatives are added in a cosmetic formula to ensure their safety to the consumer, some reactions of tolerance during the use of cosmetics are observed from most of the preservatives in the current market. These reactions range from mild irritation of the skin to estrogenic activity which in some cases has been correlated with mammary tumors.

Furthermore, the preservative or preservative system should be stable, compatible, effective and with low cost. Several factors can affect the stability of a preservative. High solubility and a good O/W partition coefficient will enhance its activity in the aqueous phase of the formula [22]. The pH of the formula can provoke the decomposition of the antimicrobial agent or modify its conservating activity[23]. The temperature during the manufacturing process or during products use can affect preservative stability in a much higher degree when the compound is volatile.

A preservative must be highly compatible with other ingredients of the formula such as surfactants, solvents, perfumes or active compounds. Some preservatives can be inactivated because of the antagonistic action of another compound. The presence of non-ionic surfactants can alter the antimicrobial activity of parabens. Solid materials or organic solids such as cellulose and starch, can absorb preservatives when they are in high concentrations. On the other hand, some polyols and sunscreen filters can boost preservative efficacy. Chelating agents such us EDTA are well known to act as preservative boosters. Physical compatibility is also important. The preservative must be colorless and odorless and not alter the organoleptic characteristics of the final formula.

Microorganisms have mechanisms of resistance to the preservatives. Scientists claim that the reason why this is happening is the use of preservatives in very small quantities due to their high toxicity. The reactivation of the preservative agent, the reduction in preservative efficacy, or a tolerance of microorganisms is called preservative resistance [24]. It has been observed that the most resistant forms are bacterial endospores. Mycobacteria are more resistant that Gram negative bacteria and it is easier for preservatives to affect Gram positive bacteria [25]. Preservative resistance rises the emergency for the development of new antimicrobials or preservation techniques to overcome the phenomenon.

1.1.2. Current preservation strategies in food industry

Foods may be contaminated by microorganisms at any stage until their consumption. The primary sources of microbial contamination are soil, air and food processing machinery. The term food preservation refers to the techniques followed to prevent food from spoilage and extend its self-life, though, it is the main purpose of food processing. The microbiological risk is minimized by using the appropriate container, the application of Good Hygiene and Manufacturing Practices and the Hazard Analysis Critical Control Point (HACCP) principles.

Commission Regulation (EC) No 2073/2005 on microbial criteria for foods, is applicable from the 1st of January and lays down food safety criteria *for relevant foodborne bacteria, their toxins and metabolites, such as Salmonella, Listeria monocytogenes, Enterobacter sakazakii, staphylococcal enterotoxins and histamine in specific foods* [26]. The microbiological criteria have been developed in accordance with internationally recognized principles, such as those of Codex Alimentarius and with the scientific advice from the European Food Safety Authority (EFSA)[26].

Listeria monocytogenes is a small, Gram -positive bacillus and may cause a disease called listeriosis that may affect humans and animals. Listeriosis can cause bacteremia, septicemia, meningitis, meningoencephalitis, rhombencephalitis, brain abscess, local infection and it is more dangerous in the case of pregnant women, adults older than 65 years old and generally immunosuppressed people (27). L. monocytogenes is a psychrotrophic bacterion which is capable to grow at -1.5°C, and thus remains active at refrigeration temperatures. Furthermore, it is a facultative anaerobe, which means that it can grow in the presence or absence of oxygen. Although pasteurization of milk kills Listeria, Queso fresco and other soft cheeses are likely to cause Listeria infection. Among these, one can be infected from raw sprouts, melons, pattes, lunch meats and cold cuts, smoked fish and raw milk.

Salmonellae are facultative anaerobic Gram-negative bacillus from the family of Enterobacteriaceae (28). Salmonellae belong to the family Enterobacteriaceae and colonizes the gastrointestinal tract. Salmonellae do not originate in water; therefore, their presence denotes fecal contamination (29). Feedstuff, soil, bedding, litter, and fecal matter are commonly identified as sources of Salmonella contamination in farms (30). A major success story in the Eu was the coordinated control programs through the consumption of food. While since 2004 more than 200000 human cases were reported each year for 15 EU countries, it dropped to less than 90000 cases in 2014 for 28 EU countries. Animal population with specific amending or implementing acts conclude breeding flocks of Gallus callus, laying hens, broilers, turkeys, fattening pigs and breeding pigs (31).

Staphylococcal enterotoxins are members of a family of more than 20 heat stable different staphylococcal and streptococcal exotoxins. Those toxins are produced commonly by Staphylococcus aureus and are connected to significant human diseases (32). SEA, SED, and SEB are the variants most frequently involved in those outbreaks and SEB is the most toxic variant among the 23 SE serotypes known and it is found in milk.

In addition, the European commission provides food safety criteria for histamine and sampling plans for fishery products associated with high amount of histidine. Fish products contain large amounts of an amino acid called histidine. Histidine can interact with an enzyme called histidine decarboxylase which is produced by certain bacteria. The reaction product is called histamine also called Scombrotoxin (33). Histamine can be produced over a wide temperature range but is most commonly the result of high temperature spoilage (33). Histamine presence can be detected either with sensory evaluation or by chemical testing. The EU, the Codex Alimentarius, Australia, and New Zealand established histamine maximum limit above 200 mg/kg in raw fish, whereas the FDA considered 50 mg/kg for United States and Canada (34).

Food stuff can be divided into many different categories depending on the source, the date of consuming or its technological form. In this document, foodstuff is divided concerning the categorization in the guidance document describing the food categories in Part E of Annex II to Regulation (EC) No 1333/2008 on Food Additives including 1. dairy products and analogues, 2. fats and oils and fat and oil emulsions, 3. edible ices, 4. fruits and vegetables, 5. confectionary, 6. cereals and cereal products, 7. bakery wares, 8. meat and meat products, 9. fish and fish products, 10. eggs and egg products, 11. sugars, syrups, honey and table-top sweeteners, 12. Salts, spices, soups, sauces, salads and protein products, 13. foods intended for particular nutritional uses as defined by Directive 2009/39/EC, 14. Beverages, 15. ready-to-eat savories and snacks, 16. Desserts excluding products covered in categories 1, 3 and 4 17. Food supplements as defined in Directive 2002/46/EC of the European Parliament and of the Council excluding food supplements for infants and young children 18. processed foods not covered by categories 1 to 17, excluding foods for infants and young children [35].

Food preservation strategies can be divided according to the target quality attribute or to the mode of action. Preservation methods conclude (1) the inhibition of chemical deterioration and microbial growth, (2) the inactivation of bacteria, yeasts, molds or enzymes and (3) avoiding recontamination before and after processing. The most prevalent preservation techniques include thermal treatment, freezing, ultrasound, ozone treatment, pulse electric field, irradiation, the use of chemicals or fermentation by products. Food preservation by controlling water and structure is an old technique but still applied.

Among other factor like temperature and pH, water activity (aw) is the most important to control microbial growth. The minimum aw for growth of most bacteria is approximately 0.87, although halophilic bacteria can grow at aw equal to 0.75. There are two ways to reduce water activity in a product and those are the removal of water, the addition of glycols or sodium chloride. Huge varieties of drying methods are being used for dehydration. Freeze drying, edible coating and gelatinization belong to the most popular drying techniques.

The compounds that are used for food preservation are called preservatives and they are either natural or synthetic. They protect food stuff from spoilage thus extending their life, either due to their antioxidant or their antimicrobial activity. The main purpose of a food preservative is to guarantee the safety for human health while at the same time, retain the nutritional value and the overall quality. Preservatives are the most important class of additives out of the 26 major beverage additive categories. Food additives, food enzymes and food flavorings are also known as "food improvement agents". Among others, food additives preserve, color and stabilize food during its production, packaging or storage [36]. The list with the approved food additives for use in EU and their conditions of use, are in Annex II of Regulation (EC) No 1333/2008.

The most common chemical preservatives in food are sulfites and sulfur oxide, nitrates or nitrites, and organic acids such us benzoic, propionic, sorbic and acetic. Using levels of sulfites in many foods have posed health concerns for some individuals. Different maximum limits of sulfites have been adopted from different countries some with national regulations much higher than suggested by the Committee.

The most commonly used organic acids in food, acetic, benzoic, citric, formic lactic and propionic acid are applied for their antimicrobial activity in different food sectors. Nitrates and nitrites are chemicals found naturally in fresh vegetables, fruits and water. They may also be added to preserve processed meat and dairy products and also help hinder the growth of harmful microorganisms, such as Clostridium botulinum, the bacterium which is responsible for foodborne life threatening illness named botulism. Nitrites and nitrates, are also added to meat to keep it red and give flavor, while nitrates are used to prevent certain cheeses from bloating during fermentation.

Lysozyme named E1105 is a permitted preservative for food products. It is a basic globular protein found mainly in eggs and its functionality relies on the ability to accelerate hydrolysis of main components of the peptidoglycans on bacteria's cell membrane. 'Lysozyme is more effective against Gram positive bacteria and can act with other preservatives synergistically.

Chemical preservatives have safety concerns and sometimes can alter organoleptic characteristics of the product. For example, nitrites, when used as food additives, contribute to the formation of a group of compounds known as nitrosamines, some of which are carcinogenic. The most common way to avoid that is to use them in combination with other preservation techniques so as to minimize their concentration.

The use of natural antimicrobials is a highly increasing consumer demand. Fermentation is a natural process and is being used in today's food industries as a potential preservation technique to preserve many food stuffs in a large scale. Produced bacteria can use a wide variety of metabolites and can produce a wide variety of bacteriocins. Nisin A is a heat-stable bacteriocin, produced by certain Lactococcus lactis ssp. lactis strains, with a proven track record as an effective antimicrobial for selected dairy and meat products. Nisin has been approved for use in over 50 countries [(37)] and was granted generally recognized as safe (GRAS) status by the FDA in 1988 [(38)]. It is suitable for clean label applications and is primarily active against gram-positive bacteria such as L. monocytogenes and S. aureus [(39)].

Several researchers have encapsulated nisin with a view to extending its antimicrobial activity by allowing a controlled and sustained release of nisin into the food matrix, thereby maintaining a minimum antimicrobial concentration during product storage but with limited effectiveness. [(39, 40, 41, 42)].

Natamycin is a poorly soluble, polyene antifungal agent used in the food industry for the surface treatment of cheese and sausages, for yogurts and in some countries, juices and wine. It shows in vitro activity against yeasts and filamentous fungi but it is not effective against Gram-positive and Gram-negative bacteria. It is used in topical treatment of fungal eye, mouth, skin and vaginal infections. In food industry, natamycin, is considered as natural because it is produced via fermentation of the bacterium Streptomyces natalensis and it is preferable to other preservatives due to the fact that it is an odorless and tasteless molecule [43]. Natamycin is not soluble in water, extremely sensitive in UV light and unstable in extreme pH values. Natamycin can be regarded as safe for the surface treatment of sausages and cheese but recent concern is being raised regarding the use of natamycin as an additive to beverages and yoghurt, especially when used natamycin-cyclodextrin inclusions where natamycin concentrations are higher. When faecal Candida spp is exposed in high natamycin concentrations may foster the development of resistance to polyenes in Candida spp. and jeopardize the efficacy of other polyenes like amphotecin B when used to treat serious life-threatening fungal infections [43].

Pediocin is a bacteriocin produced from Pediococcus acidilactici, is pH and heat stable. Pediocin facts on the cytoplasmic membrane of Listeria monocytogene. Enterocin as-48 is a cationic bacteriocin produced from Enterococcus faecalis S-48, is pH and heat stable as well and effective against Gram-positive bacteria such as Listeria monocytogenes. The most important property of eneterocin as-48 is its sensitivity in digestive proteases.

2. Applications of nanotechnology in cosmetics and food industries

The applications of nanotechnology for the preservation of cosmetics and food concern nanoparticles, nano-delivery systems and nanocomposites. Properties, mode of action and the most promising studies are presented. Since packaging plays a crucial role for the preservation of both cosmetics and food and taking into consideration that over 95% of the literature reports applications of nanomaterials in packaging for preservation purposes, the section analyses in depth the most recent advances in this field.

2.1. Smart Packaging for the shelf-life extension of cosmetics and food

According to the Commission Implementing Decision 2013/674/EU, 'a *packaging material is the container (or primary packaging) that is in direct contact with the formulation'* (44). Primary packaging plays an important role in the preservation and safety of the cosmetic product not only because it protects it from microbial spoilage but because at the same time it can interact with the product either due to the migration of substances it may contain or due to the transport of atmospheric agents such as oxygen in the product. This is the reason why, cosmetic file should contain specific characteristics of the primary container such us composition, possible impurities and possible migration. Moreover, compatibility tests with the product and composition are mandatory. The EU Framework Regulation for food contact materials (Regulation (EC) No 1935/2004) requires that '*materials are manufactured according to Good Manufacturing Practices and do not release their constituents into food at levels harmful to human health and provides rules for compliance documentation and traceability'* (45). The European Union essentially relies on the relevant legislation on food packaging and acknowledges that once a packaging material has been accepted for food, then it is more easily approved for cosmetics as well (44).

Smart packaging

There are four ways to improve food packaging being the improvement of its mechanical and barrier properties, the delivery of antimicrobials that slowly release into the product, the incorporation of sensors that can detect harmful substances, microbial spoilage or gas and finally, the development of a packaging made from biopolymers. This classification of functional packaging and the types of nanomaterials involved is showed in figure 1 (46).

