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Applications of Nanomaterials in Food Industry: A Review †

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Abstract: The functionalization of nanostructured materials finds many applications in the food industry. Some of these areas include nanosensors and new packaging materials. Nanosensors are used for the detection of toxic and nonedible components in food. In food packaging, it can be possible to obtain antioxidant-featured nanomaterials using nanoparticles, nanofibers, nanocrystals, and nanoemulsions. It is important to find suitable food nanomaterials for both the consumer and the environment. Therefore, researchers have studied the risks of food nanomaterials for humans in case of a long time usage.

Keywords: nanosensors; food packaging materials; nanotoxicology

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1. Introduction

Nanotechnology can be defined as designing, producing, and applicating the materials whose size are in the nanoscale range (1–100 nm) [1]. Nanomaterials can be sorted into two groups with respect to their material and shape. The material group includes metallics, carbon, organic, boron nitride, minerals, and silicon, while the shape group involves quantum dot, nanowire, nanofiber, aerogel, nanorod, nanosheets, and nanotubes, etc. [2]. Nanomaterials have unique features such as a high surface energy, adsorption capacity, and biological effectiveness. Degrading the size of material to the nanoscale improves several of the chemical and physical properties of the material such as diffusivity, strength, and solubility, meaning they have a low density, and a high stability chemically, mechanically, and kinetically as a result. Due to these unique features of nanomaterials, nanotechnologies can be applied across several areas such as medicine, agriculture, environment, and food [3]. Within the scope of medicine, it has been known that carbon quantum dots can be a promising candidate to drug delivery in cancer treatment due to its properties such as its high biocompatibility, small size, and low toxicity [4]. Additionally, Xie et al. [5] showed that mesoporous silica aerogels can be effective as potential carriers in antibacterial agent delivery applications. Another study showed that metal–organic frameworks can be used in magnetic resonance imaging (MRI) and computed tomography (CT) for clinical diagnosis [6]. In terms of agriculture, one study that is relevant for this context was published by Tran et al. in 2023. These researchers observed that gold-added ZIF-67 can be used a solution to detect some harmful pesticides in Raman spectroscopy rapidly and with a high sensitivity [7]. In addition, Siddiqui et al. [8] produced a few-layer MoS_2 nanosheet which can function as a long-lasting soil moisture sensor. Furthermore, there are many studies available in the literature which are about nanomaterial usage in environmental issues. For example, it has been presented that graphene-based nanomaterials can be effective in polycyclic aromatic hydrocarbon (PAH) removal from wastewater through adsorption processes [9]. Zhang et al. [10] published an interesting review article about nanomaterials usage in electromagnetic wave absorption. They revealed that MoS_2 nanosheets are among some of them. Alavi et al. [11] used graphene nanoplatelets and ZnO nanoparticles to degrade already used lubricating oil which was composed of environmentally hard decomposable hydrocarbons via pyrolysis. Saleem et al. [12] showed in their paper that nanomaterial-based sensors can be effective for the detection of harmful gases such as sulfur dioxide and hydrogen sulfide. Yu et al. [13] conducted an investigation regarding dye adsorption with hybrid nanomaterial-based adsorbents. They observed that the adsorbent, which was composed of carbon nanofibrils and graphene nanoplates reached 1178.5 mg g^{-1} and 585.3 mg g^{-1} adsorption capacity for the methylene blue and Congo red dyes, respectively. Hu et al. [14] used the ZIF-67 type nanomaterial to produce glycerol carbonate through a carbon dioxide–glycerol conversion. Martinez et al. [15] conducted their research regarding catalytic biodiesel production using magnetic nanoparticles which can function as carriers for the relevant enzymes.

Interestingly, all foods which are plant or animal-based can include nanomaterials, including for example, DNA, which has a 2.5 nm width. In addition, milk encompasses nano-sized components including whey protein and lactose [16]. Nowadays, nanotechnology is mainly used for packaging and nanosensing in the food sector. Another important topic is nanotoxicology, which originates from nanomaterial usage in food [17]. The aim of this study was to reveal novel studies regarding these topics across the food industry.

