Research Article

Green Synthesis of Bioactive Nanocomposites and Their Antioxidant Potential in Adolescent Health Applications

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Abstract

Green-synthesized bioactive nanocomposites have emerged as promising multifunctional materials that combine sustainable fabrication with enhanced biological performance. This review critically examines recent advances in the green synthesis of bioactive nanocomposites and their antioxidant potential, with particular emphasis on applications relevant to adolescent health. The review discusses environmentally friendly synthesis strategies utilizing plant extracts, microorganisms, and other biological resources, together with the influence of synthesis parameters on nanocomposite properties and functionality. It further summarizes the composition, physicochemical characteristics, and characterization techniques that determine biological performance, while highlighting the molecular mechanisms responsible for antioxidant activity and the methods used for antioxidant evaluation. Potential biomedical applications, including nutraceuticals, wound healing, oral healthcare, dermatology, targeted drug delivery, and wearable health technologies, are comprehensively reviewed. Safety, toxicity, biocompatibility, and regulatory considerations are also examined to identify key barriers to successful clinical translation. Additionally, emerging developments in artificial intelligence, precision nanomedicine, and multi-omics technologies are discussed as promising approaches for optimizing nanocomposite design and accelerating personalized healthcare solutions. Although considerable progress has been achieved, further standardization, long-term safety assessment, and interdisciplinary collaboration are required to translate these sustainable nanomaterials into clinically effective interventions. Green-synthesized bioactive nanocomposites have significant potential to support future antioxidant-based strategies for adolescent health and broader biomedical applications.

Keywords: Green synthesis, Bioactive nanocomposites, Antioxidant activity, Adolescent health, Nanomedicine.

1. Introduction

Oxidative stress is becoming more and more a cornerstone in the development of many inflammatory conditions, metabolic, dermatological and degenerative diseases. It is caused by the imbalance of the overproduction of reactive oxygen species (ROS) and the antioxidant defense system of the body, which causes lipid peroxidation, protein oxidation, DNA damage, and dysfunction. Adolescents are a unique population with several physiological changes, hormonal changes, increased nutrition requirements and greater exposure to the environment, which may make them more vulnerable to oxidative stress. Thus, new strategies are needed to develop safe and efficient antioxidant interventions to improve the health and disease prevention in this population [1].

The application of nanotechnology has led to remarkable advancements in the formulation of antioxidant therapeutics through a variety of approaches to improve the inherent biological activities of nanoscale materials, to target their delivery, and to improve their physical or chemical stability. One of these innovations, bioactive nanocomposites, has gathered much interest in that it is composed of two or more functional materials that can produce synergic therapeutic effects which cannot be achieved with traditional formulation. The multifunctional systems have shown great potential in the fields of modern biomedical science due to their antioxidant, anti-inflammatory, antimicrobial and regenerative properties. The antioxidant nanocomposites seem to have gained clinical importance in recent times as they have been found to effectively modulate the oxidative pathways and hamper the occurrence of tissue damage in immune-mediated and skin related conditions [1,2].

In general, the synthesis of nanocomposites typically requires high energy consumption, environmentally unsustainable manufacturing and hazardous chemicals. To overcome these drawbacks, green synthesis which uses the plant extracts, microorganisms, algae, fungi and naturally occurring biomolecules as the reducing and stabilizing agents has been developed as an alternative sustainable approach. This is an eco-friendly way of synthesizing nanomaterials that produces minimal toxic by-products and enhances the biocompatibility, stability and biological activity of the materials synthesized. Additionally, the naturally sourced phytochemicals added during the green synthesis process can also improve the antioxidant activity and decrease the cytotoxicity of such nanocomposites, which is of great interest in the biomedical field [3,5–7].

New developments have shown that nanocomposites synthesized using green methods, such as zinc oxide, selenium and gold nanoparticles showed an extraordinary free radical scavenging activity and could regulate the oxidative stress by several molecular pathways. They have the capacity to promote wound healing, tissue regeneration, controlled drug delivery, dermatological therapy, and immune modulation, highlighting their versatility in the healthcare sector. While all of this is good news, the majority of published work has only studied the materials in the laboratory and their synthesis, and in-depth studies of their therapeutic relevance to adolescent health are still limited [4,6–8].

Keeping these facts in mind, this review aims to critically assess the current status on the green synthesis of bioactive nanocomposites, their antioxidant mechanism, characterization, biomedical applications, and safety considerations with special emphasis on their newfound importance in the field of adolescence. In addition, the review highlights current research gaps, translation hurdles, and future prospects which could aid the development of clinically relevant, sustainable, and next-generation antioxidant nanocomposite systems.

2. Green Synthesis of Bioactive Nanocomposites

Green synthesis has been evolved as a sustainable approach towards the synthesis of bioactive nanocomposites by combining the principles of nanotechnology with green chemistry. Green synthesis offers an alternative to the traditional synthesis techniques which rely on toxic chemicals, high temperatures and energy intensive processing and instead uses naturally available reducing and stabilizing agents to synthesize the nanomaterials under environmentally benign conditions. This is a way of reducing toxic waste production, reducing energy consumption, increasing the safety of the process and also aids in the development of eco-friendly biomedical materials [9]. In the context of the growing importance of sustainability as a goal in materials science, the green synthesis has proved to be effective

in preparing high performance nanocomposites with low environmental impact as compared to conventional methods of synthesis [10].

Biological resources are key to green synthesis of nanocomposites. Plant extracts are the most commonly used due to the presence of large number of phytochemicals such as flavonoids, phenolics, tannins, alkaloids, proteins and polysaccharides, which all act as reducing, stabilizing and capping agent in the formation of nanoparticles [11]. Microorganisms (bacteria, fungi, algae and yeast) also have shown great potential for the synthesis of nanoparticles with controlled morphology and biocompatibility. In recent years, farm wastes and byproducts of food production have also become the focus of interest as promising sources of bioactive compounds, which can also be valorised in terms of waste reduction, cost reduction and practices of circular bioeconomy [12].

