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Perspective Article

Bio-nanocomposites as future food packaging materials: A multi-faceted comparison

Murat Yanat [a,b,*], Karin Schroën [a]

[a] Laboratory of Food Process Engineering, Wageningen University and Research, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands
[b] Department of Food Engineering, Akdeniz University, 07000 Antalya, Turkiye

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ABSTRACT

Although bio-nanocomposites hold advantages over fossil-based materials, e.g., their price and barrier properties do not measure up to those of classic plastic materials, which prevents their wide-spread application. Still, due to their biodegradability, and lower environmental impact, bio-nanocomposites have attracted considerable interest, especially to address the growing issue of plastic pollution in the environment. In this review, we explore bio-nanocomposites as potential future food packaging materials from multiple perspectives. We focus on key topics related to their use, including their biodegradability, functional features, and their potential for replacing conventional plastic packaging. Furthermore, we highlight significant advancements in bio-nanocomposite research, particularly their ability to improve food preservation through antimicrobial and antioxidant properties. In addition, we address critical challenges that must be overcome for the widespread adoption of bio-nanocomposites in food packaging. These challenges include regulatory issues, the need for standardized legislation, and integration of bio-nanocomposites with existing waste management systems to ensure their environmental benefits are fully realized.

1. Introduction

Plastic is abundantly used in society as a result of its lightweight, durable nature, and low production costs [1,2], which also has led to environmental concerns given its single-use, and fossil-based nature. Around 40 % of global plastic production is dedicated to packaging [3], and many of it ends up in nature, remaining there for centuries due to its slow degradation. This has created a rising demand for alternative packaging materials. Bioplastics, a term that covers plastics that are either biobased and/or biodegradable or compostable has been termed as eco-friendly alternative to traditional fossil-based plastics [4]. It is important to mention that bioplastics include non-biodegradable plastics and may be derived from fossil fuels [5], and this has led to misconceptions about their environmental impact. There are bio-based and biodegradable polymers such as polylactic acid (PLA) and polyhydroxybutyrate (PHB) can help reduce dependence on fossil fuels, and contribute to reducing plastic pollution.

For transitioning from conventional plastics to eco-friendly alternatives, the properties of such materials must match those of fossil-based plastics. Nanocomposites, that are obtained by incorporating and dispersing nano-sized substances into polymers have been suggested for this purpose [6,7]. Silica, clay, graphene, titanium dioxide, iron oxide, and silver nanoparticles have been put into bioplastic matrices, yielding significant enhancements, particularly in mechanical strength and barrier properties [8–10]. For instance, incorporating montmorillonite and multi-walled carbon nanotubes into PLA improved thermal properties [11]. However, when applied in food packaging, the nanoparticles must be safe for food contact, be biodegradable, not lead to adverse environmental effects, and be economically feasible. Therefore, in this study, we focus on materials of which both the base polymer and the particles are comprised of bio-based and biodegradable substances.

This review focuses on key topics related to the potential application of bio-nanocomposites in food packaging, highlighting key advancements and matters that require further exploration. It summarizes the progress in bio-nanocomposite design, specifically focusing on food packaging applications, highlighting functional features. The final sections discuss key points regarding the future use of these materials from both technological and societal perspectives.

* Corresponding author at: Laboratory of Food Process Engineering, Wageningen University and Research, Bornse Weilanden 9, 6708 WG Wageningen, the Netherlands
E-mail address: muratyanat@akdeniz.edu.tr (M. Yanat).

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2. Biobased and biodegradable plastics

Table 1 compares the properties and costs of fossil-based and bio-based plastics. Bio-based plastics, particularly PLA and PHB are competitive with fossil-based plastics in terms of mechanical properties but require improvements in barrier properties compared to the current industrial benchmark, PET.

While bio-based and biodegradable plastics have some features that are comparable to those of 'regular' plastics, their higher costs remain a constraint. They are expected to become price-competitive in the future, driven by fluctuating and most probably increasing oil prices, the finite nature of fossil resources, and advancements in production technologies. Besides, the properties of biodegradable plastics are still in need of improvement. This can be achieved by adding plasticizers to enhance flexibility, although this may be at the expense of tensile strength and gas barrier properties [23]. Multilayer films can significantly improve barrier properties, but challenges remain in creating fully biodegradable options and in recycling these complex structures [24]. Nanoparticles hold the potential to improve polymer material properties because the extent of their influence goes beyond their size. In a recent paper, we connected the various scales that are relevant in nanocomposite design and highlighted the interphasial layer effects that stem from the presence of nanoparticles, and are transferred to the bulk material to an extent much greater than the mass percentage used in the formulation would suggest [6,25].

