

# Integrating Nanocomposites and Biosensors: Towards an Intelligent Food Packaging System

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**Abstract:** This paper delves into the transformative role of nanotechnology in food packaging, focusing on biosensors and nanocomposites. It highlights their potential to enhance food safety by detecting microbial contaminants and improving nutrient retention, offering a sustainable alternative to conventional packaging materials with their biodegradability. Despite facing challenges such as biosensor limitations and nanoparticle migration, the paper proposes an innovative integration of indicators within packaging systems and possible methods to address challenges to advance intelligent food packaging. It underscores the necessity for further research to address these challenges, ensuring the safety and efficacy of these novel packaging solutions.

## 1. Introduction

Nanotechnology, deriving its prefix "nano" from the Greek word "dwarf," involves the creation and utilization of materials, technologies, and systems through the manipulation of matter at the nanometer scale. This scale operates at the level of atoms, molecules, and supramolecular structures. It encompasses the design and application of functional structures characterized by at least one dimension at the nanoscale—where a nanometer [nm] equals one billionth of a meter [ $10^{-9}$ m]. The recent advancements in nanotechnology have paved the way for its integration into the realm of food industry.

Numerous endeavors within the industry now strive to employ nanotechnology in the creation of food packaging materials, aiming to enhance food quality and safety.<sup>[1]</sup> The benefits extend beyond merely enhancing mechanical attributes and barrier systems.<sup>[2, 3]</sup> Nanotechnology offers a means to ascertain the present state of a food product, with the ultimate objective being the extension of the product's shelf life—a feat achievable through the implementation of nanostructures. This potential is recognized by scholars and industry stakeholders alike, who have discerned applications for nanotechnology across diverse segments of the food sector.<sup>[4, 5]</sup> A prime example lies in food packaging, where nanotechnology finds extensive application.<sup>[6]</sup> This encompasses the incorporation of pathogen, gas, or abuse sensors; the integration of anti-counterfeiting mechanisms; provision of UV protection; and the creation of more robust and less permeable polymer sheets. Notably, food nanoscience research and development are most fervently pursued within this arena.

Nanotechnology's benefits for the food packaging industry are unmistakable. Its capacity to detect microbial contamination holds promise for enhancing nutrient bioavailability and bolstering mechanical barriers. Moreover, nanotechnology finds utility in food processing, augmenting attributes like flavor, color, texture, and nutritional content. Nanocapsules, for instance, are harnessed to heighten the bioavailability of nutraceuticals. Similarly, nanoemulsions and nanoparticles play a role in enhancing nutritional dispersion and availability. Nanocapsules are employed as additives or supplements, effectively concealing unpalatable flavors and facilitating the distribution of insoluble additives without necessitating surfactants or emulsifiers. Already established techniques for bioactive nanoencapsulation further contribute to controlled nutrient release or delivery.<sup>[7]</sup>

As the paradigm shifts towards bio-based materials in lieu of conventional synthetic plastics, their application as indicators and sensors is on the rise. Natural dyes and extracts, serving as alternatives to synthetic counterparts, can impart color changes to dietary ingredients based on physiological shifts. These pigments are frequently incorporated into polymer matrices, responding to microbial-induced pH fluctuations. This approach aligns with prevailing EU policy, prioritizing product sustainability through enhanced biodegradability and compostability of bio-based compounds serving as indicators or sensors.<sup>[6]</sup>

Hence, nanotechnology emerges as a revolutionary force with boundless potential across the entire spectrum of the food industry, encompassing food processing, packaging, safety, and functional food innovation. This review sheds light on nanotechnology's utility and advantages within biosensors, food safety, and food

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packaging, exploring its various types, classifications, and safety considerations.

## 2. Biosensor

Fresh produce or meats that have decayed or lost their appeal emit distinctive scents, hues, or sensory attributes detectable by consumers. When packaging materials limit substantial sensory experiences, consumers must rely on sell-by dates. These dates, determined by producers, stem from a set of idealized assumptions regarding food storage and transportation. However, these assumptions may prove inadequate; for instance, a carton of milk's sell-by date, implying a two-week shelf life, loses relevance if stored above optimal temperature for an extended period, such as within a delivery truck or warm automobile.