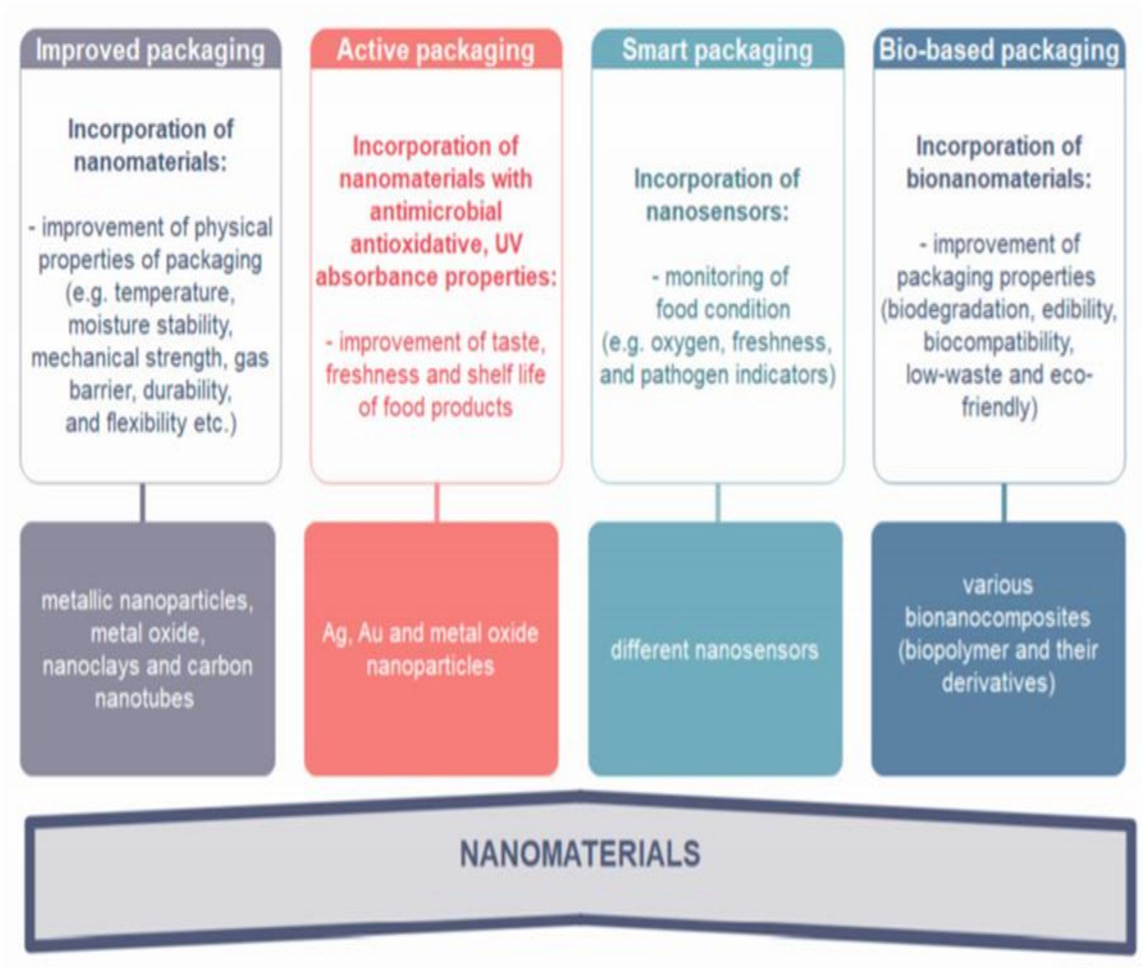

Figure 1 Classification of functional packaging [46]

Improved packaging

The main characteristics of improved packaging is the strong mechanical and physical properties named gas permeability, mechanical strength, flexibility, humidity and temperature stability. This is achieved with the introduction of nanoparticles, nanocomposites and structures into the polymer matrix. The most popular representative improved packaging type are films and edible coatings that are applied on fresh fruits, meat, cheese and bakery. An edible film or coating is any construction with a thickness of less than 0.3 mm which is formed from a combination of biopolymers and different additives dispersed in aqueous media. The difference between the two terms is that the coating is formed directly on the food, while the film is ready to be adhered to the product. They create a controlled environment and act as a semi-penetrable barrier for gases, vapor, and water. Edible films and coatings are produced using synthetic or naturally derived materials. Mechanical and barrier properties depend on the type of the material or mixture. Edible films and coatings are lately produced from by-products from agricultural and marine sources. One of the most interesting properties of coatings and films is that they give the possibility to incorporate bioactive molecules or living microorganisms either in their free form or entrapped in a nanostructure.

Active packaging

Active packaging technology, is used to extend products shelf life by incorporating preservatives, oxygen scavengers, moisture absorbers, carbon dioxide emitters and ethylene scavengers into the packaging material (Table 1). Active packaging creates a microenvironment between food and packaging materials which can scavenge oxygen or moisture, prevent the evaporation of volatile substances such as flavors and ethanol and finally, offer antimicrobial activity [(47)]. During the last decades a variety of antimicrobial agents have been incorporated into packaging materials, films and coatings to extend their shelf life and avoid bacterial spoilage. This is called 'antimicrobial active' packaging and concerns packaging systems that deliver antimicrobial agents and release them within the product, in some cases, in a controlled manner. Among biodegradable polymers those that are used most to deliver preservatives in food are polylactic acid (PLA), cellulose, carrageenan, starch, and chitosan. In some cases, two or more different polymers are applied as a mixture to take advantage of their different properties in the end product [(48, 49)].

Table 1 Active packaging agents

Type	Function	Agents
Oxygen scavengers [(50)]	Prevent fat oxidation	nanocrystalline titania particles, Iron nanoparticle, nanoclays
Moisture absorbers [(51)]	Reduction of water activity	nanocellulose, nano encapsulated tea polyphenols, nano clays

Carbon dioxide emitters [52]	Prevent microbial growth	sodium bicarbonate, sodium ascorbate
Ethylene scavengers [53]	Reduction of fruit and vegetable ripening	ZnO nanoparticles, silica gel, natural clays

A plethora of antimicrobial agents have introduced in antimicrobial active packaging systems being Nisin, pediocin, sodium benzoate, potassium sorbate, propyl paraben, antimicrobial essential oils and extracts [54, 55, 56, 57, 58] and their applications are found in different types of products, fresh meat, fish, nuts, fresh fruits, beverages and others. Recently, cosmetics industry obtained from food industry the technology of active packaging to prevent contamination [59].

Intelligent packaging

Along with the active packaging, 'intelligent' packaging has also been developed and together compose the term 'smart' packaging. Intelligent packaging is the container, coating or film that can detect impurities of dangerous substances as well as biochemical or microbial changes of the product. This is achieved by the use of sensors into the packaging and the science behind this achievement is based in nanotechnology. Two types of nano-sensors can be used in food packaging, electrochemical and optical. The incorporation of nanomaterials into sensing systems imparts properties such as optical, thermal, plasmonic, catalytic and others improving their performance. Copper nanoparticles are applied in soft drinks and detect carbohydrate oxidation [60] , graphene nanoribbons find applications in detecting various antioxidants in mixed fruit juices [61], carbon nanoparticles detect the presence of melamine in milk [62], gold nanoparticles can detect heavy metals in water [63] and when they are electrodeposited on graphene ribbons, they can detect the presence of Tert-butylhydroquinine in edible oils [64] .

2.2. Nanocomposites

As already mentioned, the packaging of food and cosmetics plays an important role in their preservation by preventing the entry of germs. The evolution of nanotechnology and the multitude of properties that nanoparticles have, has brought the packaging technology further with the creation of active and intelligent packaging. The release of preservatives from the container to the product has made it possible to extend the shelf life of the product as well as to reduce the concentration of chemical preservative systems within the product improving its safety. Consumer demands and environmental impact for biodegradable packaging and waste disposal management, has led to the development of packaging including films and coatings using only biodegradable materials called also biopolymers. Among these biopolymers, cellulose, carrageenan, agar, starch, and chitosan, the latest has investigated more. Extended research concluded that packaging production using biopolymers has drawbacks, mainly in terms of strength and permeability, named mechanical and barrier properties. Systems that have been shown to improve these properties are nanocomposites.

A nanocomposite is a heterogeneous system of two or more constituents with different characteristics, chemical and physical, and one of the components has at least one dimension in nanoscale. Nanocomposites in packaging are based on biopolymers as the continuous phase and nanofillers being the discontinuous phase. Biopolymers, when fabricated in nanoscale have special properties that make them ideal materials for creating antimicrobial active films, such as the so-called 'bacterial' nanocellulose. This refers to a natural nontoxic biopolymer synthesized from special bacterial species with unique nanostructured morphology giving elastic properties in combination with high surface area, crystallinity, porosity and resistance. Within its pores, bacterial nanocellulose can be the guest of several molecules been held from its hydroxyl groups such as antibacterial agents. The second most abundant polysaccharide resource in nature is chitin which is derived from shellfish waste and it differs from cellulose having an amino group at the C-2 position instead of hydroxyl group. Its partially deacetylated form is called chitosan and it can be functionalized in derivatives that contain cationic or other moieties. Among structural properties, chitosan and its derivatives represent antimicrobial activity which is depended from its molecular weight, cationic charge density, degree of acetylation, hydrophobicity, positioning of cationic charge and other functional groups it may contain [(65)]. Different mode of action is observed for Gram positive and Gram-negative bacteria due to the differences in their cell wall composition. The corresponding proposed modes of action for the two types of bacteria is illustrated in figure 2. As it seems, chitosan and derivatives need to overcome the outer membrane barrier in order to interact with the bacteria. In both bacterial cases, antimicrobial activity is based on the cationic charges in the chitosan backbone.

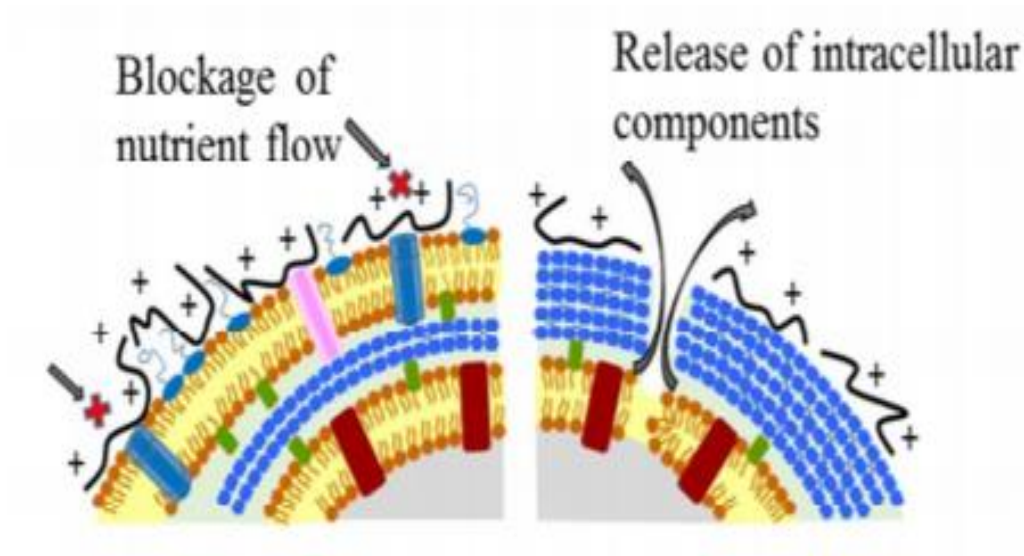

Figure 2 From left to right: the effect of chitosan on Gram Negative and Gram-Positive outer cell envelope [65]

Nanofillers that have incorporated into such composites include nanoparticles, nanorods, nanotubes and nanofibrils. Applications of different nanofillers for preservation purposes are summarized in table 2

Table 2 Applications of carbon based nanofillers for cosmetics and food preservation

Composition	Carbon based nanomaterial	Target microorganism	Application
polylactic acid (PLA)/carbon nanotubes (CNTs)/chitosan (CS) composite fibers	carbon nanotubes [66]	Staphylococcus aureus, Escherichia coli, Botrytis cinerea and Rhizopus spp	strawberries
Polylactide/graphene oxide nanosheets/clove essential oil	graphene oxide sheets[67]	Staphylococcus aureus and Escherichia coli	n/a

chitosan-iron oxide nano-composite hydrogel	iron oxide coated graphene oxide [68]	Methicillin-resistant Staphylococcus aureus, Staphylococcus aureus and Escherichia coli and also with opportunistic dermatophyte Candida albicans	n/a
paper	graphene oxide platforms [69]	Pseudomonas syringae and Escherichia coli	eco-friendly fruit switches
nanocellulose matrix	carbon dots [70]	Escherichia coli and Listeria monocytogenes	films
Low density polyethylene	Halloysite nanotubes [71]	Escherichia coli	Films for hummus spread

2.3. Carbon – based nanomaterials - fullerenes

Carbon based nanoparticles include graphene oxide, carbon dots, carbon nanotubes and fullerenes and they found already applications in tissue engineering, drug delivery, imaging, diagnosis and therapy of cancer. In cosmetics industry, carbon nanotubes are used as delivery systems for bioactive compounds. Fullerenes are valuable skin rejuvenating agents due to their ability to scavenge free radicals about 172 times more than vitamin C, figure 3.

