ICJK

Journal of Composites Engineering and Sustainability
http://dx.doi.org/10.62762/JCES.2025.447373

REVIEW ARTICLE

Check for updates

Upcycled Nanomaterials from Wastewater Treatment for Active and Smart Packaging- A Review

K. Arun Prasath[1,*], **A. M. Shanawaz**[2], **Y. Carlin Calaph**[1], **T. Raj Pradeesh**[3] **and Ruby Celsia Arul Selvaraj**[4]

[1] Department of Mechanical Engineering, PSN College of Engineering and Technology, Tirunelveli 627152, India
[2] Department of Mechanical Engineering, Sethu Institute of Technology, Kariapatti, Madurai 626115, India
[3] Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil 626126, India
[4] Department of Food Technology, K S Rangasamy College of Technology, Namakkal 637215, India

Abstract

Usage of nanomaterials in the wastewater treatment provides added value from the perspective of preparation and market perspectives, adding to the demand for sustainable and intelligent packaging solutions, resulting in a market interest in smart and active packaging based on the modification of nanoparticles derived from wastewater treatment. In this paper, the advantages and their applications for the fibrous nanomaterials recovered from wastewater treatment processes, physical/chemical properties, environmental advantages, as well as their potential purposes are investigated through case studies on smart and active packaging systems. Nanomaterials such as graphene derivatives, nanocellulose, nano chitosan and metal and metal oxide nanoparticles, synthesized and recovered from wastewater possess specific physicochemical characteristics that can be tailored for the development of new food packaging materials endowed with sensing, antibacterial and barrier functions. In turn, the paper addresses the scalability, safety and regulatory concerns by exploring a discussion of extraction techniques, materials characteristics and environmental and social impacts. This article also explains how these nanoparticles can be used in such a packaging to improve their sustainability, helping to make them a more environmentally sustainable option, as well as keep products for longer and increase their shelf life. In this paper, the potential of up-cycling and micro-fabrication technologies for giving birth to innovative green packaging repurposed from waste water management is demonstrated according to the circular economy principles.

Keywords: nanomaterials, wastewater treatment, smart packaging, sustainability.

1 Introduction

The use of nanomaterials has emerged as a key factor in active and smart packaging development. The "Heterogeneous catalytic bridge" of transition metal nanomaterials (having unique physicochemical properties such as high surface area, enhanced

Submitted: 18 March 2025
Accepted: 15 April 2025
Published: 19 May 2025

Vol. 1, **No.** 1, 2025.
10.62762/JCES.2025.447373

***Corresponding author:**
✉K. Arun Prasath
aruncmr12@gmail.com

Citation
Prasath, K. A., Shanawaz, A. M., Calaph, Y. C., Pradeesh, T. R., & Selvaraj, R. C. A. (2025). Upcycled Nanomaterials from Wastewater Treatment for Active and Smart Packaging- A Review. *Journal of Composites Engineering and Sustainability*, 1(1), 3–14.

mechanical strength, tunable optical and electronic properties etc) has ushered in transformative breakthroughs. For example, researchers are collaborating with industries to tackle food waste, contamination, and environmental sustainability issues associated with the use of nanomaterials advances with food packaging systems [1]. Active and smart packaging has made great progress in meeting the increasing demand for novel packaging solutions globally. Advanced packaging technology doesn't just protect products from the elements, it also protects what's inside them all the way to the store shelf, products that use to be hidden away behind plastic or glass now protect themselves and their contents. Active Packaging: This active packaging is the inclusion of additives in it, which reacts with the product/environment, for example, oxygen scavengers, moisture absorbers, antimicrobial agents, and so on to perform functions. In contrast to conventional packnings that act merely as physical barriers, smart packaging integrates devices such as sensors and indicators to monitor and convey the status of goods in order to provide real-time data to systems affected [2]. Nanoparticle-based, complementary packaging technologies have been developed for high efficacy, low environmental impact. Now food degradation by gases such as carbon dioxide and oxygen can be arrested by blending nano clays with polymer matrices. This forms an impenetrable layer that could decrease or eliminate gas permeability. Several metal nanoparticles (NPs), such as zinc oxide and silver, showed strong antibacterial properties and significantly extended the storage lifetimes of perishables. There are several smart packaging techniques that utilize carbon-based nanomaterials like graphene and carbon nanotubes. Being electrical conductors, they can be used to build sensors that are capable of sensing humidity, temperature on spoilage, kg. Packaging is an important component of the preservation and protection of foods, pharmaceuticals, and other category of perishable products [3]. The history of traditional packaging starting as simple impermeable barriers up to complex static single active systems is indeed an incredible story. There are materials and systems that interact with the package contents and the environment to enhance quality and / or to give new functionality to the package, thus extending the shelf-life of the package. They're known as active packaging. These functions can be to control moisture, scavenge oxygen or perform an antibacterial function. Whereas smart packaging goes one level further by being able to actively monitor as and to communicate product status through the use of sensors, indications or communication technology. Smart packaging solutions can alert consumers or manufacturers to spoilage or contamination, thereby saving resources or ensuring safety. Modern packaging has become increasingly sophisticated, as a result of advances in active and smart packaging technologies [4]. Such innovations have wider-reaching goals than merely securing a product: they add to the utility of the packaging to deliver more product than ever, and do so with minimal environmental footprint and maximum longevity. Nanomaterials are the new thing when it comes to active and smart packaging systems. Nanomaterials have many advantages over traditional materials due to their high surface area, reactivity and molecular level phenomena. Nanomaterials are a class of materials with properties or structures that are at the nanometre scale (1-100 nanometres). One application could be nanomaterials, which could enhance the properties of packaging such as barrier, mechanical and thermal stability tremendously. Examples of this would be: Nanomaterials including nano clays, carbon nanotubes, and nanocomposites improve barrier properties of packaging materials and provide resistance to oxygen, moisture, and UV light. Goodness where it matters, like food and medicines, requires these qualities to maintain for longer shelf lives. Furthermore, functional nanomaterials allow for active and intelligent characteristics, such as antimicrobial and self-healing effects or nano sensors incorporated into the package that respond to environmental variations in the package [5]. The use of nanomaterials in packaging systems can result in all these improvements, making food packaging systems more sustainable. Nanomaterials can be drawn from waste, including wastewater, offering a new way forward to minimize the environmental footprint of production but also introducing new, high-performance packaging material. Such new active packaging systems, based on innovative natural nanomaterials obtained from waste treatment processes are also reviewed in this work covering aspects of sustainability, innovations and deployment in the context of the circular economy framework [6] Wastewater waste nanoparticles can change the face of packaging technology It will help solve real world problems such as pollution and resource scarcity leading to sustainable development and eventually to smarter eco-friendly packaging. Figure 1 represents the introduction on Nanomaterials in Wastewater Treatment for Active and Smart Packaging.

