Nanotechnology Approaches for Improving the Healthiness and Sustainability of the Modern Food Supply

David Julian McClements*

ABSTRACT: Nanotechnology has been successfully used in many commercial applications to create innovative products with new or improved functional attributes. In this article, the utilization of nanotechnology to improve the healthiness and sustainability of the modern food supply is demonstrated with various examples. The food industry has been highly successful in producing a diverse range of safe, affordable, tasty, and convenient foods, but many of these foods and their production methods are having damaging effects on the health of people and the environment. Nanotechnology is helping to create a new generation of foods with lower calorie densities, slower digestibility, and higher satiety, as well as to fortify foods with vitamins, minerals, and nutraceuticals in a bioavailable form. It is also being used to create nanopesticides and nanofertilizers to improve yields and reduce waste associated with agricultural production. Moreover, nanotechnology is being used to create tiny sensors that provide information about food quality and safety. Finally, it is being used to convert waste materials into valuable commodities, such as plant-based packaging materials to replace plastics.

1. INTRODUCTION

Nanotechnology involves the design, fabrication, and application of materials that have critical length scales that lie within the nanometer range, typically taken to be from around 1 to 100 nm, but sometimes extended up to around 1000 nm. The properties of nanomaterials are often different from those of conventional materials due to their smaller dimensions, higher specific surface areas, and modified surface reactivities.1 As a result, nanotechnology can be used to create innovative materials with new or improved functional attributes. This new generation of nanomaterials is already being used in many industrial and medical applications. In this article, the focus is on the utilization of nanomaterials in the food and agricultural industry, with emphasis on the development of a healthier and more sustainable food supply (Figure 1).

The food industry has been highly successful in manufacturing an abundance of safe, affordable, and convenient foods but less successful in creating a food supply that is healthy and sustainable.2 In particular, there have been large increases in diet-related chronic diseases over the past few decades, including overweight, obesity, diabetes, stroke, and heart disease. Moreover, some forms of food production lead to increased land and water use, greenhouse gas emissions, pollution, and biodiversity loss. Consequently, there is interest in using modern science to improve both the healthiness and sustainability of the food supply.

2. NANOTECHNOLOGY AND SUSTAINABLE FOOD PRODUCTION

Humanity will need to increase the productivity and efficiency of the food system if it is going to feed a global population that is expanding and becoming more affluent.3 In particular, it will need to produce more food, reduce food waste, and distribute food more equitably. At the same time, it is important to do this without damaging the environment for future generations. A few selected examples of how nanotechnology can contribute to the development of a more sustainable and environmentally friendly food supply are given here.

2.1. Valorizing Waste Streams. Nanotechnology can be used to optimize the efficiency of separation processes like gravitational settling, centrifugation, or filtration.4 Consequently, it can be used to develop more efficient methods of isolating valuable components from waste streams generated by the food and agricultural industry, which can then be purified and converted into value-added functional ingredients, while also reducing waste and pollution. For instance, controlling the colloidal interactions between macromolecules or particles over nanometer length ranges can be employed to manipulate their...
aggregation state, which may be useful to isolate them or to keep them suspended. These approaches can be used to extract functional ingredients from waste streams, such as proteins, polysaccharides, polyphenols, lipids, vitamins, or minerals.

Alternatively, functional nanomaterials can be isolated from solid waste produced during agricultural or food production. For instance, cellulose can be isolated from wood, cotton, or food waste and converted into functional nanofibers that have a broad spectrum of applications in the food or other industries. As an example, adding nanocellulose to foods can reduce the rate of lipid or starch digestion under gastrointestinal conditions, which could benefit human health by mitigating blood sugar or lipid spikes after food ingestion. Nanocellulose is also being utilized to decrease the calorie density of fatty foods, like dressings, sauces, bakery products, and meat products, by simulating some of the desirable textural and mouthfeel attributes typically associated with fats. Nanocellulose can also be utilized as a structural component in food packaging materials to produce more environmentally friendly and sustainable alternatives to plastics. In non-food applications, the ability of dried cellulose nanofibers to absorb and retain large amounts of fluids (such as blood and urine) is being utilized in the development of more sustainable tampons, diapers, and incontinence pads.

Biochar is another nanostructured material with considerable potential as a functional material in food and non-food applications. It is produced by incinerating agricultural waste materials at a relatively low oxygen concentration. The resulting material contains high levels of carbon and minerals, so it is suitable for use as a fertilizer on agricultural crops. Moreover, its application may have additional benefits because it improves soil quality and reduces greenhouse gases (carbon dioxide) emissions into the environment.