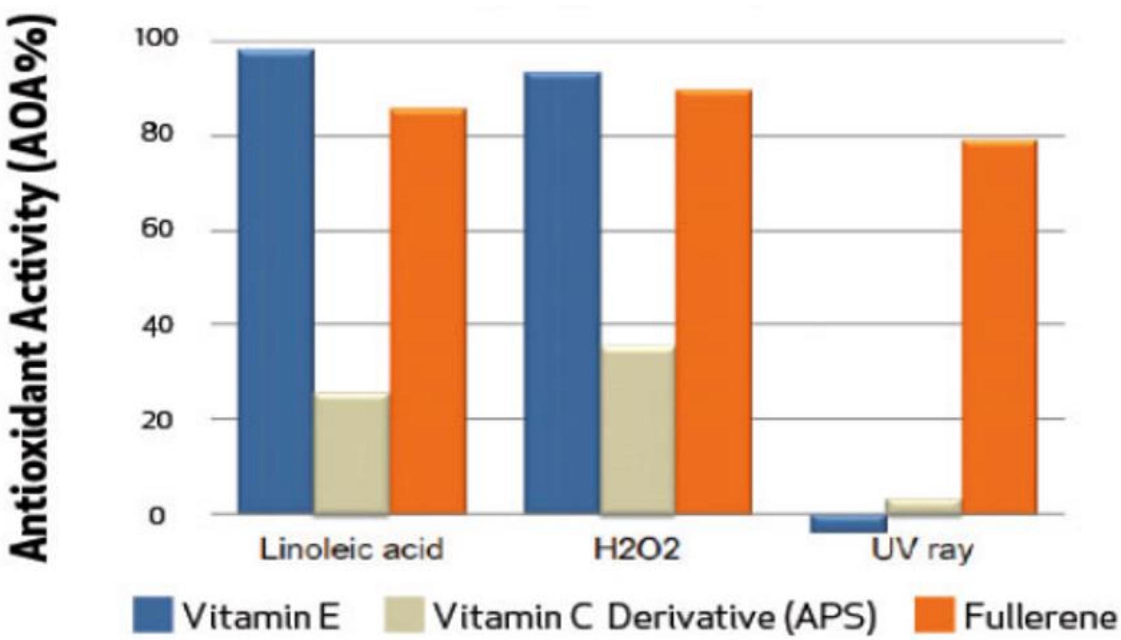

Figure 3 Radical scavenging activity of fullerene [72]

Indeed, scientists investigate their cytoprotective therapeutic potential for several dermatological recovery treatments [73]. Fullerenes are usually dispersed into squalene or wrapped in polyvinylpyrrolidone. Yet, the applications of both type of ingredients are limited. Regarding fullerenes, the main obstacle is their poor solubility however, this is found that can be overcome either by using their derivatives or by encapsulating them into liposomes [74]. The most commonly used fullerenes in cosmetics industry are fullerene C60 (figure 4) and fullerene C70 and although they are approved as antimicrobial and skin conditioning agents, they are applied in anti-ageing, whitening or sun care products [75, 76, 77]. Very recently, on the 6th of July, 2021, the European Commission requested scientific opinion on fullerenes and their derivatives from the Scientific Committee for Consumer Safety. This was triggered from 19 requested notifications for new cosmetic products containing fullerenes. The deadline for the results was set at six months.

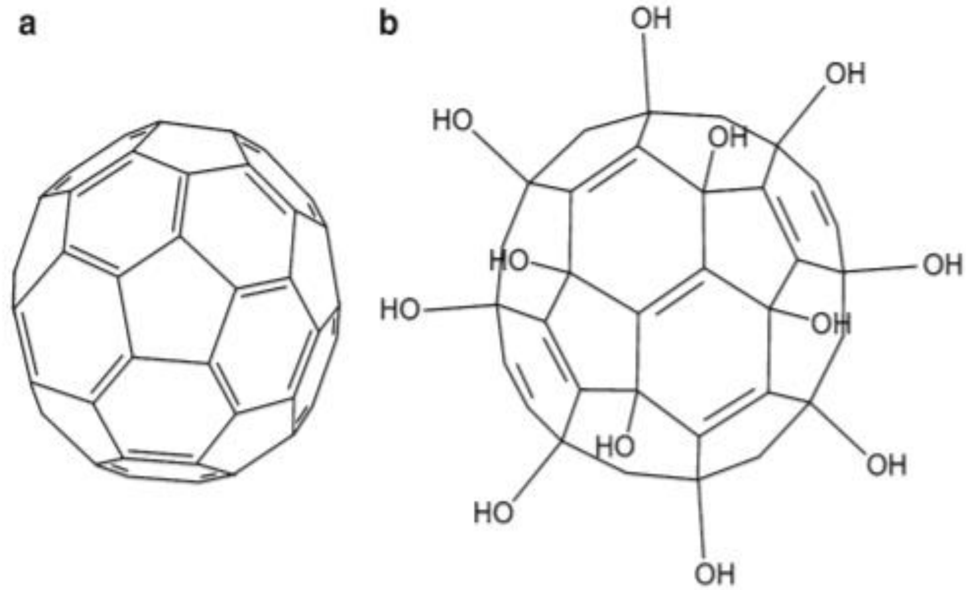

Figure 4 Molecular structure of Fullerene C_{60} and fullerenol $C_{60}(OH)_{24}$ [78]

Carbon dots, nanotubes and graphene oxide are already finding applications that improve antimicrobial activities of active packaging. Regarding fullerenes, such application has not reported yet. However, a promising study where the antimicrobial activity of the fullerene C_{60} and three types of fullerenols $C_{60}(OH)_{12}$, $C_{60}(OH)_{36}\cdot 8H_20$ and $C_{60}(OH)_{44}\cdot 8H_2O$ were evaluated, reported that although the pristine C_{60} didn't manage to kill microorganisms, fullerenols showed good antimicrobial activity against Propionibacterium acnes, Stapphyloccocus epidermis, Candida albicans and Malassezia furfur[79] . Although the preferred final application refers to anti-acne or anti-dandruff cosmetics, the study indicates that they could be tested as preservatives for the final application, especially $C_{60}(OH)_{44}\cdot 8H_2O$ which showed a broad-spectrum activity.

2.3.1. Graphene based nanomaterials

Among the various allotropes of carbon, graphene, planar graphitic sheet of graphite, exists the most biofunctional properties due to the ability to enrich its surface with several functional groups.

Graphene based nanoparticles can damage bacterial cells following two ways. Either via the production of ROS or by trapping microorganisms in its aggregated sheets [80, 81]. The main advantage of graphene oxide when used in packaging, is that it can increase packaging hardness and strength while decreasing its weight. For example, carbon nanotubes were incorporated in a film composed by chitosan and polylactic acid for strawberries preservation. Results showed that the film had low permeability, increase tensile strength and was effective in antimicrobial activity. In another study, graphene oxide nanosheets and clove essential oil were incorporated in a polylactic acid-based film and researchers proved its activity against Gram positive and Gram-negative bacteria while oxygen permeability decreased due to the planar configuration of nanosheets. Graphene can additionally be applied for the coating of the antibacterial agent iron oxide and with the use of chitosan produce a nanocomposite useful in both biomedical and food industries. Hemolysis tests indicated no toxicity of the nanocomposite. Due to safety arguments regarding the extended use of preservatives, the possibility to have a preservative in packaging films, not in contact with the product but available on demand drove researchers to study the introduction of the phenolic compound salicylaldehyde in graphene oxide platforms. The successful release of the preservative stimulated by synthesized acids at ripening stage, led to the conclusion that these nano-composite can be applied for the preparation of eco-friendly fruit switches.

2.3.2. Carbon Dots

The preparation of carbon dots can be achieved either using 'bottom up' or 'top down' methodologies. Interestingly, they can be extracted through a one-step physical method, from carbon black, the coloring agent commonly used in cosmetics and listed in the catalogue of nanomaterials used in the European cosmetics market [82], figure 5.

Figure 5 Schematic presentation of carbon dots extraction from carbon black [82]

The properties of carbon dots that make them valuable in most applications are the tunable photoluminescence, high quantum yield, low toxicity, small size, biocompatibility, and low-cost sources [83] . In cosmetics, carbon dots were recently proposed for hair dying applications taking into advantage the interactions between carbon dots and hair proteins. On the assumption, various carbon dot species were doped on hair during dying with commercial colorants. Three species of Carbon dots, were found to make hair glow under 365 nm light and those were the ones having the lowest absolute zeta potential and the fluorescence of hair observed after hair drying is figured in figure 6 [84] .

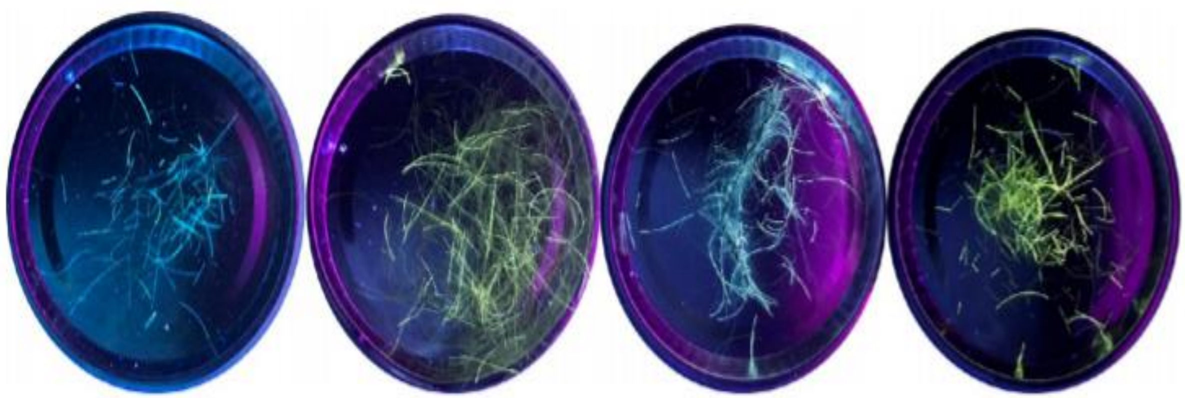

Figure 6 Left to right: Hair alone, Orange-CD-doped hair, fraction 1 with citric acid and o-phenylenediamine, second fraction with citric acid and o-phenylenediamine doped [84]

Although the photolumicent mechanism is not fully investigated, this study proves their potential application both in hair and nail colorants. In addition, some recent studies investigate the introduction of carbon dots in sun care products, promising a non-toxic, broad-spectrum and eco-friendly ultraviolet absorbers [85]. In food industry, they are currently used for the food quality and safety detection usually using fluorescence recovery or fluorescence quenching as detection principles to detect quality biomolecules, such as ascorbic acid, tannic acid and melamine in fruit juices, wine and milk respectively, or bacteria and their metabolites such as Salmonella typhimurium and aflatoxin B1 [86]. Carbon dots classification and their main preparation techniques are illustrated in figure 7. Due to their properties, carbon dots can be adsorbed on bacterial cell surface and induce ROS production when are exposed to light. This gives them antimicrobial characteristics. In a recent study, Kousheh et al. introduced carbon dots in cellulose matrix and prepared a nanopaper that offers antimicrobial and ultraviolet protection[87] . Carbon dots were produced from beneficial bacteria biomass which is a beneficial green approach. Generally, carbon dots can be produced from natural sources including plant extracts rich in phytochemicals and fructose. This kind of resource were used to obtain carbon dots, being white mulberry extract. Very recently, researchers prepared a nanopaper based on bacterial cellulose, doped with carbon dots and supported its potential application in food preservation [88]. In addition, both studies reinforce the production of carbon dots from natural sources not only due to the green approach but because of the high cost using organic material as a precursor. No studies were reported applications of carbon dots for the preservation of cosmetics.

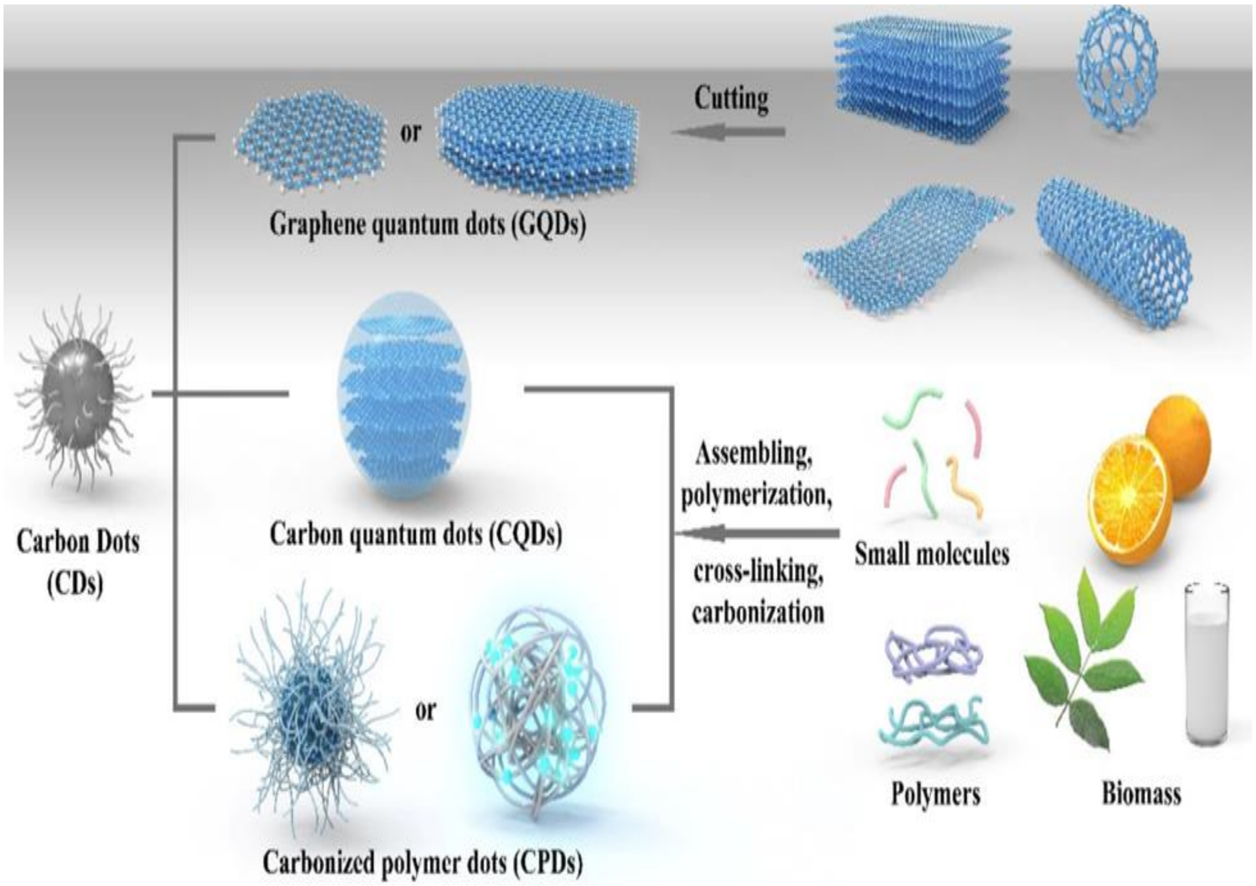

Figure 7 Classification and preparation techniques of carbon dots [83]