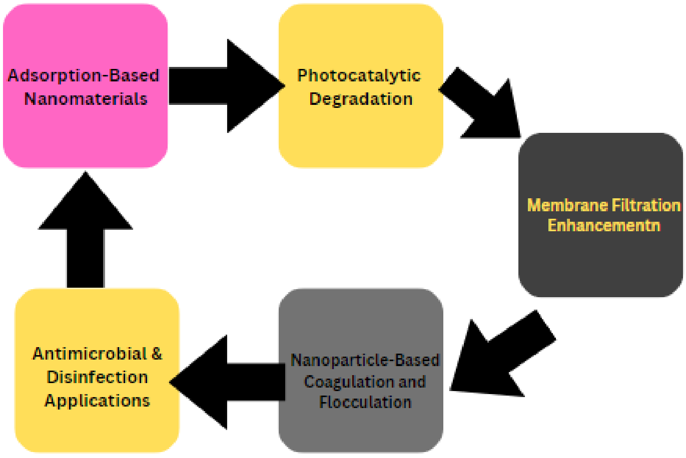

Figure 1. Nanomaterials in wastewater treatment.

2 Use of Nanomaterials for Wastewater Treatment

Industrial wastewater consists of many valuable components, including organic compounds, nanoparticles, and metallic ions. Wastewater with high concentrations of metal ions (i.e. silver, gold, and copper) is generated by various industries such as electroplating, mining, and electronics manufacturing. This paves a pathway for producing nanocomposites if state-of-the-art recovery methods used directly produce nanomaterials from the respective ions. Additives and colours used in the dye and textile industries in some cases can be sequenced on reusable nanoparticles which are present in the wastewater. Agricultural wastewater, which is rich in organic compounds and also contains fertilisers and pesticides, is another possible source. Particularly studies about recovering nanomaterials from this source and often investigate inorganic molecules such as zeolites [7]. Zeolite is a powerful compound for converting organic molecules into carbon-based nanomaterials (like graphene or carbon nanotubes).

These materials exhibit impressive barrier properties and possess antibacterial activity, which renders them ideal for active packaging. Given this background and to solve pollution problems, meet the social needs of the circular economy, and efficiently recover value-added products in the form of nanomaterials from agricultural wastewater. Nanomaterial is one type of leftover resource. Municipal wastewater consists of urban runoffs and domestic raw sewage which contain a variety of both organic and inorganic compounds [8, 9]. Sludge collected by municipal wastewater treatment plants may be a source of nanomaterials. These materials can be processed into valuable nanostructures (biochar-based nanocomposites, iron oxides, and silica nanoparticles) via chemical precipitation, hydrothermal carbonisation, and pyrolysis. The FILM method adapted to nanoparticles is applied to make active packaging that enhances product longevity and quality. This book article reviews the various types of nanomaterials used in wastewater nano remediation and enumerates several types of nanomaterials that can be effectively recovered from wastewater [10] and depends on wastewater's initial composition and recovery method. Metal nanoparticles (such as silver, gold, and titanium dioxide) are widely utilized due to their antibacterial and catalytic properties. These characteristics can be used in active packaging to avoid the growth of microorganisms in products. Carbon - the raw ingredient for graphene, carbon nanotubes, and nano diamonds - is also in high demand They are suitable for smart packaging due to their enhanced mechanical strength, electrical conductivity, and thermal stability. The integration of these nanoparticles into packaging materials enhances functionality (e.g., temperature monitoring, gas detection, real-time product tracking), thereby improving the end-user experience. Nanomaterial: Currently scientists have been focusing on the nanomaterials include the organic materials, theses organic materials extracted from the biomass present in the wastewater such as nanocellulose and the chitosan nanoparticles. With the increase of environmental consciousness and the ability of materials to biodegrade, there is a huge demand for sustainable packaging solutions. Chitosan has antimicrobial activity and nanocellulose possesses excellent mechanical properties and transparency, making them promising candidates for active packaging. Wastewater is a major environmental challenge as well as a resource with high socioeconomic value that is still underused [11]. The materials have multiple sources, including some from industrial, agricultural, and municipal processes. Provided that recoveries are done correctly, they possess significant potential for further new applications as active and smart packaging. This will not only contribute to close the material cycle but also enable reducing the environmental impact of nanomaterials, which will mean less pollution in general.

Development of nanomaterials based on wastewater as smart or active packaging material can be used in several applications. Innovation in recovery and synthesis that turns waste to value allows us to address both environmental and economic issues. Apart from contributing to a circular economy and lessening the need for virgin raw materials, this approach also drives sustainability because it encourages innovation in packaging technology. The utilization of nanomaterials from wastewater treatment is depicted in Figure 2.

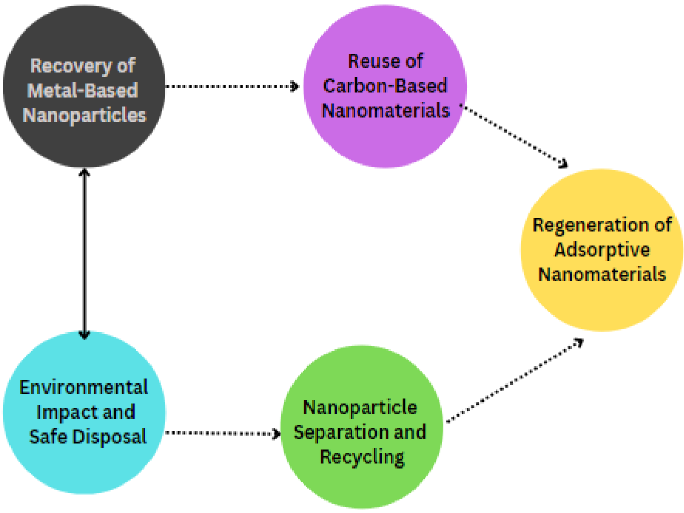

Figure 2. Nanomaterials from wastewater treatment.