Nanotechnology can also be used to create a new generation of filters capable of efficiently extracting substances from waste streams. For instance, nanofilters can be created by electrospinning solutions of natural or synthetic polymers to form mats of entangled nanofibers. These nanofilters have a tunable composition, high specific surface area, high aspect ratio, and controllable pore size, so they can be designed to be highly efficient and selective at isolating particular molecules or particulate matter from solutions. This type of nanofilter is being employed to purify water and isolate valuable molecules from waste streams.

2.2. Enhancing Pesticide and Fertilizer Performance. Nanotechnology is also being employed to improve the performance of the pesticides and fertilizers used to treat agricultural crops. In particular, it is being used to create nanoparticle-based delivery systems to increase the potency and decrease the negative environmental impacts of pesticides and fertilizers.

2.2.1. Nanopesticides. A substantial proportion of the agricultural crops and livestock products produced by the food supply chain are wasted because they are damaged by pests, including microbes, insects, and animals. It is therefore critical to decrease these losses so as to increase the efficiency and sustainability of the food supply. The judicious use of pesticides is essential for increasing crop yields and reducing crop losses, but their overuse can lead to contamination of air, water and land resources, as well as the food crops they are used to treat. Exposure to elevated levels of certain kinds of pesticides can promote chronic diseases, including cancer, obesity, and asthma.

Moreover, the routine widespread use of conventional pesticides is causing some pests to develop resistance, thereby decreasing pesticide efficacy. For these reasons, there is great interest in creating more potent pesticides so less needs to be used, ideally from natural substances so less damage is caused to the environment. In addition, there is interest in developing smart pesticides that are released in response to a specific trigger only when required, again decreasing the total amount needed and reducing the environmental impact. Nanotechnology has great promise for addressing many of the problems associated with current pesticides.

Pesticide potency and specificity can be enhanced by encapsulating them within nanoparticles, whose composition, dimensions, morphology, and surface properties can be tailored for specific applications (Figure 1). For instance, copper-based nanoparticles have been shown to better at protecting watermelon from root fungal diseases than conventional copper-based pesticides, with their efficacy depending on the characteristics of the nanoparticles, such as composition and size. Various other kinds of inorganic nanoparticles have also been shown to be effective pesticides against a variety of pests on different crops, including those fabricated from zinc, silicon, iron, silver, zinc, silicon, and aluminum. The strong potency of nanoparticle-based pesticides is often linked to their small dimensions. Smaller particles can more easily penetrate into the interior of plants through the pores in their leaves, stems, and roots, where pathogenic bacteria are often located. In addition, the surface characteristics of nanoparticles, such as their hydrophobicity and charge, can be engineered to make them adhere more strongly to plant surfaces, thereby reducing their tendency to leach into the environment. As an example, the surfaces of pesticide-loaded nanoparticles can be designed to be cationic, so they are electrically attracted to the anionic surfaces of plants or pests. Finally, smart pesticides can be created by trapping pesticide-loaded nanoparticles inside polymeric microgels: the release rate can then be modulated by changing the diameter or pore size of the microgels, whereas the release can be triggered by using microgels whose properties respond to...
specific environmental changes, such as pH, temperature, humidity, or enzyme activity.

Recently, there has been interest in developing plant-based pesticides to treat crops, rather than use inorganic ones, mainly because these may be less damaging to the environment and human health. Plants naturally produce a broad spectrum of secondary metabolites, some that exhibit strong antimicrobial activity or other biological activities that may prevent pests from destroying crops, such as undesirable aromas, bitter tastes, or substances that are toxic to specific species. These secondary metabolites can be isolated from plants and used as natural pesticides. Essential oils derived from various plants are one of the most widely explored natural pesticides for this purpose. Their efficacy can be greatly increased by converting them into oil-in-water nanoemulsions, which contain small essential oil droplets suspended in water. These essential oil nanoemulsions can be sprayed onto plants or applied to soils to protect them from certain kinds of pests. Many other types of phytochemicals, such as alkaloids, flavonoids, and phenolics, have also been shown to exhibit strong antimicrobial activity, and so may also be used to formulate plant-based nanoparticles. In the future, it may be possible to reduce the levels of synthetic pesticides used by formulating more efficacious plant-based alternatives.