2.3.3. Carbon nanotubes

Carbon nanotubes are cylindrical molecules that consist of wrapped sheets of single-layer carbon atoms. They can be single-walled with a diameter of less than 1 nanometer (nm) or multi-walled, consisting of homocentric interwoven nanotubes. Nanotubes have 8 nm diameter cavities that can encapsulate various functional materials in the food or cosmetic articles. A couple of patents have been filed in the field of hair colorants and cosmetic compositions [89, 90]. Single walled nanotubes have also displayed bactericidal activity against both Gram-positive and Gram-negative bacteria, but not much work has been done in this direction. Their microbial toxicity is believed to be either oxidative stress that interrupts the continuation of the cell membrane or their adhesion onto the microbial surface [91] The application of carbon nanotubes as nanofillers in gelatin films has been successfully demonstrated following good results regarding the improvement of tensile strength, mechanical, thermal and antimicrobial properties[92]. For instance, multiwalled carbon nanotubes were incorporated in a composite based on polylactic acid and chitosan to extent the shelf life of strawberries [66] . Researchers, with the knowledge that chitosan lags behind in heat stability and mechanical properties, added carbon nanotubes in the composite and suggested a way to strengthen systems deficiencies.

Another type of carbon nanotubes called Halloysite nanotubes, have been introduced in nanocomposites to develop functional packaging for the extension of the shelf life of food and cosmetic products. Halloysite nanotubes are naturally occurring tubular clay nanomaterials, made of aluminosilicate kaolin sheets rolled several times. Biomaterials can interact with their surface due to aluminol and siloxane groups and form hydrogen bonds. Clay nanotubes have been studied for the deposition of hair dyes or anti-hair loss active ingredients on hair [93] and are lately used in nail polish and nail care products. It has already mentioned the effectiveness of some essential oils as preservatives but their incorporation into active packaging has important drawbacks. High temperatures required for the formation of packaging can degrade such sensitive compounds and make them loose functionality. Halloysite nanotubes can protect the active molecules keeping their quality and functionality in food packaging systems [65]. Researchers studied the entrapment of carvacrol and thymol within halloysite nanotubes and concluded that using this method the sensitive bioactives retain their antimicrobial properties even in temperatures up to 250°C [71] . The synergistic effect of the two components to preserve humus spread was well demonstrated. Interestingly, the release of the two essential oil compounds within the product didn't alter the organoleptic characteristics of humus spread. Halloysites can be loaded both with liquid and solid phase ingredients and interestingly, can promote the slow release and slow down release rate of those ingredients either by the admix of small nanoparticles to make the end of the tube narrower or by coating the halloysite with higher-molecular-weight polymers like chitosan or gelatin in order to provide an additional barrier for the released ingredient [94]. In cosmetics, they have been applied to control release glycerol and solid sunscreen filters with success. The controlled release of the glycerol loaded inside the lumen of halloysite is represented in figure 8.

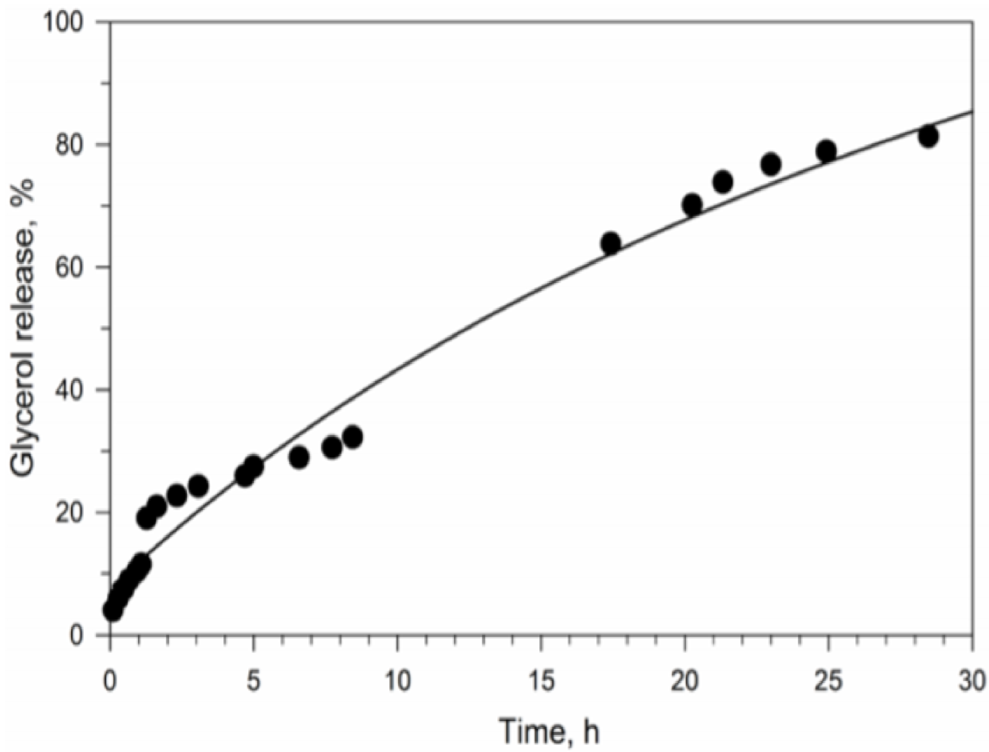

Figure 8 Sustained release of loaded glycerol [94]

Although no applications are reported for the delivery of preservatives in a cosmetic product, it is expected that they could be a promising delivery system for them and a way to minimize their toxicity if their sustained release within the product for a long period is managed.

2.4. Nanoclays

Nanoclays are nanosize fluky soft silicate particles with a characteristic platelet form, having nanopores. They can be classified into the following major groups, the kaolinite group from zeolite or halloysite, the illite group, the montmorillonite/smectite and the chlorite group. The montmorillonite group has gained more attention in packaging sector due to the advantage of high surface area with a large aspect ratio (50–1000) and good compatibility with most of the organic thermoplastics [95]. Many nanoclay materials are commercially focus on the development of improved food and cosmetics packaging such us Nanoshel ®, Nanocor ®, Aegis ®, Dellite ®, Cloisite ®, and Shelsite ® [96, 97, 98]. They can be manufactured in many forms such us rigid containers for beverages, flexible films for bread like Debbie Meyer BreadBags™, or Aisaika

Everfresh Bag for fresh fruits and others [99] . The incorporation of nanoclays in polymers depends on the type of polymer, the process and the application which determines packaging attributes and these nanocomposites give unique mechanical and barrier properties to the container (figure 9).

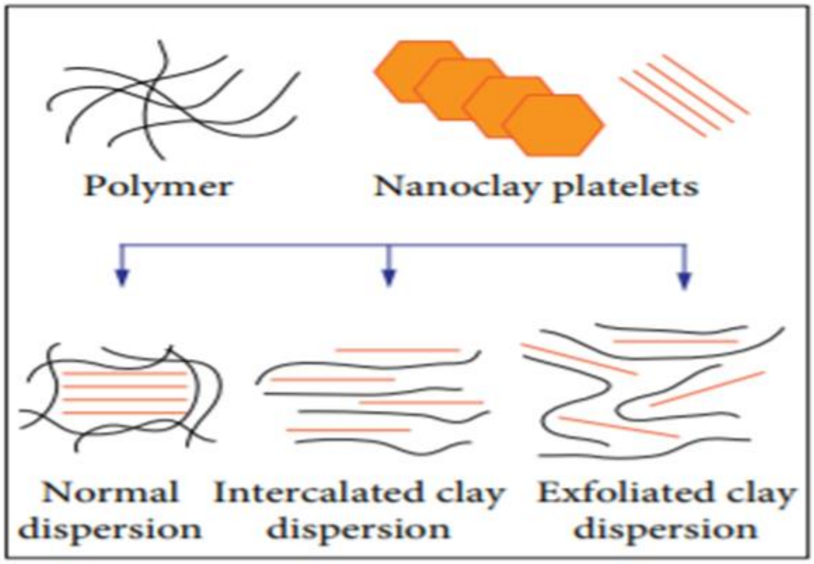

Figure 9 Incorporation of nanoclay in polymers [98]

Except for improving packaging properties, nanoclays can be used as functional materials for active and intelligent packaging. They can provide to the package system antimicrobial or controlled release activity and in the case of intelligent packaging, they can be used as colorimetric indicators. Several reports are found in literature demonstrating their antimicrobial function. For example, the addition of montmorillonite nanoclay in chitosan films applied on Gouda cheese, increased their antimicrobial activity against Escherichia coli, Staphylococcus aureus, mold and yeast [100]. The minimum antimicrobial activity observed for molds and yeasts. It is observed that this type of nanoclay is more effective against Gram positive bacteria than Gram negative ones. An explanation for this, is the fact that Gram positive bacterial membranes are less complicated and the cationic groups of nanoclay, ammonium or pyridinium, that are responsible for the antibacterial activity, bind on cells surface easier.

The ability of nanoclays to entrap active ingredients and slowly release them into a product, make them valuable delivery systems for antimicrobial agents for the preservation of products on demand. Nanocomposites loaded with Salvia macrosiphon seed mucilage, Rosmarinus officinalis extract, carvacrol, potassium sorbate and grapefruit seed extract found to improve the antibacterial effect of active packaging while at the same time maintaining food quality [101, 102, 103

2.5. Metallic nanoparticles and their nanocomposites

Metallic nanoparticles such as silver nanoparticles, titanium dioxide nanoparticles and zinc oxide nanoparticles are extensively applied to make nanocomposites due to their antimicrobial properties and most of applications are found in food industry. Bhuyan et al., presented the various antimicrobial mechanisms of metallic nanoparticles in figure 10 [104]. Silver nanoparticles release silver ions (Agþ) that cling on cell surface, disorganize cell membrane leading to the destruction of DNA and ending to cell death. More specifically, the uptake of free Ag^+ ions forces the production of ATP and in combination with the disruption of the DNA replication, ends up creating reactive oxygen species (ROS)[105]. Regarding the mode of action of titanium nanoparticles, this is triggered from the exposure to UV irradiation that causes the production of reactive oxygen species leading to the lipid peroxidation of phospholipids in the cell membranes and bacteria death [106].

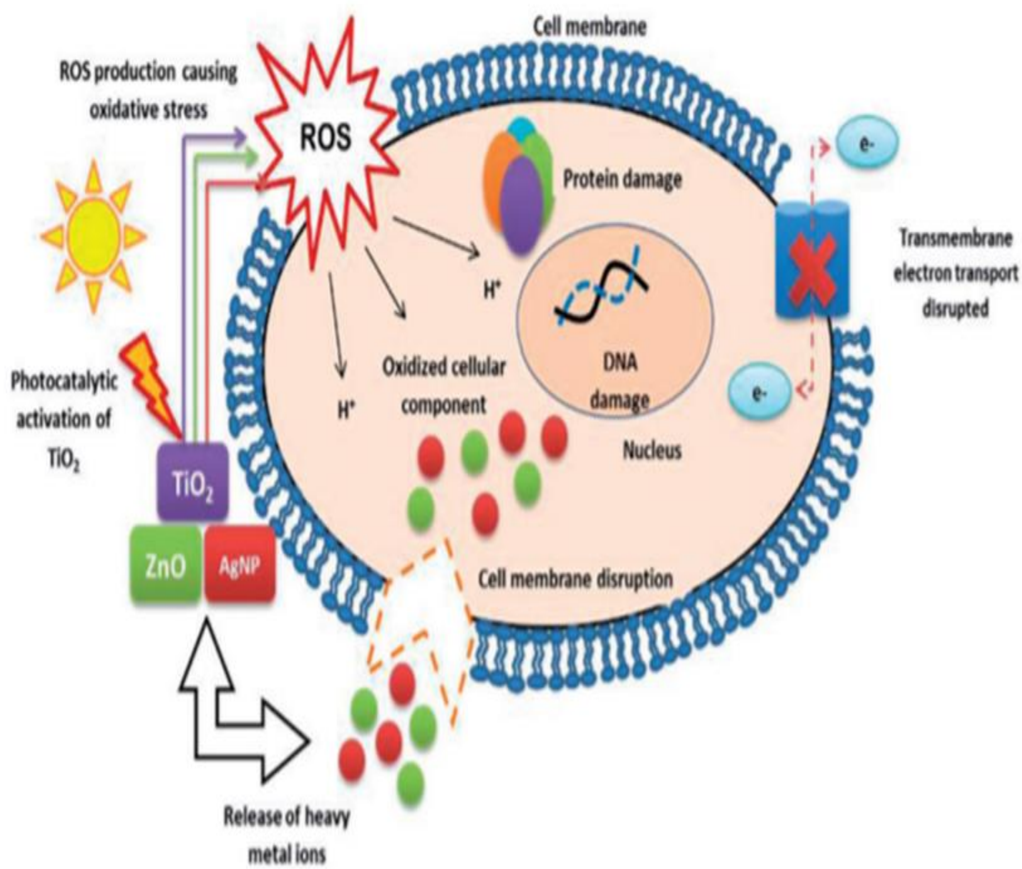

Figure 10 Antimicrobial mechanisms of metallic nanoparticles upon bacterial cells [104]

This photocatalytic activity as the starting point of Titanium nanoparticles activation is the major handicap in the selection of this nanoparticle as a preservative. Even though Zinc nanoparticles possess high photocatalytic efficiency among all inorganic photocatalytic materials it has been observed, that the antibacterial activity of ZnO can be verified likewise in the dark to inhibit the bacterial growth [(107)].