Nanoscale particles, boasting distinctive chemical or electro-optical properties, present solutions to this predicament. Bottom-up engineering yields nanomaterials capable of sensing gases, odors, chemical pollutants, infections, and environmental changes. This confers benefits not only to quality control, ensuring optimal freshness and flavor for consumers, but also holds potential to enhance food hygiene and diminish instances of foodborne illnesses. Stakeholders encompassing consumers, industry players, and food regulators stand to gain from this technology. While certain firms already offer nanotechnology-based products aiding consumers in assessing edibility, much research concerning nanosensors and food-related analytical substances remains in nascent stages.<sup>[8]</sup>

Intelligent packaging systems integrate sophisticated freshness indicators that provide real-time insights into the progressive deterioration of product quality. These indicators, often manifesting as colorimetric responses, stem from intricate chemical or microbiological transformations interacting with embedded sensors, thus transmitting discernible signals that correlate with shifts in product attributes, frequently associated with pH variations.<sup>[9]</sup> These indicators manifest as dynamic labels, tags, or visual prompts, categorized as either direct or indirect modalities. Direct indicators engage in specific interactions with targeted metabolites or toxins, whereas their indirect counterparts respond through cascading chemical or microbial alterations within the immediate environment. The strategic adoption of pH-sensitive natural dyes resonates harmoniously with the contemporary drive toward sustainable, bio-sourced alternatives. This approach underscores virtues such as renewability, minimal environmental impact, and negligible toxicity. By embracing such natural and ecologically benign dyes, the intelligent packaging paradigm aligns seamlessly with the trajectory of responsible innovation, efficaciously intertwining cutting-edge technology with ecological mindfulness, thereby fostering a holistic synergy between consumer demands and environmental stewardship.

In summary, nanobiosensor research constitutes a critical exploration of emerging technologies with profound implications for the detection of human and animal diseases, compound identification and analysis,

biomaterial characterization, and biocatalyst development. These technologies encompass the development of nanostructured biologically active interfaces and specialized instruments for meticulous characterization. A key goal of nanotechnology-driven biosensors is their seamless integration into compact biochips featuring integrated electronics, sample manipulation, and comprehensive analysis capabilities. This integration paves the way for the creation of compact, portable, cost-effective, disposable, and adaptable diagnostic tools, representing a significant advancement in diagnostic capabilities. Laser-driven nanosensors, in particular, enable real-time analysis of proteins and biomarkers within the complex milieu of living cells. Despite remarkable progress over the past two decades, the ultimate aspiration of achieving low-cost, high-throughput, and multiplexed therapeutic diagnostic lab-on-a-chip devices remains a formidable challenge. Additionally, the precise architectural configurations of nano biosensors tailored to distinct diagnostic tasks remain an area of ongoing investigation, with optimized designs yet to be fully elucidated. This underscores the need for continued research and development to unlock the full potential of nano biosensors in advancing diagnostic technologies.<sup>[10]</sup>

## 3. Nanocomposite

The plastics industry has experienced rapid evolution through the development of diverse petrochemical-derived polymers, offering exceptional durability, lightweight characteristics, and cost-efficiency. These attributes have led to the ubiquitous adoption of plastics. Similarly, metals and glass find utility in food packaging, tailored to specific requirements such as containing meats or beverages. However, glass, while utilized for products, is constrained by its weight and fragility.<sup>[11]</sup>

Prominent plastic variants encompass low-density polyethylene, high-density polyethylene, polyethylene terephthalate, polyvinyl chloride, and polystyrene. Nevertheless, the extensive application of plastics encounters challenges, notably in terms of degradability and limited recyclability, thereby contributing to the pressing issue of plastic pollution. Packaging assumes a pivotal role in preserving the enclosed environment. Historically, its purpose has been to safeguard food against microbial contamination. Nonetheless, concerns have arisen due to potential chemical migration from plastics to food items, prompting health-related apprehensions. Particularly, substances like phthalates, inherent to plastics, exhibit the potential to detrimentally impact human health upon ingestion. Furthermore, the interplay between plastics and substances like alcohol can curtail the shelf life of specific food items by influencing factors such as carbon dioxide retention.<sup>[12]</sup>

Efforts to mitigate these constraints have led to the emergence of ingenious solutions. The incorporation of environmentally friendly and biodegradable materials has garnered considerable attention. Notably, materials such as Polyhydroxyalkanoates (PHA) and Poly (lactic acid) (PLA) films have garnered prominence due to their

potential in augmenting packaging efficiency and facilitating biodegradation.<sup>[13]</sup>