2.2.2. Nanofertilizers. Agricultural crops require sufficient water and nutrients to grow and remain healthy, which are not typically available in the natural environment. As a result, farmers must administer appropriate amounts of natural or synthetic fertilizers to crops to ensure high yields, healthy plants, and reduced losses. Fertilizers typically contain macronutrients (e.g., nitrogen, phosphorus, and potassium) and micronutrients (e.g., copper, manganese, and zinc). Like pesticides, however, fertilizers must be used judiciously to ensure they do not have a negative impact on the environment by causing pollution of water resources and soils, e.g., eutrophication.

The efficiency of fertilizers can be improved using nano-technology approaches similar to those used to enhance the efficiency of pesticides. Nanofertilizers can be created by trapping fertilizers inside small particles. The functional performance of these nanofertilizers can then be tailored by altering the composition, dimensions, morphology, or surface properties of the nanoparticles (Figure 2). Numerous studies have shown that nanofertilizers behave differently from conventional fertilizers due to their small dimensions. For instance, nanofertilizers have been reported to be more effective at promoting the growth, reducing the loss, and enhancing the nutritional quality of plants. Nevertheless, there are also reports that some nanofertilizers have the opposite effects when applied to certain kinds of agricultural crops. Consequently, it is important to optimize the formulation and dose of nanoparticles used in specific applications. There are a number of reasons why nanofertilizers may be more effective than conventional ones. First, their small dimensions allow them to penetrate through the pores in the leaves, stems or roots of agricultural crops, thereby allowing them to reach the interior of the plants where the nutrients are required. Second, the surfaces of nanofertilizers can be engineered so they strongly adhere to plant surfaces more effectively, thereby reducing the amount of fertilizer that leaches into the environment and pollutes the surroundings. Third, different kinds of fertilizers and/or pesticides can be incorporated into a single nanoparticle-based formulation.

If nanoparticles and nanofertilizers do prove to be safe and efficacious, then it will be important to ensure they are commercially viable. Conventional fertilizers are relatively inexpensive substances that are utilized globally in huge quantities. In contrast, many of the nanoformulations created in academic laboratories require expensive ingredients or processes that are difficult to economically scale-up. It should be noted, however, that the higher price of a nanoformulation may be offset by the savings made by increasing crop productivity and reducing crop losses. As an example, it has been reported that spending an additional $26 per acre on using a nanoparticle-based fertilizer increased watermelon yields by around $4600 per acre.

The numerous steps required to develop the next generation of nanopesticides and nanofertilizers have been detailed elsewhere. These authors highlight the importance of carrying out detailed life-cycle analyses to establish the transfer route of nanoparticles from soils to plants to insects to animals to humans and to the environment. In addition, they describe the need to have improved knowledge of the potential adverse effects of nanoparticles on crops, people, and the environment. In particular, there is a need to better understand how long nanoparticles persist in the environment and to establish their potential impact on the microbiomes of plants and soils.

2.3. Nano-assisted Precision Agriculture. Improved yields, decreased losses, and enhanced nutritional quality of agricultural crops can be achieved by closely monitoring their maturity, health status, and nutritional needs as they grow, and then responding in an appropriate manner. For instance, automated systems can be employed to apply an optimized dose of water, pesticides, or fertilizers to plants precisely when they require them, or automated machines could harvest the plants when they have reached their peak. To work effectively, these automated systems need to have detailed information about the plants status, which depends on the availability of sensor technologies. Nanotechnology is being utilized to develop a new generation of sensors that can provide information about the maturity, health, and nutritional requirements of plants.

Researchers are developing affordable portable sensing devices that workers on a farm can use to rapidly acquire real-time data about the status of agricultural crops, soils, and environmental conditions. These devices often employ nano-
materials to improve their sensitivity and selectivity. A test sample, which may be soil or plant tissue, is collected, mixed with water, ground up, and then put into a small sample chamber. These devices contain sensors that provide a measurable output (such as an electronic signal or color change) when the test sample contains a target substance, such as a marker of the maturity, nutrition, or health status of the plant. The farmer can then make a rapid decision on how to treat the crops based on this information. In some cases, valuable information can be obtained from remote sensors, such as those based on measuring the emission of electromagnetic radiation (such as visible or infrared) by plants using instruments attached to tractors, harvesters, drones, planes, or satellites.

A new generation of nano-enabled sensors is being created that are located within the soil or crops themselves, and designed to continuously send data to a remote computer. The utilization of this kind of sensor would enable greater control over the production of agricultural crops. Nevertheless, it will be important that this next generation of sensors is affordable, dependable, robust, and safe so that they can be widely employed in the field. Similar kinds of sensors may also be suitable for the detection of crop pathogens, such as pathogenic microorganisms or toxic chemicals, thus enhancing the safety of the food supply. Moreover, more rapid detection of pests would enable farmers to apply pesticides to their crops before they were damaged, thereby decreasing losses and increasing sustainability. As an illustration of the potential of this technology, it has been shown that agricultural plants can internalize carbon nanotube-based sensors, which transmit signals to a smartphone when the plants become contaminated with pesticides. It is likely that these kinds of nano-enabled sensors will be used as part of precision agriculture in the future. Nevertheless, it will be important to ensure that the sensors themselves do not contaminate the crops, and that the sensors are affordable, reliable, and robust.