3 Some of the functional Properties of Nanomaterials

Nanomaterials possess unique antimicrobial properties because of their high surface area to volume ratio and the presence of reactive surface groups. These characteristics help them to engage with the microbial cells that disrupt cellular membrane and metabolism pathways. Notably, metallic nanoparticles (such as silver, zinc oxide, and titanium dioxide) have broad, anti-microbial features that are essential for ensuring packaged products' cleanliness [12]. High nanomaterial's loading and stability made it possible to extend the long-term antimicrobial activity by use of nanomaterials in polymer matrices for producing packaging materials. Nanomaterials are promising excellent antimicrobial agents due to their nanoscale dimension as well as surface functionalization, resulting in improvement in antimicrobial activity, barrier and material volume recovery, sensing, and monitoring. Nanomaterials can also be used to promote the preservation of packaged goods, which serves as a barrier to gases, water, and other pollutants and extends the shelf life and quality of the good. Nanomaterials increase the resistance of the transfer of oxygen and water vapour to the packaging by creating dense structures and decrease the permeability of the packaging films. This is particularly beneficial in food packing as optimum conditions help to maintain freshness and reduce spoilage. The recovery of materials from wastewaters is a sustainable and circular economy approach. For instance, wastewater biomolecules yield nanomaterials like cellulose nano crystals, carbon-based nanostructures, and mineral nanoparticles. Therefore, the recovered materials exhibit functional properties equivalent to those achieved with the conventional sources of nanomaterials, supporting resource efficiency and reducing environmental impacts [13]. Biowaste and other waste could be recycled into nanomaterials and providing for the industry to reduce efforts lavished on virgin raw materials and reduce a large part of pollution from industries. Nanomaterials also activate sensory and monitoring functions in smart packaging systems. These can be embedded nano sensors that respond to changes to temperature, humidity, pH or traces of spoilage, providing information in real time about the state of packaged goods. In many senses, this means that the packaging along with its contents are having active communication where consumer safety, consumer health, safety of the packet is ensuring best consumption. The interaction of nanomaterials with electronic components also gives rise to the development of sophisticated packaging that can monitor the condition of the product and communicate this status to relevant stakeholders to ensure quality control throughout the food supply chain [14, 15]. Nanomaterials may have functional properties,as shown in Figure 3.

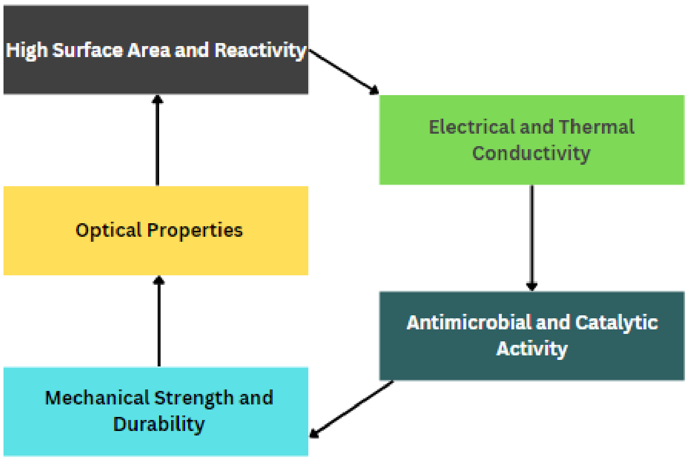

Figure 3. Functional properties.

4 Extraction and Synthesis of nano materials

Nanostructured materials derived from the processes of wastewater treatment emerge as highly promising materials for innovative active and smart packaging applications. They need to be properly recovered, synthesized and functionalized to function properly. This paper reports the methodologies, which provide recovery and their incorporation in the modern packaging systems. Overall, recovery of nanomaterials from wastewater is a multistep procedure that is carefully arranged to encourage the separation and purification of nanoscale materials (specific qualities (structure, shape, size) of nanoscale materials). Some of the conventional methods are precipitation, adsorption and membrane filtration. Liu's team engineered chemical reactions to break up soluble nanoparticles from liquid precursors in wastewater. These nanoparticles are removed either through centrifugation or sedimentation [16]. Adsorption techniques employ selective adsorbents, such as activated carbon or functionalized polymers to immobilize up NPs from complex waste water matrices. In bio available nanoparticles, separation strategies based on size exclusion and surface charge interactions have been established, and thus nano- or ultrafiltration membranes are membrane filtration systemscalable separation strategies. Novel innovative approaches, like electrochemical-based reclamation and magnetic separation, are becoming more prevalent due to their high selectivity and high efficiency. Electrochemical methods are advantageous through the application of electric fields for the precipitation or coagulation of the nanomaterials and energy- and cost-efficiency, while using their magnetic properties (e.g., iron oxides) and magnetic separation for the selective recovery of the nanomaterials. High-end industrial methods and hybrid techniques inspired by membrane filtration, adsorption or electrochemical processes also improve the recovery process while also addressing different issues such as mass transfer depletion, fouling, low selectivity, among others. Nanomaterials synthesis and functionalization, which is vital for tuning properties to meet active and intelligent packaging requirements, follows the recovery. Key methods include sol-gel synthesis, hydrothermal methods, and green synthesis. The sol-gel synthesis is a process that provides nearly exact control of the particle dimensions and morphology in going from a colloidal solution to a gel state. Hydrothermal methods allow for the preparation of crystalline nanoparticles at low energy input under controlled pressure and temperature conditions, thus serving as an important sustainable approach [17, 18]. For applications seeking environmental friendliness, green synthesis, based on plant extracts or microbial processes, obeys principles of sustainability and eco-friendliness and is thus a favorable choice. To be effective and efficient, the function of these nanomaterials must be combined in a sensory optimization process within packaging systems. Functional nanomaterials (antimicrobial, antioxidant, or oxygen-scavenging) should be homogeneously distributed in the packaging matrices in order to perform their functions. Nanomaterials are incorporated into films/layers by cholera, coating, and electrospinning methods. Extrusion is used to create polymer-nanomaterial composites when the thermal and shear conditions are controlled devising the matrix in which the nanomaterials are to be incorporated. Functional nanomaterials can be incorporated on nanofibers from electrospinning surface and reactivity of nanofibers increases. The surfaces of films packaging can be coated by nanomaterials films using dip-coating or spray-coating and other coating processes [19]. One of the critical stages to ensure that active and smart packaging is effective is to optimize its sensory properties. It also covers nanomaterials construction, where specialized analytical instruments such as spectroscopy, electron microscopy and thermal analysis are used to analyze and characterize the structure, composition and performance of the nanomaterials-based packaging. Increasingly, computational modelling and machine learning algorithms are being implemented to predict material behaviour in packaging systems, enabling the design of materials with desired functionalities [20]. In summary, wastewater treatment-focused recovery and synthesis of nanomaterials offers a transformative approach to the development of active and smart packaging systems that push the envelope on sustainability and performance. While these innovations carry enormous promise, the fact remains that novel materials in the packaging systems will bring new environmental challenges and require an in-depth development of the packaging technology, So the approaches introduced in this paper can be the path for leading to a usage of these packaging materials. With this, the idea of such wastewater-derived nanomaterials and its application in the packaging derivatives connecting the dots opening a way towards sustainable future and circular green economy [21]. Methods of extraction and synthesis of nano materials is shown in Figure 4.