3. Why bio-nano?

Bio-nano particles can be sourced from various waste or side streams of agrifood products, and are thus wildly available. Due to their renewable nature they are a sustainable option, that is if their production can be carried out in a sustainable way [25,27]. Bio-nanoparticles can be produced from the polysaccharide structures they are part of through simple methods, such as ultrasonication and acid treatments. Thus these particles can be a relevant choice for enhancing biodegradable plastics. Their nanometer size leads to a high surface area available for interaction with the matrix material thus possibly improving strength. Compared to inorganic or metallic nanoparticles, bio-based particles are less harmful to ecosystems and organisms [16,23,26].

Incorporation of bio-nanoparticles has led to considerable improvements in biodegradable plastics as summarized in Table 2. Bio-nanoparticles not only improve the mechanical properties, flexibility, and biodegradation of bioplastics but also offer other functionality like antimicrobial and antioxidant effects [15,28]. For example, chitin nanocrystals and chitosan nanoparticles have been shown to enhance the mechanical strength of films and have antioxidant capacity, and their properties can be tailored which increases their versatility [32,33].

From the perspective of mechanical properties, uniform distribution of nanoparticles is preferred. To mitigate nanoparticle agglomeration, surface modification was used [32,33]. The extent to which material functionality is affected depends on the particle size; small particles create bigger effects. For example, chitin nanocrystals have up to five times higher antioxidant activity compared to crude chitin powder, and this is also a function of the position of the nanocrystals (1 to 5 %) in PLA films, with particles at the surface giving stronger effects [34]. The particles should not be released, which was confirmed using food simulant media on chitin-reinforced PLA [35], implying that non-migratory active packaging concepts may be within reach. Current active packaging concepts often rely on release of phenolics, essential oils, or synthetic antioxidants (BHA, BHT) from the food package [36–38] which may lead to negative sensory effects. Additionally, such ingredients may cause discoloration during processing or storage. Using bio-nano-fillers, such as chitin nanocrystals and chitosan nanoparticles, which inherently possess antioxidant and antimicrobial properties, is expected to prevent undesired sensory changes in packaging during storage [28–34] due to their no-migratory behavior. This underscores the potential of enhancing the functional properties of biodegradable polymers on various aspects including long-lasting and stable antioxidant and/or antimicrobial effects.

Table 2
Bio-nanocomposite examples made of various polysaccharide nano-fillers and biodegradable plastics.

Nano-filler	Source	Film type	Achieved properties	Reference
Lignin NPs	Rice husks	PLA	▪Enhanced elongation at break ▪Providing UV-blocking property ▪Antioxidant activity	[29]
Cellulose NCs	Not specified	PHB	▪Improved gas barrier properties ▪Higher glass transition temperature	[30]
Starch NPs	Cassava	PLA	▪Improved polymer's thermal stability ▪Slight increases in the elastic modulus and tensile strength	[31]
Chitin NCs	Sea crustaceans	PLA	▪Enhancing mechanical and barrier properties ▪Antioxidant and antimicrobial activities	[15]
Chitosan NPs	Sea crustaceans	PLA	▪PLA's degree of crystallization improved ▪Antioxidant and antimicrobial activities	[28]

*NPs; nanoparticles, NCs; nanocrystals.

4. Beyond active packaging

In today's world, 'smart' systems have become an integral part of our lives, and that will become more and more the case for food packages that rely on active packaging in combination with intelligent monitoring of foods during their life time (Fig. 1). These packages offer information,

Table 1
Mechanical, thermal, and barrier properties of fossil-based and biobased plastics. Data from [12–22]. LDPE: Low-density polyethylene, PET: Polyethylene terephthalate, PP: Polypropylene, PS: Polystyrene, PLA: Polylactic acid, PHB: Polyhydroxybutyrate, PCL: Polycaprolactone, PBAT: Polybutylene adipate terephthalate, PBS: Polybutylene succinate.