2.4. Nanobased Functional Materials. Nanotechnology is also being used to create a new generation of more sustainable and environmentally friendly materials to replace those based on synthetic polymers (plastics), which are known to be damaging the environment. In particular, there has been a considerable amount of work on the construction of biodegradable nanostructured packaging materials and coatings for agricultural and food products. These materials are typically assembled from natural polymers, such as proteins and polysaccharides. In addition, they may contain organic or inorganic nanoparticles embedded in the polymer matrix to improve their functional attributes, such as their appearance, mechanical strength, or barrier properties, as well as their antimicrobial or antioxidant activities. They may also contain other natural ingredients, such as anthocyanins, to act as natural sensors that provide information about the freshness or quality of the packaged foodstuff. The design of effective natural packaging materials requires knowledge of the structural organization and interactions of the various constituents at the nanoscale. This knowledge can then be used to enhance their functional performance. In the future, it will be important to ensure that these kinds of packaging materials can be mass-produced at an affordable cost, and that they maintain their desirable functional attributes under the conditions they are exposed to in real applications.

3. NANOTECHNOLOGY AND HEALTH

Researchers are also utilizing nanotechnology to increase the safety and improve the healthiness of foods. In this section, a number of promising applications of nanotechnology within this area are highlighted.

3.1. Improving Food Safety. Foods are prone to contamination by spoilage and pathogenic microorganisms that can increase food waste, as well as increasing the risk of foodborne illness and death. Traditionally, microbial contamination of foods was controlled using processing or storage technologies, such as thermal processing, dehydration, freezing, or pH control. More recently, chemical preservatives were developed for this purpose, including various kinds of organic acids, benzoic acid, sulfur dioxide, and nitrates. Nevertheless, many chemical preservatives are losing their efficacy as microorganisms develop antimicrobial resistance to them. In addition, the food industry is attempting to replace synthetic preservatives with more natural ones in response to consumer demands for “clean label” products. In particular, there has been interest in the identification of plant-based antimicrobials that are efficacious, but also more environmentally friendly. Researchers are therefore using nanotechnology to create a new generation of inorganic and organic nanoparticles that can be used as effective antimicrobial agents in foods.

Inorganic nanoparticles, such as those constructed from copper, gold, silver, and titanium, have been shown to be effective antimicrobials. These nanoparticles interact with the cell membranes of microorganisms, leading to the formation of small pores through which vital organelles leak out. In addition, some inorganic nanoparticles generate reactive oxygen species (ROS) that damage the cellular machinery inside the microorganisms, including DNA, RNA, proteins, or phospholipids. Despite being effective antimicrobials, inorganic nanoparticles are not particularly label friendly and there is some concern about their potential toxicity. As a result, many researchers are using nanotechnology to create antimicrobials entirely from natural organic ingredients.

In particular, there is great interest in developing antimicrobial nanoemulsions from essential oils, such as those extracted from edible botanical sources, such as cinnamon, cloves, garlic, lemon, orange, peppermint, and thyme. As mentioned earlier, essential oils are produced by plants to protect themselves against pests, such as bacteria, fungi, yeasts, and insects. These oils contain a complex mixture of different antimicrobial molecules to combat the variety of pests they have been exposed to throughout their evolution. Antimicrobial nanoemulsions containing these oils can deactivate microorganisms by disrupting their cell membranes and interfering with key biochemical processes. These nanoemulsions are able to reduce bacterial contamination of fresh produce, such as alfalfa seeds, mung beans, and radish seeds. In the future, these nature-derived antimicrobials may replace some of the synthetic ones currently used in the food industry.