2.5.1. Silver nanoparticles

Concerning cosmetics, among the registered nano-ingredients in Europe, those that claim antimicrobial properties are nanoparticles based on colloidal gold, platinum and silver. The term colloidal implies that particles are in aqueous suspension. In spite of their claimed antimicrobial activity, none of these metallic nanoparticles have approved as preservative. Nano-Colloidal gold and platinum suspensions are currently used in antiaging products to stimulate cell turnover and natural healing. This ability is based on the property to promote electron transfer between metal ions naturally found in the skin. About 19 trade ingredients of colloidal gold and 8 of colloidal platinum are registered[(108, 109)]. None of them is listed in the preservatives list. Nano-Colloidal silver, is intended to be used as an antimicrobial agent in cosmetics including toothpastes and skin care products with a maximum concentration limit of 1%. It is commonly used in cosmetic products with bactericidal effects. It is known that silver ions and Silver-based compounds have strong antimicrobial effects [(110, 111)]. However, these Silver-based compounds gradually precipitate in solutions resulting the jeopardizing of its efficacy. On the other hand, silver nanoparticles do not apply these limitations and are more effective as cosmetic preservatives [(112)]. The reduction of the particle size results in more stable silver solutions, with higher efficiency in killing both bacteria and fungi without penetrating human skin [(112)]. A recent comparative study between silver and gold nanoparticles reported differences concerning the structure of the product where they were applied. More specifically, silver nanoparticles created agglomerates but gold nanoparticles did not[(113)]. It was reported in the same study, that the fungicidal properties against Aspergillus niger and Saccharomyces cerevisiae of both nanoparticles were different. Sensory profile, smell and color assessments of the tested creams demonstrated that the 200-mg/kg gold nanoparticle cream had a better performance (Figure 11).

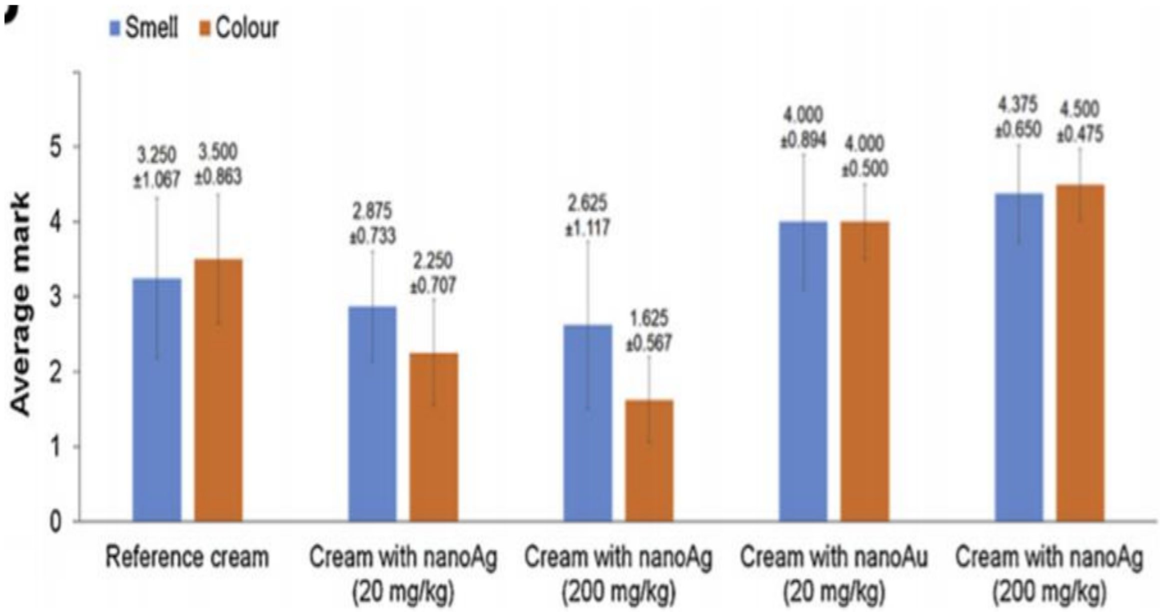

Figure 11 Sensory profile, smell and color assessment (113)

Silver nanoparticles and their nanocomposites are among the most widely used nanomaterials in the food industry[114] . Silver has been authorized by EU EFSA as E174 food additive for coloring food but colloidal silver is banned as food ingredient. Colloidal silver proteins are consumed in US as functional food. The bacteriostatic and bactericidal concentrations of electrically generated silver was determined in 1976 [115]. Since silver is not approved for direct addition to food, most of its applications are found in food packaging. A recent study demonstrated that a polyethylene composite film when containing nanosilver showed a great potential in developing antibacterial and acid food packaging system while at the same time enhanced its barrier properties [116]. Other applications using silver nanoparticles in food packaging and films are presented in table 3. As it can be seen, this kind of technology finds applications in a wide range of food such as raw chicken fillets, bread and nuts.

Table 3 Applications of silver nanoparticles for preservation

Composite production method applied	Composition	Target microorganism
solid ion exchange[117]	Silver - nanoclay (Montmorillonite clay)	Gram negative
sol–gel procedure[118]	Silver/TiO2 nanocomposite	Bacillus subtilis and Bacillus cereus

Extrusion (119)	silver nanoparticles embedded in distinct carriers (silica and titanium dioxide) with Low density polyethilene	Escherichia coli and Staphylococcus aureus
Extrusion (120)	silver nanoparticles in Low density polyethylene	fungi and Gram-negative bacteria
Spray coating (121)	silver-coated low-density polyethylene films	Pseudomonas fluorescens, Staphylococcus aureus and microflora isolated from raw chicken
in situ melt blending method (122)	dodecyl mercaptan-functionalized silver nanoparticles integrated with polypropylene nanocomposite	Gram-negative (Escherichia coli) and Gram-positive (Staphylococcus aureus)
solution casting method (123)	Silver nanoparticles & pullulan & pectin	Escherichia coli , Listeria monocytogenes, Salmonella typhimurium, Staphylococcus aureus, Bacillus cereus
solution casting method (124)	Silver nanoparticles & pectin	Escherichia coli and Listeria monocytogenes
laser ablation method (125)	Silver nanoparticles & agar	Listeria monocytogenes) and Escherichia coli
γ-ray irradiation (126)	Silver nanoparticles & Poly(lactic acid)	Escherichia coli and Staphylococcus aureus
Extrusion (127)	Polyethylene nano- silver composite films	molds

Instead of using nanoparticles as preservatives alone, a wise application is to reduce the number of related risks of conventional preservatives by conjugation. For example, a recent study applied conjugated silver nanoparticles on the surface of sodium benzoate and created a stable antimicrobial composite with significant efficiency against the food borne Salmonella typhimurium type 2, Shiga-toxin-producing Escherichia coli, Bacillus cereus and Staphylococcus aureus. Given the fact that sodium benzoate-functionalized silver nanoparticles were produced in water, and the requested amount of sodium benzoate was reduced, this application offers a green and safer alternative for food preservation [128].

2.5.2. Titanium Dioxide Nanoparticles

Titanium or zinc nanoparticles are extensively used in cosmetics industry but not for preservation reasons. Titanium dioxide is applied mainly in sunscreens for its ultraviolet protection or in color cosmetics in order to neutralize color pigments. Even though it does not present any health risk, the SCCS does not recommend its use in sprayable formulations. In food industry, titanium dioxide is approved as a food additive named E171 even though EFSA expressed concerns regarding its toxicity in humans causing its ban from some European countries. Due to its ability to scatter visible light, it is added in food formulations in order to make products look white and bright. As already mentioned, the mode of action of titanium nanoparticles, is triggered from the exposure to UV irradiation that causes the production of reactive oxygen species leading to the lipid peroxidation of phospholipids in the cell membranes and bacteria death.

Titanium nanoparticles are usually among the key ingredients constructing multilayered nanocomposites added in active packaging and extend the shelf life of specific food products. A nanocomposite film consisting of glycerol, cellulose nanocrystals, TiO2 nanoparticles and wheat gluten were coated over a kraft paper in three layers and exhibited excellent antimicrobial activities against Saccharomyce cervisiae, Escherichia coli, and Staphylococcus aureus after 2h of exposure to UVA light illumination [129]. In another study, an extension of 6 days was observed from the application of a nanocomposite film composed of TiO2 nanoparticles and rosemary essential oil on a lamb meat during refrigeration [130]. Similarly, a packaging system made of silver and titanium nanocomposite were able to extend the shelf life of bread stored in a summer environment [131].

2.5.3. Zinc Oxide Nanoparticles

Zinc oxide is referred as a valuable active ingredient for the treatment of various skin conditions since ancient years and it is the key ingredient in diaper rash ointments. In addition, zinc nanoparticles are the broadest spectrum UVA and UVB ingredient approved for use by European and US authorities. Being a promising preservative for pharma and cosmetics industries, zinc oxide has been studied in various sizes and concentrations against different microorganisms. A recent study explained the effect of the size of zinc nanoparticles in its antimicrobial efficacy and demonstrated that this increases by decreasing its size [132]. This activity can be enhanced by γ irradiation maybe because of the effect on the nanoparticle diameter after irradiation [133].

Zinc nanoparticles exist higher migration phenomena when are in contact with acidic environment. This was confirmed in a recent study where a homogeneous dispersion of the zinc nanoparticles was incorporated in a starch-based flexible coating for food packaging paper (134). Even though migration is a negative issue, this can be measured and checked if there is within legislative limits (135).

2.6. Nanoencapsulation and delivery systems for preservatives

Encapsulation is the entrapment of molecules within a system and aims to protect the molecule from the effects of environmental factors while transferring them to the target without losing any of its properties. Encapsulation can be promoted in micro or nanoscale. Nanoencapsulation offers the advantages of increasing the solubility of some specific molecules and promote their slow release. Nanoencapsulation for the delivery of antimicrobial agents for the preservation of cosmetic and food products can be managed with the production of nano-emulsions, nanoliposomes, lipid carriers, nanofibers and polymeric nanomaterials.

2.6.1. Nanoemulsions for the delivery of preservatives

Nanoemulsions are oil-in-water or water-in-oil colloidal dispersions where the diameter of the droplets of the inner phase range ranges between a few nanometers to 200nm (136). The small droplet size gives them unique properties including solubility enhancement, optical transparency and stability against sedimentation and creaming for the delivery of a wide range of bioactive compounds. In comparison to macroemulsions, they are kinetically stable. Their preparation method requires high or low energy and the final polydispersity index is typically low. Surfactant concentration and length as well as ultrasonication time, control the final droplet size. Nanoemulsions are used in food industry to create processed food like dressings. The use of nanoemulsions as antimicrobial agents is a new and very promising innovation. Their mode of actions relies on the electrostatic attraction between the cationic charge of the emulsion and the anionic charge of the bacterial membrane. Due to the attractive forces, nanoemulsion particles fuse with lipids of the bacterial cell membrane and when enough particles are fused, a part of the trapped emulsion energy is released resulting in cell lysis.

Several raw material companies have used nanoemulsions as delivery systems to preserve bioactive compounds. Vitamins, plant extracts and essential oils are facing oxidation or solubilization problems and need a vehicle to deliver them effectively on skin increasing their bioavailability. The replacement of synthetic preservatives with natural alternatives is a growing demand in both cosmetics and food industry. Essential oils contain terpenes, terpenoides, phenylpropanoids and other molecules that demonstrate antimicrobial properties. For instance, a comparative study between essential oils of Lavandulla officinallis, Melaleuca alternifolia and Cinnamomum zeylanicum with methylparaben, which is effectively used as a cosmetic preservative, showed that those essential oils can replace methylparaben and guarantee no microbial spoilage during its shelf life and use (137) . Another study investigated specific essential oils, when combined with common cosmetic preservatives and in certain cosmetic preparations, and showed that they increased the effectiveness of the preservative against Pseudomonas Aeruginosa and Staphylococcus Aureus (138). The incorporation of essential oils as preservatives in cosmetics or food products has limitations especially regarding their volatile aromatic compounds that give undesirable smell and taste to the final product. Because of their limitations, essential oils cannot be added in formulations in high concentrations, leading to the loss of their effectiveness. The entrapment of essential oils or their bioactive compounds in nano emulsions to improve their preservation function, has found applications in many different products and some examples are presented in table 4.