Property	LDPE	PET	PP	PS	PLA	PHB	PCL	PBAT	PBS
Tensile strength (MPa)	10–12	55–79	15–27	24–60	37–74	20–44	10–30	14–24	32–42
Elongation at break (%)	300–500	15–165	100–600	1.6–2.5	0.5–9.2	5–10	200–1250	80–500	30–275
Oxygen permeability (cm^3/m^2 day bar, at 23 °C, 50 % RH)	2000	10	800	1500	150	250	530	450	110
Water vapor permeability (g/m^2 day, at 23 °C, 85 % RH)	1.4	4	0.8	20	30	12	47	27	37
Glass transition temperature - (T_g) (°C)	−110	76	−20	90	55	9	−62	−25	−30
Transparency (Clarity)	High	Excellent	Poor	Excellent	High	High	High	High	Poor
Price (€/ton)	1510–1580	1160	1460–1660	2050–2140	2500–4000	4000–15,000	3500–7500	3500–4500	5250–5750

Fig. 1. Biodegradable smart packaging design.

for example, through a QR code or a NFC (near-field communication) tag, enabling consumers to access information about the product, including its origin, nutritional content, or recommended use [39]. Beyond this, the packaging is evolving to include sensors and indicators that provide real-time information about the freshness of the contents, helping consumers determine when a product is no longer safe to consume—surpassing the limitations of traditional 'use before' dates. These innovations are expected to be particularly relevant for the fast moving consumer goods sector, where ensuring product freshness and safety is critical. This can enhance supply chain efficiency and sustainability, which are key challenges in this industry, although it is good to mention that there are still legal matters that need to be solved. It is good to realize that current indicators are made of non-renewable and non-biodegradable synthetic materials [40–42], which are not easily separated from packaging. Recent developments have led to bio-based and biodegradable sensors, indicators, and data carriers that do not need to be removed [43–46], which is an important step toward the development of fully biodegradable smart packages.

For future food packaging design, technological advancements as well as environmental concerns need to be taken into account. Plastic pollution can be seen as a result of our failure to predict the impact of this break-through invention. Packaging materials will be developed to be more in accordance with the food properties that need to be maintained, and the needs of the consumer. Anticipating this change now and designing packaging in harmony with nature will need to be prioritized.

5. Integrating bio-nanocomposites in modern food packaging practice

In recent years the prices of bioplastics have notably decreased although they are high compared to conventional plastics (Table 1), which prevent their use. Still, there are areas in which bioplastics can be used e.g., as part of multilayer packaging that combines the strengths of diverse materials to create protective, functional barriers [47–51]. By incorporating bio-nanocomposites it is possible to enhance gas barrier functionality, as well as create additional functionality such as antimicrobial protection. Still, making multi-layered materials and recycling them is a complex matter [52,53].

In essence, we need to rethink packaging, giving equal importance to end-of-life considerations and the required functionality during their life-time. Extending the shelf life of high-carbon-footprint foods, such as meat and its derivatives, through advanced packaging offers noteworthy potential for reducing food waste and enhancing sustainability (clearly, not producing these foods would make an even bigger sustainability impact). A Life Cycle Analysis (LCA) study by Pauer et al. (2020) revealed that the carbon footprint of bacon stored in flexible multilayer packaging is 54 times greater than the packaging itself [54]. This underscores the room for advanced packaging design to curb environmental impact, away from replacing conventional plastics with bio-nanocomposites which is a boost in this direction [55]. For recent information, we refer through to papers on biodegradable multilayer packaging [55–58].

6. Safety and legislation

Global organizations like FAO, WHO, EU, and FDA have nanotechnology-related regulations for the food industry, yet specific legislation directly addressing bio-nanocomposite packages remains limited. The safety and inertness of Food Contact Materials (FCMs) were first outlined in Commission Regulation (EC) No 1935/2004, emphasizing that materials must not release harmful substances into food or alter its composition, taste, or odor [59]. Additional EU regulations, like Commission Regulation (EC) No 450/2009 [60], require a case-by-case evaluation for materials containing nanomaterials. Although Commission Regulations (EC) No 975/2009, 1282/2011, and 202/2014 for plastic materials do not directly address bio-nanocomposites, they do specify migration limits and conditions for nanomaterial use [61–63]. Commission Regulation (EU) No 1245/2020 provides detailed guidelines on migration limits for chemical substances in food (simulants): Cu (5 mg/kg), Zn (5 mg/kg), and Mg (0.6 mg/kg) [64]. The fact that nanoparticles have very low migration tendency compared to the chemicals mentioned earlier, this positions them favorably for application in food packaging.

7. Integration with waste framework directive

Another vital aspect to consider is the end-of-life options for these materials. Governments and international organizations have started paying more attention to plastic pollution, and production and disposal guidelines have been published [65–68]. According to the Waste Framework Directive issued by the European Commission [65], the majority (86 %) of plastic waste generated in Europe is handled using linear methods [69], and is thus not part of circular solutions or economies (Fig. 2).