An innovative nanotechnology approach for creating antimicrobial treatments has been developed at Harvard University. Pure water can be converted into a mist of nanometer-sized droplets (“Engineered Water Nanostructures”, or EWSN) containing reactive oxygen species using an electrospray/ionization method. As discussed earlier, ROS are particularly effective antimicrobial agents that can damage bacteria when they come into contact with them. This approach has been used to kill bacteria on fresh fruits and vegetables by...
passing them through a fine mist of nanodroplets. More recently, the efficacy of this approach has been improved by including natural antimicrobial agents (such as hydrogen peroxide, lysozyme, nisin, and/or citric acid) in the EWNS.21

There are various ways that antimicrobial-loaded nanoparticles can be utilized to deactivate food pathogens and spoilage organisms. They can be sprayed onto the surfaces of produce or the produce can be dipped into or washed with water containing the nanoparticles. They can be applied to the surfaces of food processing facilities or home kitchens to sanitize them. They can be incorporated into food packaging materials to deactivate microorganisms in the environment or on the food. They can be introduced into foods and beverages themselves as functional ingredients, as long as they are safe to consume. One potential problem associated with the ingestion of antimicrobial nanoparticles in foods is that they could pass through the gastrointestinal tract (GIT) and disturb the gut microbiome, which could have an adverse impact on human health.22 Consequently, it is important to ensure that the new generation of nano-enabled nanoparticles is safe for utilization.

3.2. Modulation of Macronutrient Digestion. It has been hypothesized that the steep increase in overweight, obesity, and diabetes during the past few decades is a result of the consumption of ultra-processed foods.2 The human GIT evolved to be highly efficient at extracting nutrients from the foods available to our ancient ancestors, which were often tough whole or minimally processed foods. Many foods produced by the modern food industry are highly processed so that their original structures are destroyed, such as soft drinks, fruit juices, breads, cookies, cakes, pastas, and snacks. As a result, these foods are quickly digested by the enzymes in our GIT, leading to a spike in the sugar or lipid levels entering the bloodstream, as well as a reduction in satiety response. Thus, ultra-processed foods may lead to dysregulation of our metabolic and hormonal systems, leading to increased risk of overeating and chronic disease.2 For this reason, many researchers are examining strategies for
Reducing the digestion of macronutrients within the GIT. Nanotechnology is one of the approaches being explored for this purpose. As mentioned earlier, it has been shown that incorporating nanocellulose into foods can reduce the rate and extent of macronutrient digestion. A number of physicochemical and physiological mechanisms have been proposed to account for this phenomenon: binding of enzymes, bile salts, or calcium to nanofibers; thickening or gelation of the gastrointestinal fluids by nanofibers, which slows down mixing and diffusion processes; and formation of nanofiber coatings around macronutrients that reduces the access of digestive enzymes. Other types of edible nanomaterials have also been shown to inhibit macronutrient digestion, including nanochitin. These types of nanomaterials may therefore be useful as functional ingredients to inhibit macronutrient digestion in processed foods, thereby helping to combat overweight, obesity, and diabetes. Nevertheless, further research is required to ensure that they are safe and do not cause undesirable health effects. For instance, recent studies have shown that nanochitin can reduce the bioaccessibility of oil-soluble vitamins.

3.3. Improving Bioavailability. The healthiness of foods can be improved by incorporating bioactive substances that have beneficial nutritional effects, such as vitamins, minerals, or nutraceuticals. Nevertheless, it is important to ensure that the incorporation of these substances does not adversely affect the quality attributes of foods, and that they are highly bioavailable after ingestion. Nanotechnology is particularly suitable for improving the food matrix compatibility and boosting the oral bioavailability of these bioactive substances. The bioavailability is usually taken to be the fraction that gets absorbed into the systemic circulation in an active form. Two different nanotechnology-based strategies have been developed to enhance the bioavailability of bioactive substances in foods: delivery and excipient systems (Figure 3). Delivery systems consist of bioactive-loaded edible nanoparticles that are designed to release the bioactive substances within the GIT so they can be absorbed by the epithelium cells. In the case of lipid nanoparticles, the delivery systems are designed to breakdown and form nanostructures (mixed micelles) within the gastrointestinal fluids that promote the transport and absorption of the bioactive substances. Excipient systems are foods that do not necessarily contain any bioactive components themselves, but are designed to increase the bioavailability of bioactive substances in natural foods consumed with them, such as fruits and vegetables. They do this by breaking down in the GIT and forming an environment that increases the bioaccessibility, stability, and/or absorption of the bioactive substances. As an example, in vitro studies have shown that the bioaccessibility of carotenoids in carrots can be greatly enhanced when they are co-ingested with excipient nanoemulsions. Excipient nanoemulsions could therefore form the basis of a new generation of creams, dressings, or sauces designed to boost the bioavailability of bioactive substances in fruits or vegetables eaten with them. In both cases, the rate of lipid digestion and bioactive bioaccessibility increases as the size of the droplets decreases (Figure 4), which is mainly attributed to the increase in surface area of the lipid phase exposed to the lipase in the gastrointestinal fluids.