5 Active and Smart Packaging applications

Wastewater treatment derived nanoparticles have gained interest recently as smart and active packaging materials. These materials could improve the

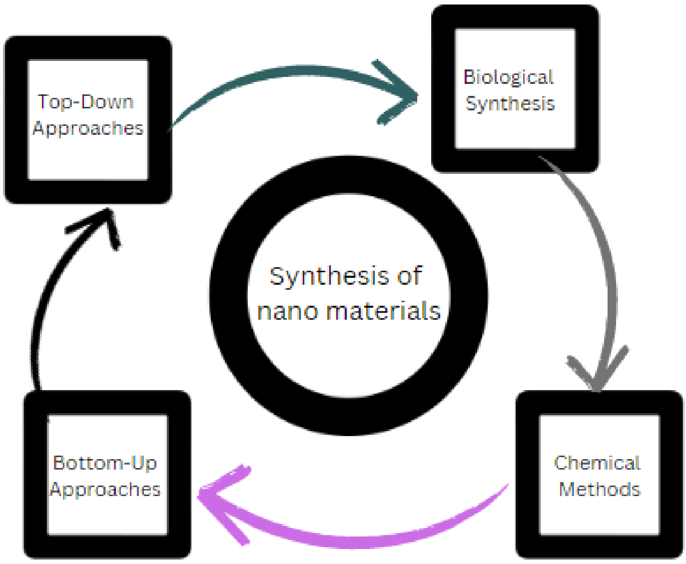

Figure 4. Extraction and synthesis of nano materials.

operation of entire packaging systems and contribute to sustainability issues in a circular economy by creating resources from wastes. This paper discusses the potential uses of these nanomaterials through key case studies, application level use cases, and context level, sensory integration of existing packaging technologies. Through several examples, the case studies demonstrate how nanoparticles can revolutionize smart and active packaging. A wonderful example of this is the antibacterial effects of silver nanoparticles from our wastewater, which enter food packaging. 3) These nanoparticles can prevent algal growth by exerting antimicrobial and antifungal properties used to keep perishable material fresh for a longer time [22–25]. Then, we execute zinc oxide nanoparticles that are derived from treated wastewater and UV (ultraviolet) blockers. sealed in polymers, they postpone the spoilage of foodstuffs and medicines from ultraviolet radiation, keeping them sound for long periods of time. The third one describes graphene oxide-and other carbon-based nanomaterials-recovery from carbon-rich wastewater. Packaging materials made of these compounds possess lower softness and humidity-permeability which are two essential properties for food preservation. When incorporated into smart packaging systems, these nanoparticles provide real-time information about the quality and safety of the product. This, for instance, the pH-sensitive nanoparticles that were initially designed for wastewater treatment are now used as colorimetric indicators in food packaging. These markers can change colour with pH fluctuations, indicating spoilage or contamination. In a related approach, sensors made of metal oxide nanoparticles obtained from wastewater could detect dangerous gases, such as ammonia that may be included in packaging. This feature ensures the safety and integrity of packed goods by providing instantaneous feedback if an object is moved outside its defined range [26, 27]. A further problem is how to add the nanoparticles to packaging without altering the properties of the packaging compared to conventional methods — an important consideration of course if consumers are to accept such modified packaging. Nanoparticles can be incorporated into packaging sheets and containers through surface coating, mixing, and lamination. Silica nanoparticles/templates recovered from treating wastewater were used to reinforce biopolymer packaging in order to increase their mechanical strength and transparency. In paper is eco-friendly, retaining packaging capabilities and inkwell used next-gen functions. In addition, because of advances in additive manufacturing and 3D printing, smart packaging materials designed with the properties of nanoparticles removed from wastewater can be generated [28]. In addition to this, multi-purpose packaging systems are also created using wastewater-derived nanoparticles. Examples of passive and potential active properties of these combinations, such as antimicrobial activity, environmental monitoring, and barrier protection, will be discussed. One instance of utilizing wastewater-derived silver as well as titanium dioxide nanoparticles is the preparation of packaging films incorporating antibacterial and photocatalytic self-cleaning characteristics. The films prevent contents from being degraded, while also minimizing external cleaning and maintenance. Nanomaterials sourced from wastewater treatment [29, 30] are an example of modern ecotronics that are enabling active and smart packaging as they are a marriage between technology advancement and ecological preservation. Case studies address the challenges of real-world implementation to demonstrate that sensory and functional integration is possible and attainable. This sets the stage for future packaging technologies to reach great new heights. Applications of nanoscale materials in active and smart packaging functionalities are listed in Table 1.

6 Environmental and Economic Impacts of nano materials

Nanoparticles synthesized from wastewater treatment could be utilized in active and smart packaging technology, providing a useful solution to the global issue of wastewater disposal that can pose major

Table 1. Nano materials applications in active and smart packaging.