An intriguing avenue for advancing food packaging capabilities is presented by nanotechnology. Nanocomposites are relatively new material made with various polymers and nano-size inorganic or organic fillers.<sup>[14]</sup> Nanocomposites material is increasing its use in commercial product. Nanocomposite materials offer distinct advantages that effectively address extant challenges. In food industry, nanocomposites material is widely used for its antimicrobial ability, thinness, and lightness.<sup>[15]</sup> It is not able to react with the food or to infiltrate into the food. In this way, the food received a high degree of protection against biological contamination. For the costumers, nanocomposites lower the risk of microbial infections. As an illustration, the nanocomposite material "Imperm" demonstrates the capacity to prevent carbon dioxide leakage while concurrently upholding an effective oxygen barrier. This breakthrough has the potential to revolutionize the packaging landscape for carbonated beverages. The advent of nanotechnology has ushered in the possibility of utilizing thinner and lighter packaging materials, thereby facilitating more efficient storage and transportation processes. The introduction of antimicrobial nanocomposites represents a significant advancement. Incorporating compounds like metal-oxide nanocomposite or silver nanoparticles has shown promising results in preventing microbial growth. Silver, renowned for its antibacterial properties, has been explored as an additive in packaging, further extending the shelf life of products.<sup>[16]</sup> Not only for making food package, nanocomposites are also used to product food and consist in the food to make the food safe. With the help of nanocomposites, the food quality is improved.

In conclusion, the ongoing evolution of the plastics industry demands innovative solutions to enhance food packaging. Nanocomposites have emerged as a promising avenue, addressing challenges related to durability, preservation, and environmental impact. The integration of environmentally friendly materials, alongside the advancements offered by nanotechnology, has the potential to revolutionize the landscape of food packaging.

## 4. Prospects and challenges of intelligent food packaging

### 4.1. Food packaging category

Food packaging can typically be classified into three categories.<sup>[17]</sup> The first category, known as primary packaging, directly comes into contact with the food and serves primarily for chemical preservation and physical containment. Examples of primary packaging include wrappers, bottles, and cans, which act as a protective barrier around the food product, preserving its freshness and quality. The second category is secondary packaging, consisting of two or more units of primary packaging. Its main purpose is to provide additional protection during transportation and storage, ensuring that the primary packaging remains free from contamination or damage.

Common examples of secondary packaging include cardboard boxes, cartons, or shrink-wrap. Lastly, there is tertiary packaging, involving the grouping together of multiple units of secondary packaging for distribution and retail purposes. Tertiary packaging is crucial for efficient handling and movement of products in large-scale supply chains, often comprising pallets or larger containers.

### 4.2. Concept of intelligent food packaging

Building an Intelligent Food Packaging System holds promising prospects for the food industry's advancement. Nanocomposite materials have emerged as ideal substrates for intelligent food packaging due to their outstanding mechanical properties, antibacterial characteristics, barrier properties, and biodegradability.<sup>[18]</sup> These materials offer enhanced protection and preservation of food products, reducing the risk of spoilage and improving food safety. Additionally, the integration of biosensors in food packaging adds extra functionalities beyond traditional packaging.<sup>[19]</sup> Biosensors are capable of detecting specific biological or chemical compounds, providing real-time data on food quality and safety. By incorporating biosensors into the packaging, parameters such as temperature, humidity, gas composition, and microbial presence can be continuously monitored.

The intelligent food packaging system, which integrates external indicators, internal indicators, and communication-facilitating markers, forms a synergistic, multidimensional system.<sup>[20]</sup> External indicators, such as time-temperature indicators and physical impact indicators, provide intuitive information about the environmental conditions that the food undergoes during transportation and storage, thereby ensuring the quality and safety of the food throughout the supply chain. Internal indicators, including oxygen leak rates, carbon dioxide levels, microbial, and pathogen indicators, monitor the quality and safety inside the packaging, helping to maintain the freshness and nutritional value of the food. Meanwhile, the markers that facilitate information flow and communication, such as specialized barcodes and anti-theft, anti-counterfeiting, and tamper-proof devices, not only provide a platform for information exchange, enabling consumers to easily access detailed information about the food but also ensure the authenticity and safety of the product throughout the supply chain. This integrated approach not only comprehensively monitors the physical and biochemical conditions of the food, reducing waste, but also optimizes supply chain management by providing real-time data on food quality, aiding managers in making more accurate decisions. Additionally, it enhances consumer trust in the brand and, by reducing the need for manual inspection, saves on labor costs and improves operational efficiency.