2. Nanomaterials for Food Packaging

It is important to produce to packaging materials which possess resistance to steam and atmospheric gases. Moreover, mechanical and thermal stability are further additional desired properties for food packaging. Up to now, non-biodegradable petroleum-based plastic packaging materials have been used in food industry. Nowadays, with respect to the green approach, researchers have investigated nanomaterials in relation to food packaging [18]. In Figure 1, the most used nanomaterials in food packaging are shown.

Figure 1. The most eminent nanomaterials for food packaging applications described in the literature.

2.1. Metallic Nanomaterials

Metal and metal oxide nanomaterials can be used in food packaging to enable antibacterial and antifungal properties of the packaging material. Ag, Cu metals, zinc, copper, iron, and titanium oxides have typically been the main nanoparticles used for this purpose [19]. Ameen [20] synthesized bi-metallic (copper and silver) nanoparticles to yield a maximum yield and achieved the inhibition of three human pathogens with this packaging material. Lu et al. [21] revealed that specifying the size of TiO_2 nanoparticles can prevent its harmful damage on human cells. They proposed a 110–300 nm scale as suitable range.

2.2. Carbon Nanomaterials

Carbon nanomaterials provide a long shelf life, and exhibits no contamination effects on food. Carbon-based nanomaterials are synthesized mainly through the green routes. They provide antibacterial protection to the food, which is thereby being preserved as a result. In food packaging, carbon dots, graphene, and carbon nanotubes can be used [22]. Goh et al. [23] synthesized polylactic acid-graphene food packaging material to provide a mechanically stable, biodegradable, resistance against both oxygen and steam. This material was found to increase the shelf life of potato chips.

2.3. Organic Nanomaterials

Natural and edible biopolymers (including starch, chitosan, gelatin, and agar) are used to protect food. Chitosan is known to be non-toxic in nature and mechanically stable. However, it has low moisture resistance. Therefore, researchers have since improved this property by reinforcing it with nanomaterials, termed as chitosan-based nanocomposite films [24,25].

2.4. Silicon Nanomaterials

It has been reported that silica aerogel incorporation to the food packaging polyvinyl alcohol film exhibits an increased thermal stability and steam resistance for chocolate packaging [26]. However, it has since been revealed that silica nanoparticles can be harmful to human cells [27].

3. Nanosensors

Nanosensors have been typically used for screening pathogens and chemicals in food. Nanosensors are designed to detect environmental changes such as in temperature, humidity, and gas composition. Nanosensors are classified as chemical nanosensors and nano biosensors. There are several nanosensor-based applications used in the food industry. Nanoelectromechanical systems (NEMS) can be applied to detect food pathogens. Electronic nose can be used for wine discrimination. Carbon nanotube-based sensors are utilized to measure capsaicinoids in chili peppers [28]. Contemporary research regarding nanosensing in the food industry are shown in Table 1.

Table 1. Current nanosensing applications published in the literature for food applications.

Material	Application	Reference
Molecularly imprinted silica layers appended to quantum dots (MIP-QDs)	Fluorescence sensor to detect saxitoxin toxin in shellfish	Sun et al. [29]
Rhodamine B/UiO-66-N_3	H_2S detection via reaction-based ratiometric fluorescent nanosensor	Gao et al. [30]
SnO_2 nanowires	Gas sensor to distinguish methanol from ethanol in alcoholic beverages	Tonezzer et al. [31]
Carboxylated multi-walled carbon nanotubes (c-MWCNT)-modified screen-printed electrode-based bionanosensor	Detecting the time of ripening of tomato with respect to its malic acid concentration	Dalal et al. [32]
Glassy carbon electrode (GCE) modified with calixarene and gold nanoparticles	Detecting two toxic food dyes (metanil yellow and fast green)	Shah [33]