No.	Features	Active Packaging	Smart Packaging	References
1	Definition	Enhances packaging by interacting with the product to extend shelf life	Monitors product conditions and provides real-time information	[22]
2	Functions	Releases or absorbs substances to maintain quality.	Senses, records, and communicates changes in the product or environment	[23]
3	Key Technologies	Antimicrobial agents, Oxygen scavengers, Moisture control	Sensors, RFID tags, Time-temperature indicators	[24]
4	Nanomaterials Used	Silver nanoparticles, Titanium dioxide, Zinc oxide, Clay nanoparticles	Carbon nanotubes, Quantum dots, Nanocellulose, Nanosensors	[25]
5	Purpose	Improves food safety, delays spoilage, enhances freshness	Provides real-time monitoring, ensures traceability, prevents counterfeiting	[26]
6	Examples	Antimicrobial films, Ethylene scavengers for fruits, UV-blocking coatings	Smart labels that change color based on freshness, RFID tracking, Spoilage indicators	[27, 30]
7	Consumer Benefit	Regulatory approval, Cost, Potential toxicity concerns	Consumer acceptance, Standardization, Cost of technology	[28, 29]

economic and ecological threats. This strategy resonates with the underlying tenets of the circular economy, which seeks not only to recuperate and recycle pricey resources trapped in our wastewater, but also to utilize innovative technology to understand the environmental and economic benefits that can both be delivered when better practices are put into place. Recovering nanoparticles from wastewater is one sustainable solution to lessen our reliance on virgin resources. The integration of these nanoscale materials with their unique properties into a range of packaging solutions can further increase their utility. There wide range of applications in active and smart packaging contributes to food safety, waste reduction, and prolong the shelf life, which are crucial global issues. One of the principles of the circular economy seeks, for example, to convert residues into valuables, such as a good that is hyphenated in part by the so-called resource efficiency and waste valorization [31]. Able to make these creative ideas financially viable is key. A detailed life cycle assessment (LCA) shows that using nanoparticles from wastewater treatment in packaging is beneficial for the environment. LCA indicates that energy use, resource depletion, and greenhouse gas emissions savings can be observed at every stage, from material recovery through to end-of-life disposal, when compared to traditional packaging materials. Such a comprehensive strategy for product usefulness, as shown in principle can help reduce the environmental footprints as well. A cost-benefit analysis found this strategy is money-saving. The reuse of nanomaterials can also be an economic process because packaging materials produced are valuable and can lead to profit when being recycled. The industry for smart and active packaging could grow dramatically because to the increasing demand from consumers for sustainable and multipurpose products. Enhancing product shelf life and minimizing the expenses tied to waste disposal are among the potential drivers of cost savings associated with the integration of nanomaterials. Producers and consumers will have economic incentives from this [32]. But the use of nanoparticles in wastewater treatment has social benefits that go beyond immediate financial indicators. Benefits among them are reduced pressure on waste management and disposal systems, new jobs (thousands of them) created in the recycling and new material manufacturing sectors and, lastly, improved public health outcomes through better food packaging safety. In this application, which explores the environmental as well as the economic aspects, one of the key aspects is the complementary relationship between technology and sustainable development goals. Treating wastewater to produce nanomaterials to enhance active and smart packaging with sustainable materials offers an excellent opportunity to promote a circular economy. This method has someone economic and environmental advantages according to comprehensive life cycle assessments and price-benefit analysis. Such paradigm change towards generating the goods of higher value by means of pxOMOPs inuences the new circular economy, improving resource management of pxOMOPs and generating economic opportunities in biorefining, bioreactors or bioprocesses [33–35]. It also bridges the gap between the waste recovery industry and the manufacturing industry. Figure 5 depicts Environmental and Economic Impacts due to the failure of proper utilization of the nano materials in the smart packaging.

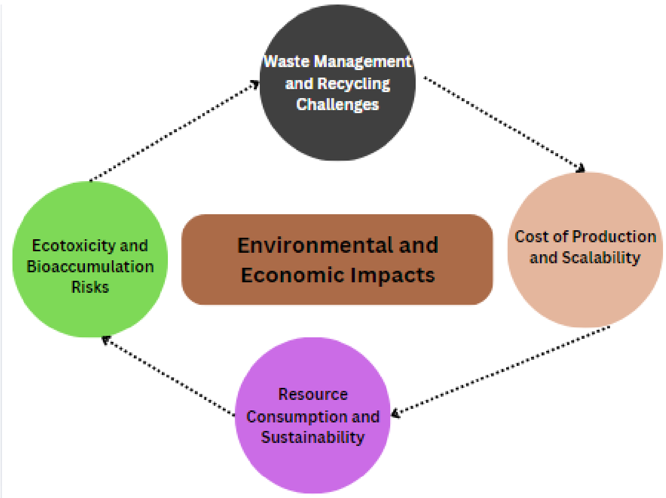

Figure 5. Environmental and economic impacts.