Similarly, In the context of intelligent food packaging, integrating nanocomposites and biosensors across the first, second, and third categories of packaging can effectively balance cost and safety. For the first category of packaging, which comes in direct contact with food, advanced nanocomposite materials and biosensors are

used, meeting high performance and safety standards to ensure optimal real-time monitoring of food quality and safety. This includes detecting microbial contamination or chemical changes, while minimizing health risks to consumers. The second category of packaging, despite potential compromises in direct human safety (e.g., detachment of nanoparticles from the nanocomposite material), employs environmentally friendly nanocomposites with robust mechanical properties for additional protection and structural support. The third category of packaging, serving as the outermost layer, is crucial in aggregating and analyzing data collected from internal sensors, coupled with external sensors, to monitor the overall physical state of the packaging. This comprehensive data integration is vital for tracking and optimizing food safety during storage and transportation, enabling prompt responses to potential issues.

This multidimensional and functional integration of specific nanocomposites and biosensors across the different packaging categories not only assures food safety but also enhances cost-effectiveness. The high-grade materials and sensors in the first category of packaging provide direct food safety assurances, while the materials used in the second and third categories focus on balancing environmental impacts and cost efficiency. This approach could optimize the equilibrium between maintaining high safety standards and reducing costs in the commercialization of intelligent food packaging, potentially leading to significant advancements and innovations in the field.

### 4.3. Challenges of intelligent food packaging

Intelligent food packaging holds significant promise for the food industry, offering enhanced preservation and safety for perishable goods. Two key components of this technology, namely biosensors and nanocomposite materials, face distinct challenges during development and implementation.

#### 4.3.1 Challenges of biosensors

The successful integration of biosensors into the intricate landscape of food packaging presents an array of formidable challenges that necessitate ingenious scientific deliberation. Effectively monitoring and ensuring the quality of consumables demand the seamless integration of micro-scale biosensors within the very fabric of packaging substrates or containers. However, the inherent limitations of nanoscale sensors, characterized by their constrained energy provisioning and capacity, underscore the compelling need for the advancement of Wireless Nanoscale Sensor Networks [WNSN].<sup>[21]</sup> This evolutionary stride assumes a pivotal stance in the burgeoning domain of intelligent food packaging, albeit current strides in harnessing WNSN for this purpose are still in their embryonic stages, primarily confined to incipient research and exploratory forays. Empirical investigations have brought to light the potential amelioration of inter-nanoscale communication dynamics through algorithmic orchestration. This orchestration, in

turn, begets the fortification of nanosensor ensembles, thereby imparting an extended operational lifecycle to WNSN.<sup>[22]</sup> Notwithstanding these advancements, the quintessential realm of efficient communication modalities and streamlined data transmission within the intricate tapestry of WNSN beckons further empirical scrutiny and refinement.

An additional conundrum ensconced within this milieu is the imperatives of biosensor specificity and steadfast stability. The pivotal role of biosensors, entrusted with the discernment of specific analytes or discernible shifts in the complex milieu of food quality, stands juxtaposed with the imperative of enduring stability and unswerving fidelity that perseveres throughout the entire trajectory of the packaging's lifecycle.<sup>[23]</sup>

A study has shown that sensors impregnated with phosphorescent platinum(II)-benzoporphyrin dye (PtBP) demonstrate notable longevity, maintaining accurate and consistent performance over at least 12 months in normal atmospheric conditions. This durability highlights its potential as an effective and reliable solution for monitoring oxygen levels in food packaging, addressing the need for long-lasting biosensors.<sup>[24]</sup>

#### 4.3.2. Challenges of nanocomposites

Nanocomposite materials, conversely, introduce a distinct array of challenges. Comprising nano-scale constituents embedded within polymer matrices, these materials are generally perceived as innocuous to human health and non-pollutants to the environment. Nonetheless, the plausible migration of nanoparticles from these materials into consumables engenders apprehensions pertaining to human well-being. Extant scholarship postulates that nanoparticles ingested through this route could endure within the gastrointestinal tract, thereby perturbing the intricate balance of gut microbiota and potentially precipitating neurologic impediments. The nascent comprehension of nanoparticles' protracted toxicological impact underscores the exigency for comprehensive toxicological investigations, aimed at certifying the innocuity of nanocomposite materials within the realm of food packaging. Stringent conformance with pertinent regulatory benchmarks assumes a cardinal role in this context.<sup>[25]</sup>