Table 4 Applications of nanoemulsions in Cosmetics and Food industry as preservation systems

Application	Essential oil	Microorganism	Nanoemulsion Formula info	Main Constituents
fish processing industry(139)	Lemon essential oil	food-borne pathogens (Staphylococcus aureus, Klebsiella pneumoniae, Enterococcus faecalis and Salmonella Paratyphi A) and fish spoilage bacteria (Photobacterium damselae, Enterococcus faecalis, Vibrio vulnificus, Proteus mirabilis, Serratia liquefaciens, and Pseudomonas luteola)	Tween 80 (1% w/w) and water (89% w/w) was homogenized by using an ultrasonic homogenizer for 15 min at 72 amplitudes	d-limonene, p-cymene, β-pinene
food, cosmetics, and	Citral essential oil	Staphylococcus aureus, Pseudomonas	Span 85 (sorbitane trioleate) and	Citral (3, 7-dimethyl-2, 6-octadienal) is a

agrochemical industries [140]		aeruginosa,Enterococcus faecalis, Salmonella typhimurium , and Listeria monocytogenes	Brij 97 [polyoxyethylene (10) oleyl ether. Two stages process (Polytron and Ultrasonic)	monoterpene that occurs naturally in herbs, plants, and citrus fruits
Cereal grains (wheat, barley and corn) [141]	thyme, lemongrass, cinnamon, peppermint, and clove	two isolates of Fusarium graminearum	-0.5 wt% Tween 80, 5 wt% of total oil phase, and 94.5 wt% phosphate buffer solution (10 mM, pH 7.0) -the total concentration of each EO in nanoemulsion was 25 mg/g	Thyme oil (f thymol, p-Cymene, γ-terpinene, and linaloo), Lemongrass oil (β-citral, αcitral, D-limonene, and geraniol), peppermint oil (menthol, L-menthone, eucalyptol), cinnamol oil (eugenol), caryophyllene, benzyl benzoate, linalool), Clove oil (eugenol,caryophyllene, α-humulene, eugenol acetate)
cosmetics & food [142]	Thyme oil	Staphylococcus aureus and Penicillium digitatum	Saponin (solvent & emulsifier)	thymol and carvacrol
stored food items [143]	Origanum majorana essential oil	fungi, aflatoxin B1 (AFB1) produced by Aspergillus flavus	Chitosan (deacetylation degree >85%), dichloromethane (DCM), dimethyl sulfoxide	terpinen-4-ol

			(DMSO), tripolyphosphate (TPP), anhydrous acetic acid, Tween 80, Tween 20, methanol, perchloric acid, sodium carbonate, chloroform,	
stored-food mite (144)	Essential oils of Ocimum basilicum, Achillea fragrantissima, Achillea santolina	Tyrophagus putrescentiae (Schrank)	surfactant (Tween 80) as a non-ionic surfactant and deionized water at a ratio of 1:2:7	Ocimum basilicum (methyl eugenol, α-cubebene, linalool) , Achillea fragrantissima (cis-thujone, 3,3,6-trimethyl-1,5-heptadien-4-one, 2,5-dimethyl-3-vinyl-4-hexen-2-ol, and trans-thujone), Achillea santolina (fragranyl acetate (26.1%), 1,6-dimethyl-1,5 cyclooctadiene (12.6%), 1,8 cineole (11.8%), and cis-thujone)
Minas Padrão cheese (145)	oregano (Origanum vulgare) essential oil	Cladosporium sp., Fusarium sp., and Penicillium sp. Genera	sunflower oil, surfactants, deionized water, and	not reported

			oregano essential oil in two formulations: -Cremophor RH 40 (9.75%) & Brij 30 (3.25%) -Cremophor RH 40 (12%) & Span 80 (8%)	
Edible coatings for fruits and vegetables (tomatoes) (146)	Citrus Sinensis essential oil	Salmonella typhi and Listeria monocytogenes	sodium alginate 10 g L−1, Tween 80 2% (W/V)	not reported
Mayonnaise (147)	Thymus daenensis L. essential oil	Salmonella Typhimurium, Escherichia coli, and Listeria monocytogenes	essentialoil:Tween 80, ratio 1:1, 15 min sonication	thymol and linalool
aqueous food systems, beverages and dairy (148)	Black cumin essential oil	two Gram-positive bacterial (GPB) strains (Bacillus cereus and Listeria monocytogenes)	pure CO or FSO or mixture of black currant with canola and flax seed oil at different ratios (2:8, 4:6, 6:4 and 8:2), respectively plus octenyl succinic anhydrite modified starch	thymoquinone, longifolene, p-cymene, β-pinene, borneol, α-pinene and α-thujene
Fruit juices (149)	Cold-pressed sweet orange (Citrus Sinensis) essential oil	Escherichia coli	3 mL of Tween 80 with 10 mL of Citrus sinensis essential oil	monoterpene hydrocarbons, oxygenated monoterpenes, sesquiterpene hydrocarbons, aliphatic aldehydes,

				myrcene, α-Pinene , sabinene, β-pinene, δ-3-carene
Edible coatings (150)	Clove and lemongrass essential oils, citral and eugenol components	Escherichia coli and Botrytis cinerea	Tween 80 (surfactant), Food-grade sodium alginate	not reported
Edible films for meat products (151)	Cinnamon essential oil	Gram-negative: (Escherichia coli, Pseudomonas aeruginosa and Salmonella typhi) and Gram-positive : (Enterococcus faecium, Bacillus cereus and Staphylococcus aureus)	first homogenizing 2 wt% cinnamon oils with 98% & aqueous emulsifier solution (1% w/v Soya protein isolate and 0.05 wt% lecithin) in high- speed blender	terpenes mixture and D-limonene
Functional food during storage (152)	Zingiber zerumbet essential oil	Aspergillus flavus, aflatoxin B1 (AFB1)	Tween-80	Camphene, Eucalyptol, Cis-Geraniol
Edible packaging for dairy and fruits (153)	Clove essential oil	Staphylococcus aureus, Escherichia coli	Tween 80 & pectin (film)	Eugenol

Tween 80 is the emulsifier used in most of the studies and formulations vary depending on the application. Oil phase composition of nanoemulsions, ripening inhibitor type and concentration can influence the antimicrobial activity of most of the studied essential oils [154]. The main destabilization process of such nanoemulsions is the Ostwald ripening phenomenon where an increase of the oil droplet size is promoted mainly in the first 24 hours after production. One of the proposed strategies to overcome such ageing is the addition of a gelling agent or a gum into the dispersed phase [155]. Aggregation is another phenomenon that can occur during the life time of a nanoemulsion. Polymer coated nanoemulsions can delay the onset of the phenomenon and recent studies suggested the cationic biopolymer chitosan due to the generation of both electrostatic and steric repulsive interactions [155].

2.6.2. Nanoliposomes

Nanoliposomes are among the most investigated nanocarriers in cosmetics and food industry. They are vesicular systems with an aqueous core and surrounded by a lipophilic bilayer offer the advantage to carry and deliver both hydrophilic and hydrophobic molecules. Nanoliposomes are produced through the assembly of amphipathic molecules usually phospholipids and the techniques of liposome preparation are divided into passive and active loading. In cosmetic industry, liposomes find applications as delivery vehicles for various bioactive compounds such us vitamins, peptides, phytosterols and phytocompounds. The encapsulation of cosmetic preservatives into liposomes has not studied yet but several studies demonstrate the benefits in using nanoliposomes as delivery systems of antimicrobial compounds, not registered as preservatives. A recent study presented three essential oils distilled from Artemisia afra, Eucalyptus globulus and Melaleuca alternifolia encapsulated in nanoliposomes based on diastearoyl phosphatidylcholine and diastearoyl phosphatidylethanolamine and tested in terms of their antimicrobial efficacy. Using the minimum inhibitory concentration assay, results for Eucalyptus globulus and Melaleuca alternifolia liposomes, showed lower minimum inhibitory concentrations while polymer coated ones improved their stability [156].

In contrast to the status in cosmetic industry, nanoliposomal formulations delivering antimicrobial agents have found a large number of applications in food industry. Some of the most promising reported studies are presented in table 5 and many of them have a potential use in cosmetics as well.

Table 5 Applications of nanoliposomes in Food industry

Application	Targeted Microorganisms	Encapsulated preservative	Formulation method
food contact surfaces [157]	Staphylococcus aureus, Listeria monocytogenes, Escherichia coli and Salmonella spp	Carvacrol	lipid film hydration technique

food contact surfaces [158]	Staphylococcus aureus or Salmonella enterica	thymol, carvacrol and thymol/carvacrol	lipid film hydration technique
milk, yoghurt, spices, juice, processed meat, mayonnaise, and tahina [159]	Escherichia coli, Salmonella and Candida	clove oil, black seed oil, thyme oil, garlic oil, rosemary oil and green tea,tetracycline	lipid film hydration technique
edible films [160]	Staphylococcus aureus	nettle (Urtica dioica L.) extract	thin-film hydration and sonication + chitosan
functional foods e.g., dairy products and beverages [161]	Staphylococcus aureus, Listeria monocytogenes, and Enterococcus faecalis	nisin	colloidosomes: (surface modification of nanoliposomes with cationic chitosan and sodium alginate) ultrasonication process
Minas fresca cheese [162]	Listeria monocytogenes	nisin	thin-film hydration
Milk, dairy industry [163]	Listeria monocytogenes, Salmonella Enteritidis, Escherichia coli and Staphylococcus aureus	nisin and garlic extract	thin-film hydration method
Tofu [164]	Staphylococcus aureus and Escherichia coli	clove oil	thin-film hydration method
Milk containers [165]	Staphylococcus aureus biofilms	salvia oil	thin film hydration method

not reported [166]	(S. aureus, E. coli, Salmonella Typhimurium, and L. monocytogenes	Eugenol	Ethanol Injection-Dynamic High-Pressure Microfluidization Method

It is well noticed that nanoliposomes delivering preservatives when are entrapped in edible films, minimize their antimicrobial activity due to the inhibition effect of their release from the matrix [160]. Another reason why nanoliposomal formulations can diminish the preservation activity of some molecules is the negative charge of zeta potential. This is because the electrostatic repulsion between negatively charged eugenol nanoliposomes and negatively charged bacteria results in lower interaction between the preservative and bacteria and as a consequence, less antibacterial activity [166]. On the other hand, surface modification of liposomes could improve the stability of the liposomal membrane while at the same time avoid lipid oxidation that can often affect liposomes [161].

2.6.3. Solid Lipid Nanoparticles and Nanostructured Lipid Carriers

Solid lipid nanoparticles are nanoparticles composed of lipids with a solid lipid matrix. Their nanometer size offers unique properties such as high drug loading capacity and long-term stability. Their production does not require organic solvents therefore they can support green chemistry claims. Nanostructured lipid carriers belong to the second-generation lipid nanoparticles and are the result of the combination between solid and liquid lipids. In comparison to SLNs, NLCs have a distorted structure with spaces for the accommodation of biomolecules and offer better loading capacity and stability. It is well established that for the last 15 years SLNs and NLCs are the most common carriers of active ingredients used in cosmetics and food industries and raised from the need to overcome the deficiencies of liposomes, nanoemulsions and polymeric nanoparticles [167]. Some of the current applications of lipid nanoparticles in both industries are summarized in table 6

Table 6 Applications of SLNs & NLCs in food and cosmetics industry

Lipid Nanoparticle	**Incorporated molecule**	**Application**
SLNs	Vitamin E [168]	Cosmetic
SLNs	Quercetin [169]	Food
NLCs	Mediteranean essential oils [170]	Cosmetic
NLCs	Phenylethyl resorcinol [171]	Cosmetic
NLCs	Retinol [172]	Cosmetic
SLNs	Tretinoin [173]	Cosmetic
SLNs	Coenzyme Q10 [174]	Cosmetic
SLNs & NLCs	Lycopene [175]	Food
SLNs	Adenosine [176]	Cosmetic
SLNs & NLCs	Resveratrol [177, 178]	Food & Cosmetic
SLNs	Citral [179]	Food
SLNs	mosquito repellent essential oils[180]	Cosmetic
SLNs & NLCs	Alpha-lipoic acid [181]	Cosmetic
SLNs	Carvacrol [182]	Food
SLNs & NLCs	Butyl 4-hydroxybenzoate [183]	Cosmetic

Lipid nanoparticle applications aim to protect the transported biomolecule, and increase its bioavailability. Many different formulations have been tested to create the ideal SLN or NLC and depending on the biomolecule, the target or the type of the final product, different lipids make up the nanoparticle. In addition to that, several manufacturing procedures are applied for each formulation such as double emulsion and melt dispersion (184) high pressure homogenization cold dispersion (185), high pressure homogenization hot dispersion (186), warm microemulsion (187), supercritical fluid (188) and solvent displacement (189). Despite the fact that there is a plethora of different formulations and manufacturing processes for solid lipid nanoparticles, scientists still investigate new cost effective and scalable production methods (190). Solid Lipid nanoparticles and nanostructured lipid carriers applied for the preservation of cosmetics and food are summarized in table 7.