7 Challenges distinguished and Future Directions

One of the biggest challenges is in scaling up manufacturing. While these techniques have demonstrated promise in laboratory investigations, implementing these methods at an industrial scale will also require addressing economic and technological barriers. For example, extracting and synthesizing nanoparticle from wastewater is a resource and energy-heavy process that lacks feasibility and economics on a large scale. While there are numerous challenges that need to be addressed to scale up, industrialize, and comply with safety and regulatory standards for nanoparticle derived active and smart packaging driven from wastewater treatment, there are also and as many opportunities [36]. Emission of wastewater from various sources has another challenge regarding standardization and mass manufacturing, as heterogeneity in the wastewater content can influence the degree of uniformity and the quality of the nanomaterials. Feature A, the industrial acceptability of these materials in the real world There must be clear evidence of better performance, sustainability, or cost savings as well, from existing solutions, to justify the jump from existing solutions to nanomaterials as a potential active and smart packaging alternative. Worry over upfront costs, potential disruptions to existing processes, and uncertainty over long-term results cause industries to hesitate to add new technology. Addressing these challenges will require robust pilot programs, detailed cost-benefit analysis, and tailored scalable manufacturing processes for each industry [37, 38]. The last part of the importance that we will be discussing is in terms of safety and compliance with the regulations. It is questionable whether the specific properties of nanomaterials may potentially be harmful to humans or the environment. Producers are further challenged by the increased focus by regulatory agencies on risk assessment and risk management. The nanomaterials produced from recycling wastewater should undergo extensive toxicity testing and characterization to ensure their safety. Regulatory frameworks vary by region, causing difficulties for companies looking to penetrate international markets as well. Widespread acceptance will require the coordination of these frameworks and the delivery of clear standards for safe nanomaterial use [39]. Despite these challenges, this sector has significant room for growth and innovation. Kindly note that this is a free-to-read article published in a high-quality, peer-reviewed journal and Made available by Elsevier, which is the leading competitor among open-access publishers and provides for free access to the papers of authors from poor countries. When regulatory agencies, businesses and universities collaborate, scalable, secure, compliant solutions can be developed in a more rapid fashion. The increased need for its sustainability from both consumers and businesses is yet another compelling reason to invest in sustainable packaging. Despite the challenges that may be faced along the way, the potential for nanomaterials regenerated from wastewater treatment to become integrated into active and smart packaging and revolutionize the packaging sector is great [40]. Scalability, and Industrial adoption, Safety, and regulatory compliance are all important stakeholders, the intersection of these may allow for innovation, sustainability, and economic growth. This brilliant researcher has a great future ahead with everyone's united efforts and focus on collaborating towards solutions. The challenges and future directions of nano materials from wastewater treatment and smart packaging as shown in Figure 6.

8 Conclusion

These nanoparticles based on treated wastewater can provide a paradigm shift in active and smart packaging, which can potentially mitigate many sustainability

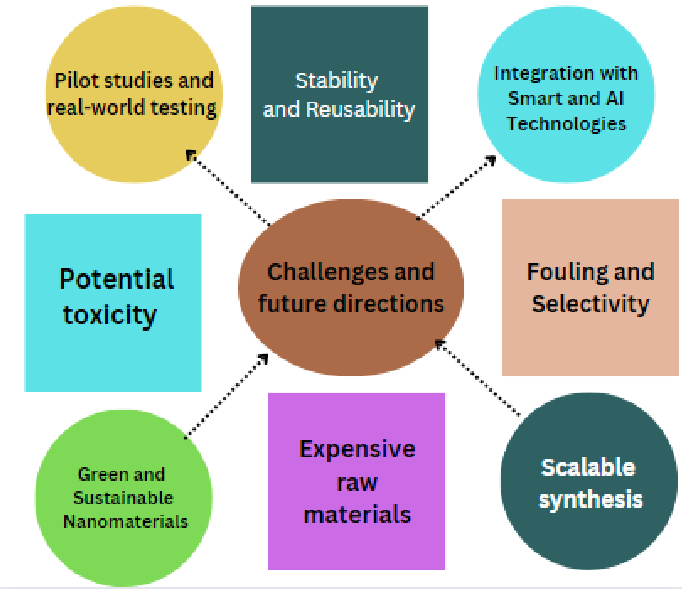

Figure 6. Challenges and future directions.

challenges. This strategy aligns with global actions for circular economy principles by turning waste streams into high-value-added nanomaterials, thereby addressing the environmental issues while reducing the need of the resources. These nanoparticles can be integrated into packaging solutions to improve functionality, thus improving shelf life and ensuring product safety. These include real-time tracking of the product, better oxygen barrier and anti-bacterial properties. With the latest advancements in this domain, we are seeing a new possibility for a paradigm shift in the packaging technology space. Recent developments in the field of nanotechnology and sustainable materials science have reduced the entry barrier for active and smart packaging solutions that meet the requirements of both consumers and regulatory authorities. However, what may be more overlooked is that the use of nanoparticles in packaging could have far-reaching consequences in relation to consumer safety. additive Toxicology, migration and environmental effect testing is needed to ensure that these products are not harmful to humans or the environment. For the development of sustainable packaging to turn into reality it will require collaboration between academics, firms, and government officials. Scalability and economic viability are driven by investments in research and technology. Conversely, new regulatory frameworks are needed to allow innovation while also protecting environmental and public health. Finally, employment of nanoparticles from wastewater treatment into packaging solutions can result in Sustainable and Resilient future. This new approach combines ecological awareness with technological progress.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Deng, F., Shi, H., Guo, Y., Luo, X., & Zhou, J. (2021). Engineering paths of sustainable and green photocatalytic degradation technology for pharmaceuticals and organic contaminants of emerging concern. *Current Opinion in Green and Sustainable Chemistry, 29*, 100465. [CrossRef]

[2] Dua, T. K., Giri, S., Nandi, G., Sahu, R., Shaw, T. K., & Paul, P. (2023). Green synthesis of silver nanoparticles using Eupatorium adenophorum leaf extract: characterizations, antioxidant, antibacterial and photocatalytic activities. *Chemical Papers, 77*(6), 2947-2956. [CrossRef]

[3] El-Fallal, A. A., Elfayoumy, R. A., & El-Zahed, M. M. (2023). Antibacterial activity of biosynthesized zinc oxide nanoparticles using Kombucha extract. *SN Applied Sciences, 5*(12), 332. [CrossRef]

[4] Fouda, A., Eid, A. M., Abdelkareem, A., Said, H. A., El-Belely, E. F., Alkhalifah, D. H. M., ... & Hassan, S. E. D. (2022). Phyco-synthesized zinc oxide nanoparticles using marine macroalgae, Ulva fasciata Delile, characterization, antibacterial activity, photocatalysis, and tanning wastewater treatment. *Catalysts, 12*(7), 756. [CrossRef]

[5] Gao, Q., & Keller, A. A. (2020). Redesigning water disinfection using recyclable nanomaterials and metal ions: Evaluation with Escherichia coli. *ACS ES&T Water, 1*(1), 185-194. [CrossRef]

[6] Huang, Y., & Keller, A. A. (2015). EDTA functionalized magnetic nanoparticle sorbents for cadmium and lead contaminated water treatment. *Water Research, 80*, 159–168. [CrossRef]