Bio-nanocomposites tap into at all stages of the Waste Framework Directive, including composting as a viable end-of-life option. The waste management hierarchy emphasizes resource reduction by product design strategies [65], that e.g., are aimed at lightweight materials, extending lifespan, and promoting reuse. Bio-nanocomposites are expected to have improved properties, possibly leading to a reduction of packaging material. The previously mentioned additional functionalities, are expected to contribute to sustainability by reducing food waste. It is good to keep in mind that use, recycling, energy recovery, and composting of bioplastics (for which substantial investments are needed) is still in the early development stages. The next steps that need to be taken for the nanocomposites are:

(i) Examining whether degradation is influenced by the presence of nanoparticles.
(ii) Assessing to what extent the mechanical properties are preserved in time.
(iii) Evaluating the material's performance from a food safety perspective.

Some positive results have been obtained with bioplastic films reinforced with silk nanocrystals that show delayed degradation, and maintained mechanical properties after repeated recycling [70,71], but overall the information is limited. The main reasons for bioplastic's status as favored polymer are its biodegradability: these materials can be broken down into water, carbon dioxide, and biomass within a couple of weeks under industrial composting conditions [72,73]. Even if their disposal is mismanaged or they end up in landfills, they will biodegrade within a matter of months to years, which compares favorably to conventional plastics that can remain for hundreds of years without considerably breaking down. Energy recovery by incineration is also an end of life option for bio-nanocomposites. For example, the thermal energy recovery of PLA (~20 MJ/kg) is comparable to conventional plastics (PET: ~22 MJ/kg, PVC: ~18 MJ/kg) [74,75], with no substances with toxicological significance produced [74].

The fact that bio-nanocomposites offer a number of end-of-life options, which may seem advantageous, but can also create confusion in society. Fig. 3 illustrates waste bins and disposal routes currently in use in The Netherlands. In theory, bioplastics and bio-nanocomposites can be disposed of as organic, plastic/metal, and municipal (mixed) waste. Conventional fossil-based and bio-nanocomposites will coexist for considerable time, and in order to arrive at a better situation, two key elements need to be taken into account: (i) revising current waste management systems by including bio-nanocomposites, and (ii) increasing public awareness for promoting better waste management.

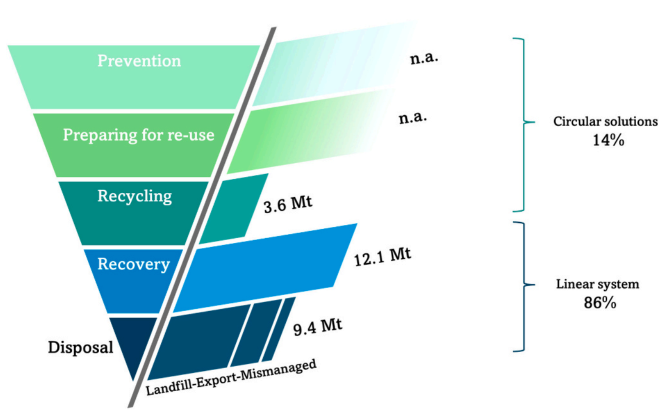

Fig. 2. The waste hierarchy described by the European Commission (left) and the distribution of how plastic waste was managed in Europe in 2020 (right, the data was taken from [69]).

Whether the most environmentally beneficial option can be put in practice, depends on the availability of composting and recycling facilities that continue to grow. The sustainable and circular disposal of bio-nanocomposites can be expected to become increasingly feasible and widespread.

8. Biodegradation

Despite the efforts to develop the waste management systems mentioned above, a substantial amount of plastic materials continues to be improperly discarded in nature. In 2019, over two-thirds of the 353 million tons of plastic waste was either sent to landfill or incinerated, and 22 % (79 Mt) was mismanaged (not properly collected, dumped in unregulated sites on land or ocean, or openly burned) [76,77]. There is no doubt that bio-nanocomposites will face the same fate when their production volumes increase. For this reason, understanding their biodegradability across various environments and conditions is of critical importance. It is generally accepted that these biopolymers degrade more rapidly at elevated or fluctuating temperatures, as well as in environments with higher microbial load. For instance, multiple studies have reported biodegradation rates exceeding 90 % for biodegradable polymers such as PLA, PHA, and PBAT when composting at 58 °C [78–82], while biodegradability can decrease significantly at lower temperatures (below 25 °C) in seawater or other aqueous environments [35,83–88]. As we go, more and more information will become available, allowing better choices to be made.