Table 7 Applications of SLNs and NLCs in cosmetics and food preservation

Lipid Nanostructure	Loaded preservative	Emulsifiers & surfactants	Target microorganism	Result
SLNs	Parabens(191)	Glyceryl distearate	Candida albicans	sustained release of parabens
NLCs	Parabens(191)	Glyceryl distearate and almond oil	Candida albicans	sustained release of parabens
SLNs	Nisin (192)	Glycerol Monostearate 40 – 55% & Poloxamer 188	Listeria monocytogenes and Lactobacillus plantarum	prolonged release of nisin
SLNs	Carvacrol (193)	Propylene glycol monopalmitate & Glyceryl Monostearate mixtures	Escherichia coli & Staphylococcus aureus.	The 2:1 and 1:1 mass ratio of PGMP:GMS were feasible to prepare stable SLNs/enhanced antimicrobial activities

Solid lipid nanoparticles made with pure precirol and nanostructured lipid carriers (NLC) made of precirol and almond oil are able to act as reservoir systems for parabens and their mixtures. (191) The sustained released of parabens minimizes product contamination during its usage from the consumer while at the same time reduces the toxicity of such preservatives in cosmetics. The prolonged antibacterial activity of nisin against Listeria monocytogenes and Lactobacillus plantarum, when encapsulated in solid lipid nanoparticles, was evident for over 15 days in comparison to free nisin. (192) Solid lipid nanoparticles were formulated with the emulsifier glyceryl monostearate and main surfactant the poloxamer 188. The manufacturing process was based on hot high-pressure homogenization. Interestingly, in another study, solid lipid nanoparticles loaded with carvacrol were more effective when fabricated with propylene glycol monopalmitate and glyceryl monostearate in a ratio 1:1 against food spoilage bacteria [193].

2.6.4. Polymeric nanoparticles

Polymers are used widely for the delivery of preservatives either in the form of nanoparticles or in more complicated forms for the stabilization of other delivery systems. A polymeric nanoparticle is a particle within the size range of 1 to 1000nm with an oily or hydrophilic core which is surrounded by a polymeric substance or a polymeric core surrounded by an adsorbed substance. Polymeric nanoparticles may have two different structures composing nanocapsules or nanospheres. Their structures are illustrated in figure 12 [194].

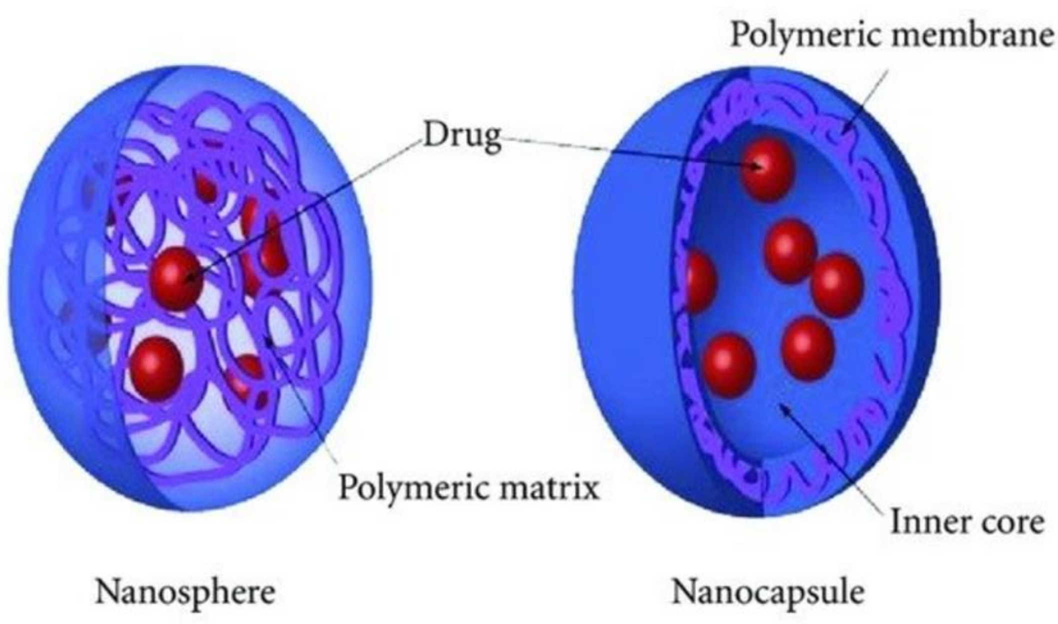

Figure 12 Nanospheres and Nanocapsules [194]

In cosmetics this type of nanoparticles is used for the protection and delivery of sensitive with low biocompatibility compounds, the delivery of aromatic compounds or to mask the odor of some chemicals. In most of the applications, especially in food packaging, metallic nanoparticles are not used alone but in combination with other materials such as nanoclays or polymers [195].

This is a way to decrease their toxicity or to increase their stability and promote prolonged protection. For example, silver nanoparticles are not stable and tend to agglomerate resulting in the reduction of its antimicrobial properties. A successful combination was achieved between carrageenan-based nanocomposites and Laponite, a synthetic clay with unique properties [196]. In this study, the polysaccharide carrageenan was chosen among other polymers due to its eco-friendly profile and strong hydrogel properties. More specifically, carrageenan hydrogels show increased water holding capacity and strong barrier function and when combined with clays, results in adhesive and strong composites with improved properties. It is suggested that chitosan, a cationic linear polysaccharide, and alginate, an anionic polysaccharide when blended to perform a coating for nanoliposomes, so called colloidosome, can overcome their stability limitations [197]. Similarly, pectin and polygalacturonic acid-coated liposomes have been studied for the effective delivery of nisin and successfully lowered the release rate of the polypeptide offering a safer delivery of the preservative into the product [198].

2.6.5. Nanofibers

Nanofibers are nanomaterials with diameter in nanometer range and can be produced by polymers with electrospinning technique. Electrospinning technique uses electric force to draw charged loads from polymer solutions to produce ultrafine fibers. Depending on the desired application and the properties required, electrospinning parameters being the electric field applied, flow rate, needle diameter, environmental conditions and solution characteristics are alternated. Electrospun nanofibers find applications in several industries due to their unique properties and mainly because different compounds can be added in the polymer solution and be trapped into the nanofiber. The Nanofibers for medical and cosmetics market size is forecast to reach $4.2 billion by 2026 [199]. In cosmetics, nanofibers find applications as delivery systems for active ingredients, and for face masks and the most common used polymer is the polyester polycaprolactone due to its biocompatibility and biodegradability.

Electrospinning technique and the sector that nanofibers can be applied, are presented in figure 13.

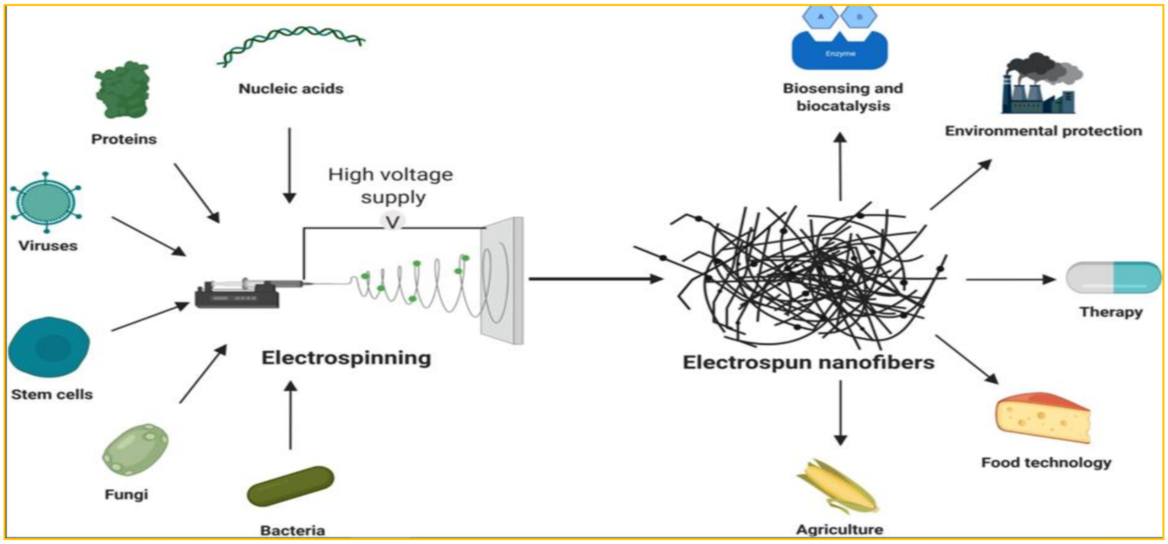

Figure 13 Electrospinning technique and applications of electrospun nanofibers in various industries [200]

The encapsulation of antimicrobial agents in nanofibers is studied and results showed that they can be applied for the preservation of different food products such as cheese, processed meat, fresh juices and yogurt mainly as a component of packaging material. Antimicrobial agents loaded in nanofibers are illustrated in Figure 14 [201].

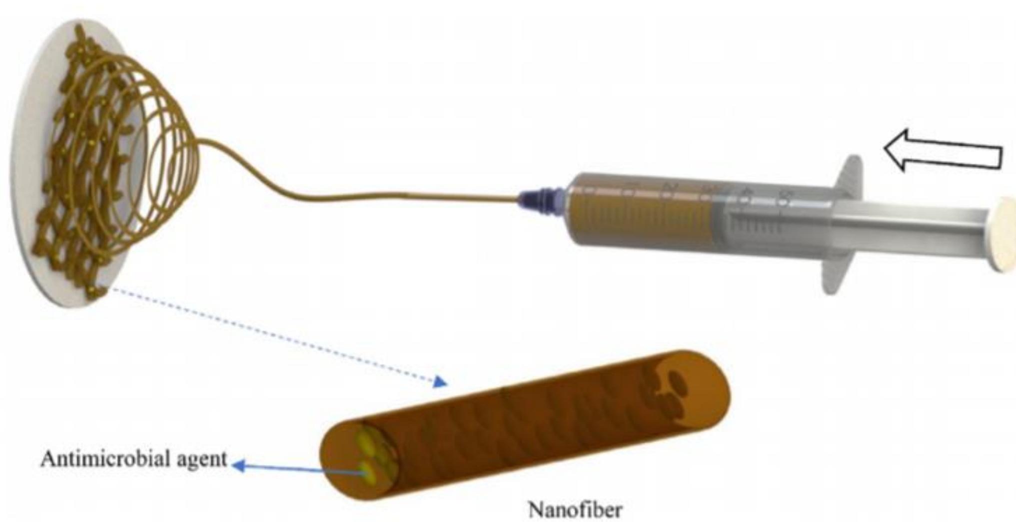

Figure 14 Antimicrobial agents loaded in nanofibers [201]

Their encapsulation in nanofibers promote their slow release in the product increasing their bioavailability and action. More specifically, the preservative nisin were successfully loaded in nanofibers made of poly-g-glutamic acid and chitosan for the slow release of the preservative in cheese against Listeria monocytogenes [202]. Nisin, when applied directly in the product can interact with other components and loose part of its preservation activity. Therefore, when it is delivered in a protected environment its bioavailability is increased. This is also demonstrated in a comparative study between free nisin and nisin-loaded chitosan/alginate nanoparticles where encapsulated nisin gave better results regarding the preservation of feta cheese extending shelf life, without affecting its taste [203].

Similarly, ginger essential oil was loaded in a polymeric blend composed of soy protein isolate, polyethylene oxide and zein at a ration 1:1:1 and its antimicrobial activity against Listeria monocytogenes was tested in situ. After the third day of storage, the bacterial counts were decreased and on day nine the counts decreased from 4.39 log CFU.g-1 to 3.62 log CFU.g-1 ($p < 0.05$), a higher reduction compared with the stored samples without loaded nanofibers [203].

2.7. Nanofluids

A nanofluid is a colloidal suspension that contains nanoparticles made from metals, carbon nanotubes, oxides, carbides and others and the base can be water, oil or ethylene glycol. Their production can be achieved via one-step or two step strategies where the main goal is to avoid sedimentation and aggregation phenomena. Nanofluids have thermophysical properties named thermal conductivity, dynamic viscosity, density and specific heat and they are influenced by their size and shape as well as temperature and the concentration of the nanoparticles in the suspension. In food industry the technology of nanofluids finds applications in those processes that require heat exchange named freezing, dying, pasteurization and others. As already mentioned, thermal pasteurization is preservation technique for milk and fruit juices. This technique efficiently extends the shelf life of such products but affects product quality and organoleptic characteristics due to the denaturation of proteins and degradation of bioactive compounds being vitamins and other nutritional compounds. Scientists focused on the investigation of reducing heat time for heat techniques to avoid such effects and introduced nanofluid thermal processing which is based in the high thermal conductivity of nanofluids in comparison to other fluids. It was found that heat transfer and thermal conductivity is increased when the particle size of suspended nanoparticles is lower [204]. Scientists used alumina nanoparticles nanofluid for the thermal processing of watermelon juice and found that the final product contained vitamin C and lycopene 6% and 10% higher concentration compared to conventional heating [205]. Other studies introduced TiO_2/water and alumina nanofluids in milk pasteurization and all of them propose nanofluids as an alternative to water for heat treatment preservation techniques [206, 207].

2.8. Nanomilling

Nanomilling is a 'top-down' process by which industry can minimize the size of a poorly water-soluble active ingredient in the nanoscale, increase its surface area and consequently increase its rate of dissolution. This technique uses microbeads from ceramics or crosslinked polystyrene and the processed compound is dispersed in a aqueous medium stabilized with a surfactant or polymer to avoid aggregation. This process is recently applied in pharma industry to generate nanoparticulate suspensions of hydrophobic APIs that are widely used such us Rapamycin, Sirolimus, Fenofibrate, Tizanidine HCl, Aripiprazole Lauroxil and Rilpivirine (208). The tremendous increase in the surface area of the drug and as a consequence its bioavailability after nanomilling process, is illustrated in figure 15.