[7] Ibarra-Cervantes, N. F., Vázquez-Núñez, E., Gómez-Solis, C., Fernández-Luqueño, F., Basurto-Islas, G., Álvarez-Martínez, J., & Castro-Beltrán, R. (2024). Green synthesis of ZnO nanoparticles from ball moss (Tillandsia recurvata) extracts: characterization and evaluation

of their photocatalytic activity. *Environmental Science and Pollution Research, 31*(9), 13046-13062. [CrossRef]

[8] Jamzad, M., Mokhtari, B., & Mirkhani, P. S. (2023). Green synthesis of metal nanoparticles mediated by a versatile medicinal plant extract. *Chemical Papers, 77*(3), 1455-1467. [CrossRef]

[9] Khan, K. A., Shah, A., Nisar, J., Haleem, A., & Shah, I. (2023). Photocatalytic degradation of food and juices dyes via photocatalytic nanomaterials synthesized through green synthetic route: a systematic review. *Molecules, 28*(12), 4600. [CrossRef]

[10] Li, Y. H., Wang, S., Wei, J., Zhang, X., Xu, C., Luan, Z., ... & Wei, B. (2002). Lead adsorption on carbon nanotubes. *Chemical physics letters, 357*(3-4), 263-266. [CrossRef]

[11] Lu, Q., Xu, Q., Meng, J., How, Z. T., Chelme-Ayala, P., Wang, X., ... & Zhang, X. (2022). Surface microlenses for much more efficient photodegradation in water treatment. *ACS ES&T Water, 2*(4), 644-657. [CrossRef]

[12] Mehmood, S., Ahmed, W., Rizwan, M., Bundschuh, J., Elnahal, A. S., & Li, W. (2024). Green synthesized zinc oxide nanoparticles for removal of carbamazepine in water and soil systems. *Separation and Purification Technology, 334*, 125988. [CrossRef]

[13] Nguyen, T. H. A., Doan, V. D., Tran, A. V., Nguyen, V. C., Nguyen, A. T., & Vasseghian, Y. (2022). Green synthesis of Nb-doped ZnO nanocomposite for photocatalytic degradation of tetracycline antibiotic under visible light. *Materials Letters, 308*, 131129. [CrossRef]

[14] Patel, S. K., Ritt, C. L., Deshmukh, A., Wang, Z., Qin, M., & Elimelech, M. (2020). The relative insignificance of advanced materials in enhancing the energy efficiency of desalination technologies. *Energy & Environmental Science, 13*(6), 1694–1710. [CrossRef]

[15] Fadlalla, M. I., Senthil Kumar, P., Selvam, V., & Ganesh Babu, S. (2019). Recent advances in nanomaterials for wastewater treatment. *Advanced nanostructured materials for environmental remediation*, 21-58. [CrossRef]

[16] Siddiqui, J., Taheri, M., Alam, A. U., & Deen, M. J. (2022). Nanomaterials in smart packaging applications: a review. *Small, 18*(1), 2101171. [CrossRef]

[17] Dizaj, S. M., Mennati, A., Jafari, S., Khezri, K., & Adibkia, K. (2015). Antimicrobial activity of carbon-based nanoparticles. *Advanced pharmaceutical bulletin, 5*(1), 19. [CrossRef]

[18] Xu, P., Zeng, G. M., Huang, D. L., Feng, C. L., Hu, S., Zhao, M. H., ... & Liu, Z. F. (2012). Use of iron oxide nanomaterials in wastewater treatment: A review. *Science of the Total Environment, 424*, 1-10. [CrossRef]

[19] Saravanan, A., Kumar, P. S., Hemavathy, R. V., Jeevanantham, S., Jawahar, M. J., Neshaanthini, J. P., & Saravanan, R. (2022). A review on synthesis methods and recent applications of nanomaterial in wastewater treatment: Challenges and future perspectives. *Chemosphere, 307*, 135713. [CrossRef]

[20] Bhatlawande, A. R., Ghatge, P. U., Shinde, G. U., Anushree, R. K., & Patil, S. D. (2024). Unlocking the future of smart food packaging: biosensors, IoT, and nano materials. *Food Science and Biotechnology, 33*(5), 1075-1091. [CrossRef]

[21] Rossa, V., Ferreira, L. E. M., da Costa Vasconcelos, S., Shimabukuro, E. T. T., da Costa Madriaga, V. G., Carvalho, A. P., ... & de Melo Lima, T. (2022). Nanocomposites based on the graphene family for food packaging: historical perspective, preparation methods, and properties. *RSC Advances, 12*(22), 14084-14111. [CrossRef]

[22] Bashir, O., Bhat, S. A., Basharat, A., Qamar, M., Qamar, S. A., Bilal, M., & Iqbal, H. M. (2022). Nano-engineered materials for sensing food pollutants: Technological advancements and safety issues. *Chemosphere, 292*, 133320. [CrossRef]

[23] Saleem, H., & Zaidi, S. J. (2020). Developments in the application of nanomaterials for water treatment and their impact on the environment. *Nanomaterials, 10*(9), 1764. [CrossRef]

[24] Kumar, S., Basumatary, I. B., Sudhani, H. P., Bajpai, V. K., Chen, L., Shukla, S., & Mukherjee, A. (2021). Plant extract mediated silver nanoparticles and their applications as antimicrobials and in sustainable food packaging: A state-of-the-art review. *Trends in Food Science & Technology, 112*, 651-666. [CrossRef]

[25] Amin, U., Khan, M. K. I., Maan, A. A., Nazir, A., Riaz, S., Khan, M. U., & Lorenzo, J. M. (2022). Biodegradable active, intelligent, and smart packaging materials for food applications. *Food Packaging and Shelf Life, 33*, 100903. [CrossRef]

[26] Bora, T., & Dutta, J. (2014). Applications of nanotechnology in wastewater treatment—a review. *Journal of Nanoscience and Nanotechnology, 14*(1), 613-626. [CrossRef]

[27] Liu, Y., Zhu, Y., Xu, Z., Xu, X., Xue, P., Jiang, H., ... & Cheng, B. (2024). Nanocellulose based ultra-elastic and durable foams for smart packaging applications. *Carbohydrate Polymers, 327*, 121674. [CrossRef]