To enhance the safety of food packaging materials, mitigating nanoparticle migration is essential. Adjusting the size of nanoparticles can achieve this. Nanoparticles, when added to food packaging polymers, integrate fully into the polymer matrix, creating an embedded structure. Research indicates that migration, based on Fick's law, occurs only when these embedded nanocomposites contain nanoparticles sized between 1-4 nm. Larger particles are immobilized within the polymer matrix, reducing the likelihood of migration to food contact surfaces. However, if nanoparticles are too large and protrude from the polymer surface, they pose a migration risk to food during use, necessitating a comprehensive risk assessment.<sup>[26]</sup>

A study on NiO nanoparticle-enhanced gelatin/chitosan nanocomposites as active food packaging demonstrates that adding a polymer film can effectively reduce nanoparticle migration and direct contact with cells. The polymer chains hinder nanoparticle migration or contact, offering a novel approach to addressing cytotoxicity caused by nanoparticle migration.<sup>[27]</sup>

Employing non-cytotoxic nanoparticles as carriers, modified to form nanocomposites, ensures that even minimal migration does not pose a direct threat to human health. TiO<sub>2</sub>, for instance, is modified with metal ions or oxides (e.g., Fe<sup>3+</sup>, Ag, or SnO<sub>2</sub>) to enhance photocatalytic and antimicrobial activities. When incorporated into packaging materials, TiO<sub>2</sub> protects against foodborne microbes and, under UV radiation, shields against odors, staining, spoilage, and allergens.<sup>[28]</sup>

Furthermore, the ubiquitous dissemination of nanocomposite materials from food packaging into terrestrial and aquatic ecosystems elicits the potential for adverse repercussions, notably encompassing the specter of heavy metal contamination and soil enfeeblement. However, the widespread distribution of nanocomposite materials from food packaging into the environment may also presents an opportunity for positive ecological interactions. Research supports the idea that integrating extracts from various plants into nanomaterials can promote plant growth, enhance nutrient delivery, and strengthen resistance to diseases. This innovative approach suggests that, with careful consideration of environmental and health impacts, the use of nanocomposite materials could contribute beneficially to both terrestrial and aquatic ecosystems, reducing concerns like heavy metal pollution and soil degradation.<sup>[29]</sup>

In essence, a scrupulous appraisal and exhaustive evaluation of these plausible perils stand as sine qua non for the vindication of the sustainability and ecological benevolence intrinsic to the paradigm of intelligent food packaging systems.

## 5. Conclusion

Nanotechnology has the potential to revolutionize the food industry through the development of intelligent food packaging. The use of nanocomposite materials and biosensors can provide enhanced protection and preservation of food products, as well as real-time monitoring of food quality and safety. However, there are challenges that need to be addressed before these technologies can be widely implemented. Biosensors face limitations in energy and capacity, as well as the need for specificity and stability. Nanocomposite materials also present potential risks, such as the migration of nanoparticles into food and the environment. Further research and development are necessary to overcome these challenges and ensure the safety and sustainability of intelligent food packaging systems. This includes exploring new materials and technologies that can address the limitations of current systems, as well as developing effective regulations and standards for their use. Simultaneously, by integrating the use of nanocomposite materials and biosensors across various types of food

packaging, we can effectively balance cost and safety. This approach provides a viable pathway for the commercialization of intelligent food packaging, facilitating its adoption in the industry while ensuring both economic feasibility and high safety standards. In conclusion, the use of nanotechnology in the food industry has great potential for improving food safety and reducing food waste. By addressing the challenges associated with intelligent food packaging, we can create a more sustainable and secure food packaging system for the future.