Specifically for nano-composites, the presence of the nanoparticles has been reported to both positively and negatively affect biodegradability. In general, hydrophobic nanoparticles, particularly metals or inorganic materials, increase polymer crystallinity, thereby slowing the biodegradation process [89–91]. In contrast, polysaccharide nanoparticles and other substances that microorganisms can utilize, may accelerate biodegradation [92–95] by improving water penetration within the polymer. Therefore, incorporating bio-nano-fillers may offer dual benefits; enhancing the properties of the biopolymer while simultaneously improving its biodegradability.

9. Other aspects

Plasticizers and compatibilizers may enhance the performance and functionality of plastics in general, e.g., improving flexibility and compatibility, but also pose safety risks through migration into food or the environment. Additives also affect biodegradability and end-of-life options; biodegradable ones aid decomposition, whereas non-biodegradable ones may hinder it, complicating recycling and composting processes [96–100]. To mitigate these risks, biodegradable additives seem the way forward.

Whether bio-nanocomposites will be able to replace conventional plastics will greatly depend on consumer acceptance. While these materials offer benefits in terms of performance and environmental sustainability, their costs could from a barrier. Especially given the current state of the art, it is crucial to communicate the long-term value of bio-nanocomposites (reduced environmental impact) to justify the price. Education and clear labeling can help build consumer trust. Ultimately, balancing cost with perceived value will be essential for fostering acceptance and integration into daily life.

10. Conclusion

The unique characteristics of bio-nanocomposites imply that they can serve as food packaging materials that meet standard functional requirements as well as provide advanced features, such as anti-oxidant and anti-microbial activity. Their most important selling point is their biodegradability, making them a logical solution to plastic pollution. Widespread bio-nanocomposite use faces challenges, including current costs, the absence of well-defined waste management systems, and gaps

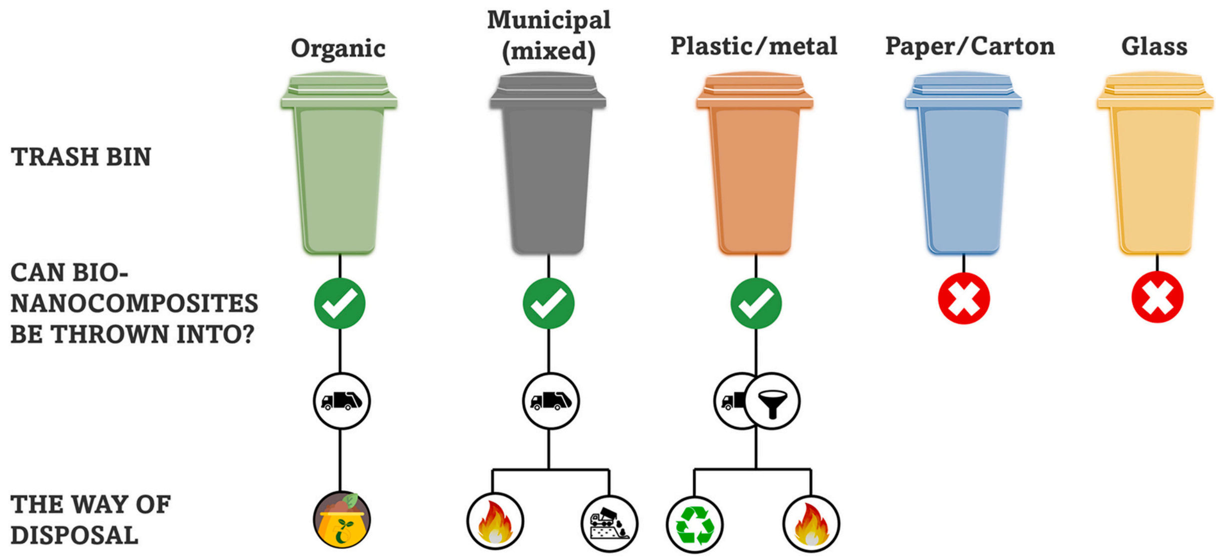

Fig. 3. Possible end-of-life routes for bio-nanocomposites in the light of current waste management systems in The Netherlands.

in legislation. The realization of their true potential and becoming a sustainable alternative to conventional plastics is only possible if bio-nanocomposites are accepted by consumers, and that is ideally tested before they enter the market. Collaboration among researchers, policymakers, businesses, and societal parties is crucial to promote awareness, create incentives, and establish infrastructure to support the production and disposal of sustainable bio-nanocomposites. In the transition from fossil-based to more sustainable packaging, bio-nanocomposite materials are expected to play a pivotal role.

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CRediT authorship contribution statement

Murat Yanat: Writing – original draft, Investigation, Conceptualization. **Karin Schroën:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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