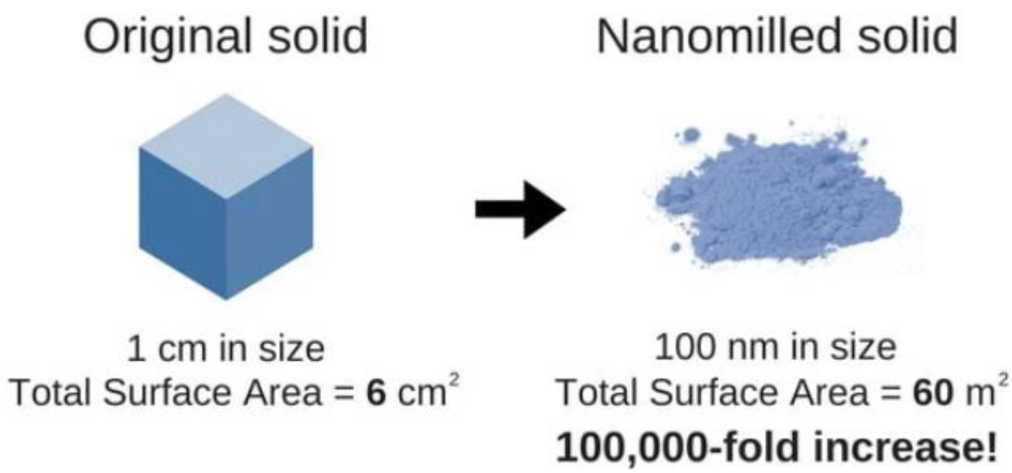

Figure 15 The increase in the surface area of solids after nanomilling (208)

Curcumin is a phenolic compound found in turmeric and possesses a plethora of activities being anti-oxidant, anti-inflammatory and anti-microbial. The main disadvantage of this molecule is its lipophilic structure which effects solubility and bioavailability. For this reason, a study based on the reduction of the size of the molecule by wet nanomilling was conducted and the effect of this reduction in nano range was measured concerning the increase of antimicrobial activity (209). Transmission electron micrograph was applied to determine the antibacterial activity and interestingly, the images taken showed that nanocurcumin particles damaged cell wall and penetrated into the cell causing its death. The suspension was based in water and microorganisms that were studied were Gram-negative (Escherichia coli and Pseudomonas aeruginosa) bacteria and two fungal strains (P. notatum and A. niger). In another study, nanomilling was applied in orange juice pulp for the preparation of orange juice [210]. A slight reduction in the content of ascorbic acid was observed but the initial microbial load was decreased while at the same time, the stability of the juice was enhanced. This is a promising approach for future applications of curcumin as a preservative to extend the shelf life of water-based products yet, more studies need to be conducted concerning the effects in the toxicity of nanomilling products on human cells.

2.9. Nanozymes

Nanozymes are also called enzyme – mimetic nanomaterials and combine the catalytic properties of enzymes with those given from their size in nanoscale. The use of natural enzymes has some drawback being the high cost for their purification which needs long time and their possible denaturation due to high temperatures involved in harsh environmental conditions. It is found that those drawbacks can be addressed with the use of artificial nanozymes. Except for recognition receptors, they are used as signal tags, named ELISA and LFIA assays, as multifunctional sensing elements when are modified with other molecules, or for the signal amplification in food detection assays working synergistically with other nanomaterials. Their functions other than catalytic are illustrated in figure 16

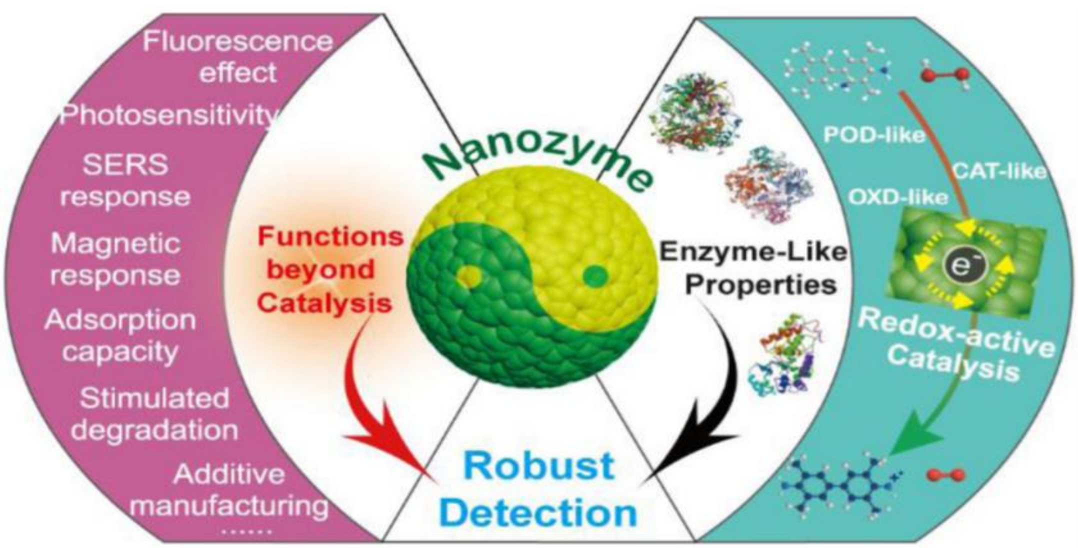

Figure 16 Other than catalytic functions of nanozymes [211]

Nanozymes are not applied as preservatives in food or cosmetics. However, their functions contribute to the improvement of current preservation strategies because their main activity is to detect undesired molecules in the product. More specifically, they can be applied to detect excessive use of some preservatives such as H_2O_2 in milk [(212)], harmful ions [(213)], antibiotics in meat products [(214)], organophosphate pesticides [(215)], mycotoxins that are produced of specific fungi and are very toxic for humans [(216)] and foodborne pathogens such as Escherichia coli, Salmonella Enteritidis and Vibrio parahaemolyticus found in sea food [(217)].

3. Prospects – discussion

Even though the application of nanomaterials in food and cosmetics industries is in its early stage, hundreds of reports demonstrate the advantage of using nanotechnology for the preservation of cosmetics and food, most of them in food packaging. A wide range of nanostructured materials from metallic nanoparticles and their nanocomposites to delivery systems for natural preservatives, has been applied in both industries transforming many domains of scientific knowledge so far in those fields. Silver nanoparticles will play an important role in designing polymeric materials used in the field of active food packaging, bioplastics will replace non-biodegradable polymers and with the support of nanocomposites will increase the shelf life and improve quality of products. Bioplastics produced by renewable biomass sources, metallic nanoparticles coming from bio-fermentation and nanoclays as extracted minerals could be one of the components of sustainable smart food. The release of preservatives from active packaging on demand eliminates harmful effects of chemical preservatives and the entrapment of natural antimicrobial agents utilizes their valuable properties and enables the consuming of more natural products. The replacement of water by nanofluids in heat treatment of fruit juices can provide beverages with the highest quality and nanomilling is a cost-effective way to enhance the preservation activity and bioavailability of natural compounds such as curcumin with a cost-effective way. Food waste, one of the major issues with impact both in public health, economy and environment, could be managed with the application of nanotechnology. The hazard of product contamination will be minimized, packaging waste will not harm the environment while improving product quality.

Further research to deeper understand the molecular mode of action of several antimicrobial nanostructures is needed. Similarly, more comparative studies between different formulations for active packaging are desired since they could contribute to underline the special characteristics of each nanomaterial. Furthermore, it was noticed that the majority of reports are applied in lab scale and the scale up could present unexpected difficulties. Similarly, even though scale up can be managed without drawbacks, the cost effectiveness of the new technology plays a crucial role for the needs of industry and it should be examined.

During this research, it was noted that very few articles are published for the applications of nanotechnology in cosmetics for preservation purposes in contrast to those published concerning food sector. Most of the reports demonstrating the application of nanotechnology in active antimicrobial food packaging claiming that results could be used to support cosmetic applications. Nevertheless, cosmetics preservation targets different pathogenic bacteria than food, cosmetics shelf life should be estimated at two or three years, much longer than most of food products and the repeated use of a face cream, for instance, makes contamination of the product by the consumer more likely. Most of processed food products have a short date after their opening.

The community has recognized the significant contribution of nanotechnology to the food and cosmetics industry as well as their contribution to the creation of maintenance systems for their products. Various projects have been funded for the development of active packaging solutions driven by nanotechnology. In 2012 European commission funded Acticospack project with the scope to develop active packaging solutions for three target cosmetic products and packages aimed to reduce the content of preservatives used in cosmetics while keeping its quality and safety along the same or even longer shelf-life. [218] . The project ended on 2017 and succeeded to reach its goal and developed a PET bottle for shampoo, a PE bottle for suncare product and a PP pot for a day cream capable to extend shelf life minimizing the use of chemical preservatives from 25 to 40%. The prototypes are presented in figure 17.

Figure 17 Acticospack project prototypes [218]

Many steps further, the European Union's Horizon 2020 funds the extension of Nanopack program for the creation of novel smart packaging bio-films that minimize the required preservative concentration in the bulk product, while at the same time meets legal, regulatory, safety and environmental requirements [219]. For this project, bread, dairy and meat industries, research institutes being the Fraunhofer Institute in Germany, Ctic Cita and Technion and universities such as Aarhus University were incorporated with the aim of creating smart packaging to extend the life of products while protecting consumer safety [220]. Halloysite natural nanotubes will be introduced in biopolymeric matrix and be loaded with essential oil compounds being geraniol, linalool, menthol, thymol, carvacrol and citral that have antimicrobial properties. The compounds will be slowly released from the packaging on the food surface and minimize microbial spoilage. The nanotubes are not expected to migrate within the bulk and belong to the passive part of the functional packaging however, migration studies should be contacted and results should be reported in the end of the project. The main goal of this fund is to minimize food waste and offer to the community an eco-friendly safe packaging. Simon van Dam, a senior member of Nanopack project said that the technology can be applied in cosmetics packaging as well [221].

One of the main drawbacks affecting the expansion of nanostructured materials in industry is their toxicological and eco toxicological effect on humans and animal health respectively. The exposure routes of nanoparticles are inhalation, skin penetration and digestion. Nanoparticles should be treated as new chemicals requiring new safety assessments before being allowed for use in any consumer product. On the 8th of October, 2020, the European parliament announced the ban of Titanium dioxide named E170 as a food additive because in many consuming foods the proportions of nanoparticles were greater than 50% and not labeled as 'nano'. This ban is not referred to the titanium dioxide added in the packaging material. The usage of nanoparticles as a food additive is more noxious than their use in food packaging applications. However, the release of them within the product should be measured. Although authorities have published testing methodologies and specific limits for migration of nanoparticles, they do not fit for all possible applications. In addition to that, a harmonized regulatory policy has not been established yet for nanostructured materials and their possible harmful effects for human and environment, resulting in consumer awareness. In this assumption, a growing demand is raised for establishing internationally granted protocols for the exposure assessments, toxicokinetics and toxicity of nanomaterials that concern the diversity of nanomaterial application in cosmetics and food.

Although, the European Union essentially relies on the relevant legislation on food packaging and acknowledges that once a packaging material has been accepted for food, then it is more easily approved for cosmetics [222] , it should be noted that since the exposure route is different, the two sectors cannot be harmonized in any way. Once a nanoparticle enters the gastrointestinal tract, several physicochemical interactions occur with other contents of the system that can affect nanoparticle properties. On the other hand, one might reasonably wonder whether the concentration of a preservative that is actually bactericidal, could also be lethal for skin cells. Several studies investigate possible toxicity of nanoparticles for human cells, depending on the route of exposure but each one concerns specific applications and sometimes cannot be categorized due to extreme diversity of other chemicals in the testing formula. In addition, conflicting results make it impossible to evaluate the real impact in human health. Last but not least, most of the studies do not manage to represent well human organism. For instance, a recent review on the impact of inorganic nanoparticles on human gut microbiome criticized the evaluation of microbial communities be sequencing 16S rRNA in mice due to the fact that the 85% of the 16S rRNA sequence of mouse microbiota represents genera that do not exist in humans (223, 224). For that reason, scientists suggest the pro-inoculation of human gut microbiota when investigating alterations in microbial populations.

With regard to that, the prospect of eliminating the possible toxicity of some nanoparticles by coating them with polymers is discussed a lot and many reports demonstrate the effectiveness of this application. This is a technique well recognized in medical science where biopolymers are commercially used for the improvement of nanoparticles biocompatibility. However, in the case of using nanoparticles as preservatives, it should be taken into consideration the importance of maintaining the antimicrobial property of the nanoparticle. It is well known that silver nanoparticles are toxic to mammalian cells. More specifically, it is found that they cause inflammatory response and induce cytotoxicity and genotoxicity in human cells. Interestingly, it was reported, that chitosan polymer matrix is a great coating to reduce toxic effects while at the same time maintain their bactericidal activity (225) .

4. Conclusions

The present work examined the involvement of nanotechnology in the evolution of food and cosmetic preservation. As it turns out, this science has already made a significant contribution to this field and rapid developments reinforce the belief that in the future much of the maintenance strategies to be pursued by the two industries will be based on nanoparticles and their nanocomposites. Many of the harmful chemical preservatives can be replaced by nanostructures and the function of natural antimicrobials can be enhanced by encapsulation and release on demand when the product is contaminated. The role of packaging is crucial to extending the shelf life of products. The possibilities offered by the science of nanoparticles are varied and nanocomposites seem to be a way to minimize the reckless use of preservatives in the product while at the same time taking care of the environment by enhancing the mechanical and physical properties of bioplastics. This rapid development makes it almost impossible for the authorities to respond immediately as new protocols for toxicity and migration testing have to be established in order to apply new limits for consumer and eco safety by the use of all new applications. With regard to this, funding should provide significant additional resources for comparative studies between applications and most importantly, case by case assessments, migration and toxicological studies. The vision of smart food and smart cosmetics could be enhanced with consumer education in food management.

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