## References

1. Bagchi, M., H. Moriyama, and F. Shahidi, *Bio-nanotechnology: a revolution in food, biomedical and health sciences*. 2012.
2. Basavegowda, N. and K.-H. Baek, *Advances in functional biopolymer-based nanocomposites for active food packaging applications*. *Polymers*, 2021. **13**(23): p. 4198.
3. Song, J.H., et al., *Biodegradable and compostable alternatives to conventional plastics*. *Philosophical transactions of the royal society B: Biological sciences*, 2009. **364**(1526): p. 2127-2139.
4. Berekaa, M.M., *Nanotechnology in food industry; advances in food processing, packaging and food safety*. *Int. J. Curr. Microbiol. App. Sci*, 2015. **4**(5): p. 345-357.
5. Duncan, T.V., *Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors*. *Journal of colloid and interface science*, 2011. **363**(1): p. 1-24.
6. Singh, T., et al., *Application of nanotechnology in food science: perception and overview*. *Frontiers in microbiology*, 2017. **8**: p. 1501.
7. Alizadeh-Sani, M., et al., *pH-sensitive (halochromic) smart packaging films based on natural food colorants for the monitoring of food quality and safety*. *Trends in Food Science & Technology*, 2020. **105**: p. 93-144.
8. Pandit, S., et al., *Nanotechnology based biosensors and its application*. *The Pharma Innovation*, 2016. **5**(6, Part A): p. 18.
9. Kurek, M., et al., *Comparison of two pH responsive color changing bio-based films containing wasted fruit pomace as a source of colorants*. *Journal of food science*, 2019. **84**(9): p. 2490-2498.
10. Sharma, R. and G. Ghoshal, *Emerging trends in food packaging*. *Nutrition & Food Science*, 2018. **48**(5): p. 764-779.
11. Andrady, A.L. and M.A. Neal, *Applications and societal benefits of plastics*. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 2009. **364**(1526): p. 1977-1984.
12. Claudio, L., *Our food: packaging & public health*. 2012, National Institute of Environmental Health Sciences.

13. Kasirajan, S. and M. Ngouajio, *Polyethylene and biodegradable mulches for agricultural applications: a review*. *Agronomy for sustainable development*, 2012. **32**: p. 501-529.
14. Wang, Z. and H. Xiao, *Nanocomposites: Recent development and potential automotive applications*. *SAE International Journal of Materials and Manufacturing*, 2009. **1**(1): p. 631-640.
15. Cummings, C.L., A.S. Chuah, and S.S. Ho, *Protection motivation and communication through nanofood labels: Improving predictive capabilities of attitudes and purchase intentions toward nanofoods*. *Science, Technology, & Human Values*, 2018. **43**(5): p. 888-916.
16. Dingman, J., *Guest commentary: nanotechnology: its impact on food safety*. *Journal of Environmental Health*, 2008. **70**(6): p. 47-50.
17. Shin, J. and S.E. Selke, *Food packaging*. *Food processing: principles and applications*, 2014: p. 249-273.
18. Youssef, A.M. and S.M. El-Sayed, *Bionanocomposites materials for food packaging applications: Concepts and future outlook*. *Carbohydrate polymers*, 2018. **193**: p. 19-27.
19. Fuertes, G., et al., *Intelligent packaging systems: sensors and nanosensors to monitor food quality and safety*. *Journal of Sensors*, 2016. **2016**.
20. Han, J.H., *Innovations in food packaging*. 2005: Elsevier.
21. Gulec, O., *Extending lifetime of Wireless Nano-Sensor Networks: An energy efficient distributed routing algorithm for Internet of Nano-Things*. *Future Generation Computer Systems*, 2022. **135**: p. 382-393.
22. Yalgashev, O., M. Bakhouya, and J. Gaber. *An Enhanced Flooding Algorithm for Wireless Nanosensor Networks*. in *2020 International Conference on Information Science and Communications Technologies (ICISCT)*. 2020. IEEE.
23. Bu, T., et al., *Diversely positive-charged gold nanoparticles based biosensor: A label-free and sensitive tool for foodborne pathogen detection*. *Food chemistry: X*, 2019. **3**: p. 100052.
24. Kelly, C.A., et al., *Stability and safety assessment of phosphorescent oxygen sensors for use in food packaging applications*. *Chemosensors*, 2018. **6**(3): p. 38.
25. Chen, J., et al., *Crosstalk of gut microbiota and serum/hippocampus metabolites in neurobehavioral impairments induced by zinc oxide nanoparticles*. *Nanoscale*, 2020. **12**(41): p. 21429-21439.
26. Franz, R., J. Bott, and A. Störmer, *Considerations for and guidance to testing and evaluating migration/release of nanoparticles from polymer based nanocomposites*. *Nanomaterials*, 2020. **10**(6): p. 1113.
27. Momtaz, M., et al., *Preparation and characterization of gelatin/chitosan nanocomposite reinforced by NiO nanoparticles as an active food packaging*. *Scientific Reports*, 2024. **14**(1): p. 519.
28. Rhim, J.-W., H.-M. Park, and C.-S. Ha, *Bionanocomposites for food packaging applications*. *Progress in polymer science*, 2013. **38**(10-11): p. 1629-1652.
29. Duhan, J.S., et al., *Nanotechnology: The new perspective in precision agriculture*. *Biotechnology Reports*, 2017. **15**: p. 11-23.