[28] Nasrollahzadeh, M., Sajjadi, M., Iravani, S., & Varma, R. S. (2021). Green-synthesized nanocatalysts and nanomaterials for water treatment: Current challenges and future perspectives. *Journal of Hazardous Materials, 401*, 123401. [CrossRef]

[29] Bassyouni, M., Abdel-Aziz, M. H., Zoromba, M. S., Abdel-Hamid, S. M. S., & Drioli, E. (2019). A review of polymeric nanocomposite membranes for water purification. *Journal of Industrial and Engineering Chemistry, 73*, 19-46. [CrossRef]

[30] Goutam, S. P., Saxena, G., Roy, D., Yadav, A. K., & Bharagava, R. N. (2020). Green synthesis of nanoparticles and their applications in water and wastewater treatment. *Bioremediation of industrial waste*

for environmental safety: volume i: industrial waste and its management, 349-379. [CrossRef]

[31] Sethy, N. K., Arif, Z., Mishra, P. K., & Kumar, P. (2020). Green synthesis of TiO2 nanoparticles from Syzygium cumini extract for photo-catalytic removal of lead (Pb) in explosive industrial wastewater. *Green Processing and Synthesis*, *9*(1), 171-181. [CrossRef]

[32] Sikiru, S., Abiodun, O. A., Sanusi, Y. K., Sikiru, Y. A., Soleimani, H., Yekeen, N., & Haslija, A. A. (2022). A comprehensive review on nanotechnology application in wastewater treatment a case study of metal-based using green synthesis. *Journal of Environmental Chemical Engineering*, *10*(4), 108065. [CrossRef]

[33] Rathod, S., Preetam, S., Pandey, C., & Bera, S. P. (2024). Exploring synthesis and applications of green nanoparticles and the role of nanotechnology in wastewater treatment. *Biotechnology Reports*, *41*, e00830. [CrossRef]

[34] Omran, B. A., & Baek, K. H. (2022). Valorization of agro-industrial biowaste to green nanomaterials for wastewater treatment: Approaching green chemistry and circular economy principles. *Journal of Environmental Management*, *311*, 114806. [CrossRef]

[35] El Messaoudi, N., Ciğeroğlu, Z., Şenol, Z. M., Bouich, A., Kazan-Kaya, E. S., Noureen, L., & Américo-Pinheiro, J. H. P. (2024). Green synthesis of nanoparticles for remediation organic pollutants in wastewater by adsorption. In *Advances in Chemical Pollution, Environmental Management and Protection* (Vol. 10, pp. 305-345). Elsevier. [CrossRef]

[36] Abel, S., Jule, L. T., Belay, F., Shanmugam, R., Dwarampudi, L. P., Nagaprasad, N., & Krishnaraj, R. (2021). Application of titanium dioxide nanoparticles synthesized by sol-gel methods in wastewater treatment. *Journal of Nanomaterials*, *2021*(1), 3039761. [CrossRef]

[37] Omerović, N., Djisalov, M., Živojević, K., Mladenović, M., Vunduk, J., Milenković, I., ... & Vidić, J. (2021). Antimicrobial nanoparticles and biodegradable polymer composites for active food packaging applications. *Comprehensive Reviews in Food Science and Food Safety*, *20*(3), 2428-2454. [CrossRef]

[38] Bakhtiari, S., Salari, M., Shahrashoub, M., Zeidabadinejad, A., Sharma, G., & Sillanpää, M. (2024). A comprehensive review on green and eco-friendly nano-adsorbents for the removal of heavy metal ions: synthesis, adsorption mechanisms, and applications. *Current Pollution Reports*, *10*(1), 1-39. [CrossRef]

[39] Bai, S., Lv, T., Chen, M., Li, C., Wang, Z., Yang, X., & Xia, T. (2024). Carbon quantum dots assisted BiFeO3@BiOBr S-scheme heterojunction enhanced peroxymonosulfate activation for the photocatalytic degradation of imidacloprid under visible light: Performance, mechanism and biotoxicity. *Science of the Total Environment*, *915*, 170029. [CrossRef]

[40] Chandrani, D. N., Ghosh, S., & Tanna, A. R. (2024). Green synthesis for fabrication of cobalt ferrite nanoparticles with photocatalytic dye degrading potential as a sustainable effluent treatment strategy. *Journal of Inorganic and Organometallic Polymers and Materials*, *34*(7), 3100-3114. [CrossRef]

K. Arunprasath is currently doing his Post- Doctoral Research Fellowship in the Department of Mechanical Engineering, Alliance College of Engineering and Design, Alliance University, Chandapura - Anekal Main Road, Anekal, Bengaluru, India. He has published over 83 articles in various SCI and Scopus-indexed Journals, including Elsevier, Taylor & Francis, Springer, Sage, and Wiley. In addition to that, He has published Twenty-Four book chapters and Three books with the reputed publishers. Currently, his h-index is 17, his i10-index is 12, and his citations are 1050, according to the Google Scholar database. He has reviewed more than 125 manuscripts for various international journals. He has been enlisted in the Top 3% Scientist recognized by AD Scientific Index based on the Citations and H index for the year 2024. He obtains best young researcher and best researcher award from various science forms since 2020. His research areas include Natural and synthetic fiber characterization, Polymer Matrix Composites, and Cellular Manufacturing. (Email: aruncmr12@gmail.com)

Dr. AM. Shanawaz, Professor, Department of Mechanical Engineering, Kariapatti, Madurai, 616 115, Tamilnadu, India. His area of expertise is Composite material. (Email: shanawazpet@gmail.com)

Dr. Y. Carlin Calaph, Associate Professor, Department of Mechanical Engineering, PSN College of Engineering and Technology, Tirunelveli, 627 152, Tamilnadu, India. His areas of expertise is Composite materials and nano materials. (Email: collinntech@gmail.com)

Mr. T. Raj pradeesh, Assistant Professor, Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, 626 126, Tamilnadu, India. His areas of expertise is Composite materials and Industrial safety engineering. (Email: rajpradeesh29@gmail.com)

Dr. Ruby Celsia Arul Selvaraj, Assistant Professor, Department of Food Technology, K S Rangasamy College of Technology, Namakkal ,637215, India. Her areas of research is nano materials. (Email: rubycelsia@gmail.com)