3.4. Controlled or Targeted Gastrointestinal Delivery. A number of bioactive substances that may be beneficial to human health need to be delivered intact to specific locations within the GIT. For instance, digestive enzymes (such as lactase or lipase) may need to be delivered to the small intestine in individuals who suffer from diseases where they lack these enzymes, such as lactose intolerance or pancreatitis. Similarly, probiotic bacteria need to be delivered to the colon if they are going to have beneficial effects on the gut microbiome. However, enzymes and probiotics are often degraded in the upper GIT by acids, digestive enzymes, or bile salts before reaching their intended destination. Consequently, there is a need to encapsulate and protect these delicate bioactive substances under certain GIT conditions, but then release them at the required site of action (Figure 5). This can often be achieved using nanostructured particles, such as biopolymer-based nanoparticles or microgels. The diameter and pore size of these biopolymer particles can be controlled to slow down the diffusion of gastrointestinal constituents into them. Moreover, antiacids can be co-encapsulated with the bioactive components to prevent their degradation in the highly acidic gastric juices.

Figure 5. Bioactive substance can be encapsulated inside nanostructured microgels and then released in different regions of the gastrointestinal tract by selecting biopolymers with different sensitivities to gastrointestinal conditions, such as pH, ionic strength, or enzyme activity.
These nano-enabled particles are being investigated for their ability to deliver a wide range of bioactive molecules through the oral route.

3.5. Nano-enabled Sensing. Information about food properties is usually obtained by analyzing food by sophisticated analytical instruments, such as spectroscopy, chromatography, or mass spectrometry devices, in a dedicated laboratory. Nanotechnology, however, is now being employed to fabricate a new generation of tiny sensing devices that can provide data quickly and cheaply without the requirement of specialized training. As a result, food producers, distributors, retailers, and consumers can rapidly assess the status of food and beverage products. These nano-enabled sensors can be incorporated into food packaging materials or coupled to mobile phones so consumers can rapidly determine the quality attributes of their foods. In principle, these sensors can provide data about food composition, freshness, quality, and safety. Various kinds of nanotechnologies are being adopted to achieve this goal. As an example, nano-enabled sensors have been created to determine the levels of artificial colors, pesticides, and toxins in foods, which are based on Raman spectroscopy analysis of inelastic scattering from metal nanoparticles.

4. NANOTOXICOLOGY: THE POTENTIAL RISKS OF FOOD NANOTECHNOLOGY

One of the main concerns with using nanotechnology in foods is the potential risk to human health of consuming nanomaterials, as well as damage to the environment. As discussed earlier, one of the main reasons nanoparticles are utilized in the food industry is due to their unusual properties, which are associated with their relatively small dimensions. For instance, small particles are digested more rapidly, have a higher surface reactivity, and can penetrate through biological barriers more effectively than larger ones. These characteristics are useful to obtain novel or improved properties in foods, but they could also have unforeseen adverse effects on human health. Consequently, it is critical for those working in this area to consider both the risks and benefits of introducing nanoparticles into foods.

5. CONCLUSIONS

Nanotechnology has already led to the introduction of a diverse range of innovative functional materials in industry and medicine. In the food industry, this technology has great potential to improve the sustainability and healthiness of the food supply, provided that it is employed wisely. In this article, only a few representative examples of the use of nanotechnology for this purpose have been given, but there are many other possibilities. Nanotechnology can be used to convert substances isolated from waste materials into valuable commercial products, thereby reducing waste and stimulating the economy. Nanopesticides and nanofertilizers can be used to increase yields, reduce losses, enhance quality, and decrease the pollution associated with the production of agricultural crops. Nano-enabled sensors can be used to improve the efficiency of food production by providing detailed information about the composition, quality, and safety of crops and foods throughout the supply chain. Nanotechnology has also been shown to be particularly suitable for creating food-grade delivery systems to encapsulate, protect, and release bioactive substances, as well as to boost their bioavailability, which may lead to improvements in human health. Nevertheless, because nanomaterials do behave differently than conventional materials it is important to thoroughly understand their behavior in the environment and within the human body, to ensure that they do not cause any adverse health effects.

AUTHOR INFORMATION

Corresponding Author

David Julian McClements — Department of Food Science, University of Massachusetts, Amherst, Massachusetts 01003, United States; Department of Food Science & Bioengineering, Zhejiang Gongshang University, Hangzhou, Zhejiang 310018, China; orcid.org/0000-0002-9016-1291; Phone: 413 545 2275; Email: mclements@foodsci.umass.edu

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04050

Notes

The author declares no competing financial interest.