4. Nanotoxicology

Nanotoxicology refers to the generated problems in human health and the environment which originate from nanomaterials. Several physicochemical properties determine whether the nanomaterial will be toxic or not such as particle size, chemical composition, surface area, shape, crystallinity, structure, surface functional groups/charge, surface coating, and reactivity. These properties can be adjusted using the relevant synthesis methods [34]. As an alternative to toxic nanomaterials, researchers have focused on incorporating nanomaterials into biopolymers, as biopolymers are regarded as biodegradable, renewable, non-toxic, and environmentally safe materials. Proteins, polysaccharides, and lipids derived from plants or animals are examples of molecules belonging to the biopolymer class. Biopolymers can be produced using microorganism-like bacteria [35]. In the last year, Gautam et al. published a study regarding the production of biopolymers from waste foods [36], which was deemed as an interesting and green topic for food recycling. In Figure 2, the process of waste food processing to biopolymer production has been illustrated.

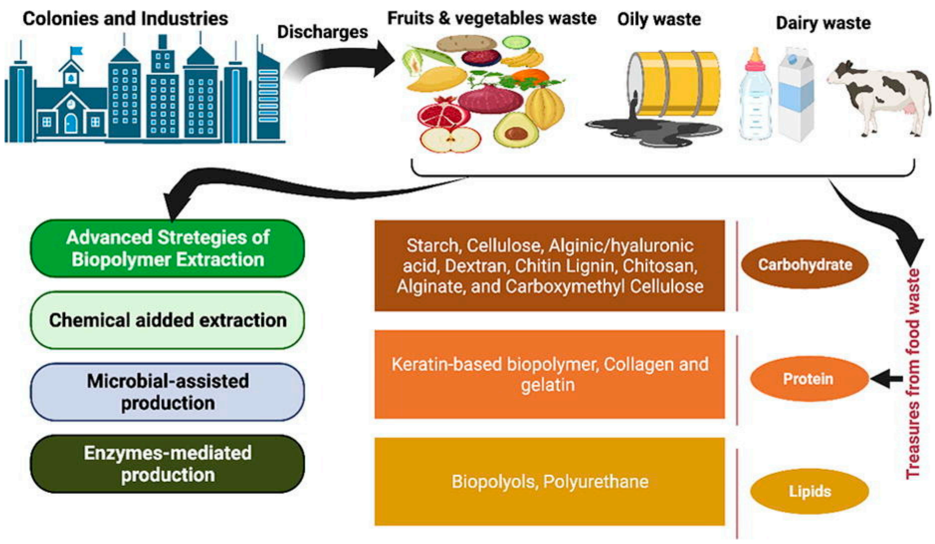

Figure 2. Biopolymer production route from food waste. Reprinted with permission from Ref. [36]. Copyright 2023 Elsevier.

5. Conclusions

Materials which are of nano-sizes possess several unique properties compared to other materials such as stability under chemical and mechanical conditions, low density, and a high surface energy and adsorption energy. The high surface energy of a nanomaterial originates from the high surface area/volume of this matter. Therefore, nanomaterials can be used across numerous sectors including agriculture, medicine, food industries, and environmental applications. In the food industry, nanotechnology takes place mainly in the forms of food packaging, biosensing, and chemical-sensing applications. In food packaging, nanomaterials are important candidates as petroleum-based plastics are mainly used in this area. Carbon materials come to the forefront in food packaging as an alternative material as they can be synthesized by applying green routes, and they do not create any contamination with the food which is in the packaging. On the other hand, nanosensors have been designed for detecting chemicals and toxic materials which can occur in the food. These materials, including quantum dots, carbon nanotubes, and gold nanoparticles can be used as nanosensor applications. However, it is important to select true nanomaterials which have no hazardous effects on both the environment and human health. Therefore, nanotoxicology, which is caused by nanomaterial usage in foods, is a crucial issue.

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