Biography

David Julian McClements is a Distinguished Professor at the Department of Food Science at the University of Massachusetts, an Adjunct Professor at Zhejiang Gongshang University, and a visiting Professor at the School of Public Health at Harvard University. He received a Ph.D. in Food Science from the University of Leeds and did postdoctoral work at the University of Leeds (UK), University of California (USA), and University College Cork (Ireland). He specializes in the areas of food biopolymers and colloids, with an emphasis on using nanotechnology and structural design principles to improve the quality, safety, shelf life, and nutritional attributes of foods. He has published over 1000 papers and a number of books in these areas.

ACKNOWLEDGMENTS

This material was partly based upon work supported by the National Institute of Food and Agriculture, USDA, Massachusetts Agricultural Experiment Station (MAS00491), and USDA, AFRI Grants (2016-08782 and 2020-03921).

REFERENCES

(1) Nile, S. H.; Baskar, V.; Selvaraj, D.; Nile, A.; Xiao, J. B.; Kai, G. Y. Nanotechnologies in Food Science: Applications, Recent Trends, and Future Perspectives. Nano-Micro Lett. 2020, 12, 45.
(2) McClements, D. J. Future Foods: How Modern Science is Transforming the Way We Eat, Springer Scientific: Cham, Switzerland, 2019.
(3) Willett, W.; et al. Food in the Anthropocene: the EAT—Lancet Commission on healthy diets from sustainable food systems. Lancet 2019, 393, 447–492.
(4) Bacchin, P.; Marty, A.; Duru, P.; Meireles, M.; Aimar, P. Colloidal surface interactions and membrane fouling: Investigations at pore scale. *Adv. Colloid Interface Sci.* 2011, 164, 2–11.

(5) DeLoid, G. M.; Sohal, I. S.; Lorente, L. R.; Molina, R. M.; Pyrgiotakis, G.; Stevanovic, A.; Zhang, R.; McClements, D. J.; Geitner, N. K.; Bousfield, D. W.; Ng, K. W.; Loo, S. C. J.; Bell, D. C.; Brain, J.; Demokritou, P. Reducing Intestinal Digestion and Absorption of Fat Using a Nature-Derived Biopolymer: Interference of Triglyceride Hydrolysis by Nanocellulose. *ACS Nano* 2018, 12, 6469–6479.

(6) Barrow, C. J. Biochar: Potential for countering land degradation and for improving agriculture. *Appl. Geography* 2012, 34, 21–28.

(7) Soares, R. M. D.; Siqueira, N. M.; Prabhakaram, M. P.; Ramakrishna, S. Electrospinning and electrospray of bio-based and natural polymers for biomaterials development. *Mater. Sci. Eng., C* 2018, 92, 969–982.

(8) Elmer, W.; De La Torre-Roche, R.; Pagano, L.; Majumdar, S.; Zuverza-Mena, N.; Dimkpa, C.; Gardea-Torresdey, J.; White, J. C. Effect of Metalloid and Metal Oxide Nanoparticles on Fusarium Wilt of Watermelon. *Plant Dis.* 2018, 102, 1394–1401.

(9) Shang, Y. F.; Hasan, M. K.; Ahammed, G. J.; Li, M. Q.; Yin, H. Q.; Zhou, J. Applications of Nanotechnology in Plant Growth and Crop Protection: A Review. *Molecules* 2019, 24 (14), 2558.

(10) Rao, J. J.; Chen, B. C.; McClements, D. J. Improving the Efficacy of Essential Oils as Antimicrobials in Foods: Mechanisms of Action. *Annu. Rev. Food Sci. Technol.* 2019, 10 (1), 365–387.

(11) Zaynab, M.; Fatima, M.; Abbas, S.; Sharif, Y.; Umair, M.; Zafar, M. H.; Bahadar, K. Role of secondary metabolites in plant defense against pathogens. *Microb. Pathog.* 2018, 124, 198–202.

(12) Ma, C. X.; White, J. C.; Zhao, J.; Zhao, Q.; Xing, B. S. Uptake of Engineered Nanoparticles by Food Crops: Characterization, Mechanisms, and Implications. *Annu. Rev. Food Sci. Technol.* 2018, 9, 129–153.

(13) Dimkpa, C. O.; Bindraban, P. S. Nanofertilizers: New Products for the Industry? *J. Agric. Food Chem.* 2018, 66, 6462–6473.

(14) Rodrigues, S. M.; Demokritou, P.; Dokoozlian, N.; Hendren, C. O.; Karn, B.; Mauter, M. S.; Sadik, O. A.; Safarpour, M.; Unrine, J. M.; Viers, J.; Welle, P.; White, J. C.; Wiesner, M. R.; Lowry, G. V. Nanotechnology for sustainable food production: promising opportunities and scientific challenges. *Environ. Sci.: Nano* 2017, 4, 767–781.

(15) Wang, P.; Lombi, E.; Zhao, F. J.; Kopitke, P. M. Nanotechnology: A New Opportunity in Plant Sciences. *Trends Plant Sci.* 2016, 21, 699–712.

(16) Atzberger, C. Advances in Remote Sensing of Agriculture: Context Description, Existing Operational Monitoring Systems and Major Information Needs. *Remote Sensing* 2013, 5, 949–981.

(17) Wong, M. H.; Giraldo, J. P.; Kwak, S. Y.; Koman, V. B.; Sinclair, R.; Lew, T. T. S.; Bisker, G.; Liu, P. W.; Strano, M. S. Nitroaromatic detection and infrared communication from wild-type plants using plant nanobionics. *Nat. Mater.* 2017, 16 (2), 264–272.

(18) Youssfi, A. M.; El-Sayed, S. M. Bionanocomposites materials for food packaging applications: Concepts and future outlook. *Carbohydr. Polym.* 2018, 193, 19–27.

(19) Wang, L. L.; Hu, C.; Shao, L. Q. The antimicrobial activity of nanoparticles: present situation and prospects for the future. *Int. J. Nanomed.* 2017, 12, 1227–1249.

(20) Landry, K. S.; Micheli, S.; McClements, D. J.; McLandsborough, L. Effectiveness of a spontaneous carvacrol nanoemulsion against Salmonella enterica Enteritidis and Escherichia coli O157:H7 on contaminated broccoli and radish seeds. *Food Microbiol.* 2015, 51, 10–17.

(21) Huang, R. Z.; Vaze, N.; Soorneedi, A.; Moore, M. D.; Xue, Y. L.; Bello, D.; Demokritou, P. Inactivation of Hand Hygiene-Related Pathogens Using Engineered Water Nanostructures. *ACS Sustainable Chem. Eng.* 2019, 7, 19761–19769.

(22) Lamas, B.; Breynier, N. M.; Houdeau, E. Impacts of foodborne inorganic nanoparticles on the gut microbiota-immune axis: potential consequences for host health. *Part. Fibre Toxicol.* 2020, 17, 19.

(23) Zhou, H. L.; Tan, Y. B.; Lv, S. S.; Liu, J. N.; Mundo, J. L. M.; Bai, L.; Rojas, O. J.; McClements, D. J. Nanochitin-stabilized pickering emulsions: Influence of nanochitin on lipid digestibility and vitamin bioaccessibility. *Food Hydrocolloids* 2020, 106, 105878.

(24) Aboalnaja, K. O.; Yaghmoor, S.; Kumosani, T. A.; McClements, D. J. Utilization of nanoemulsions to enhance bioactivity of pharmaceuticals, supplements, and nutraceuticals: Nanoemulsion delivery systems and nanoemulsion excipient systems. *Expert Opin. Drug Delivery* 2016, 13, 1327–1336.

(25) Zhang, R. J.; Zhang, Z. P.; Zou, L. Q.; Xiao, H.; Zhang, G. D.; Decker, E. A.; McClements, D. J. Impact of Lipid Content on the Ability of Exciptent Emulsions to Increase Carotenoid Bioaccessibility from Natural Sources (Raw and Cooked Carrots). *Food Bioprocess* 2016, 11, 71–80.

(26) McClements, D. J. Designing biopolymer microgels to encapsulate, protect and deliver bioactive components: Physicochemical aspects. *Adv. Colloid Interface Sci.* 2017, 240, 31–59.

(27) Wang, Y.; Duncan, T. V. Nanoscale sensors for assuring the safety of food products. *Curr. Opin. Biotechnol.* 2017, 44, 74–86.

(28) Zheng, J. K.; He, L. L. Surface-Enhanced Raman Spectroscopy for the Chemical Analysis of Food. *Compr. Rev. Food Sci. Food Saf.* 2014, 13, 317–328.

(29) Sharifi, S.; Behzadi, S.; Laurent, S.; Forrest, M. L.; Stroeve, P.; Mahmoudi, M. Toxicity of nanomaterials. *Chem. Soc. Rev.* 2012, 41, 2323–2343.