In order to achieve structural quality and reproducibility of bioactive nanocomposites, several green synthesis strategies have been developed. Common methods are hydrothermal synthesis, sol-gel technique, microwave assisted synthesis, ultrasound assisted synthesis and other low energy methods. Of these, the use of microwave-assisted synthesis has garnered much interest as this approach allows for rapid and homogeneous heating, reduced reaction time, higher crystallinity, and higher uniformity of the nanoparticles, while also being more energy efficient than traditional heating methods [13]. These developments enable the production in large scale of multifunctional nanocomposites for biomedical and pharmaceutical applications [14].

Physicochemical properties of the green-synthesized nanocomposites dramatically depend on the synthesis. The nucleation, crystal growth and stability, particle size, morphology, surface chemistry and overall stability are directly affected by factors like pH, reaction temperature, precursor concentration, extract composition, reaction duration, and metal ion concentration [15]. Furthermore, the composition and phytochemical fingerprint of the extract used to produce the biological metal ion reduction reaction and the extent of functionalization of surfaces will impact the antioxidant and biological activity of the final nanocomposite. Therefore, careful optimisation of these parameters is crucial for reproducible synthesis, to achieve improved functionality and enhance the biomedical efficacy [16].

In general, the green synthesis is an environmentally friendly and scientifically sound method to prepare bioactive nanocomposites. The synergy of renewing biological resources and optimizing synthesis approaches results in the development of multifunctional nanomaterials with enhanced biocompatibility, sustainability, and therapeutic efficacy, thus paving the way for their utilization in antioxidant-based healthcare and future translational medicine. Table 1 illustrates the key advantages and the biomedical relevance of the major biological resources and environmentally friendly synthetic methods used for the preparation of bioactive nanocomposites.

Table 1. Green synthesis strategies for bioactive nanocomposites

Green synthesis approach	Biological/Processing source	Major advantage	Biomedical significance	References

Plant-mediated synthesis	Plant phytochemicals	Eco-friendly and biocompatible	Enhanced antioxidant activity	[10,11, 16]
Microbial synthesis	Bacteria, fungi, algae	Low toxicity	Stable nanoparticle production	[15]
Food waste-mediated synthesis	Agricultural and food residues	Sustainable resource utilization	Circular bioeconomy applications	[12]
Microwave-assisted synthesis	Microwave irradiation	Rapid synthesis and uniform particles	Improved material quality	[14]
Hydrothermal/Sol-gel synthesis	Controlled aqueous processing	High crystallinity and stability	Biomedical nanocomposites	[13,15]

3. Bioactive Nanocomposites: Composition, Properties, and Characterization

Advanced multifunctional materials that are composed of two or more components at the nano-level that synergistically improve their biological and/or physicochemical properties are termed bioactive nanocomposites. Typically, these materials include metallic nanoparticles, metal oxides, carbon based nanostructures, polymers, ceramics and/or natural biomolecules that create synergies in properties that could not be obtained by the individual constituents. Bioactive nanocomposites with antioxidant, antimicrobial and anti-inflammatory properties as well as drug delivery and tissue regeneration capabilities are of great interest for numerous biomedical applications based on their compositions. Recent studies have been focused on engineering of hybrid nanocomposites with enhanced functional versatility, structural stability and therapeutic efficacy [17].

The effectiveness of bioactive nanocomposites depends on a number of physicochemical parameters such as particle size, morphology, surface area, porosity, crystallinity, mechanical property and surface charge.

Of these, particle morphology plays a significant role in biological interactions as changes in morphology affect cell uptake, diffusion behavior, catalytic efficiency and surface reactivity. The functional properties of nanostructures are different in spherical, rod-shaped, tubular and sheet-like nanostructures, and precise control of the morphology is required to achieve specific biomedical properties during the synthesis process [18].

The complete characterization of the synthesized bioactive nanocomposites is a necessary step to ensure the successful synthesis and functional properties of the synthesized nanocomposites. The verification of the formation of nanoparticles by the characteristic absorption peak has been done by ultra-violet visible spectroscopy and the identification of functional groups responsible for the reduction and surface stabilization has been done by fourier-transform infrared spectroscopy. X-ray diffraction (XRD) helps to gain knowledge of crystal structure and phase purity while scanning electron microscopy (SEM) and transmission electron microscopy (TEM) offer information on the morphology, size distribution and surface architecture of the particles. DLS also measures hydrodynamic particle size and dispersion which allows to assess the colloidal stability, relevant to biomedical formulations [19,20].

Further, surface engineering and functionalization can be used to further enhance the biological performance of nanocomposites by improving their stability, dispersibility, and interactions with biological systems. Polymer coating, ligand conjugation and biofunctional surface modification enhance resistance to aggregation and promote specific cellular interactions and extended circulation. Modification of the bio–nano interface also leads to better biocompatibility and less nonspecific interactions to improve the efficiency of the therapy and decrease any potential toxicity. Multifunctional surface modifications have now become a standard approach on the design of the next generation of nanocomposites for antioxidant therapy, controlled drug delivery and regenerative medicine [21].

The overall biological functionality of bioactive nanocomposites is governed by its composition, physicochemical properties and structural characteristics. A rational surface engineering approach with the aid of accurate characterization can be used to prepare highly-stable, biocompatible and multifunctional nanocomposites with excellent antioxidant properties and great promise in future biomedical and adolescent healthcare applications. The composition, structural properties, characterization techniques and surface-engineering strategies that control the biological performance of bioactive nanocomposites are summarized in Fig. 1.

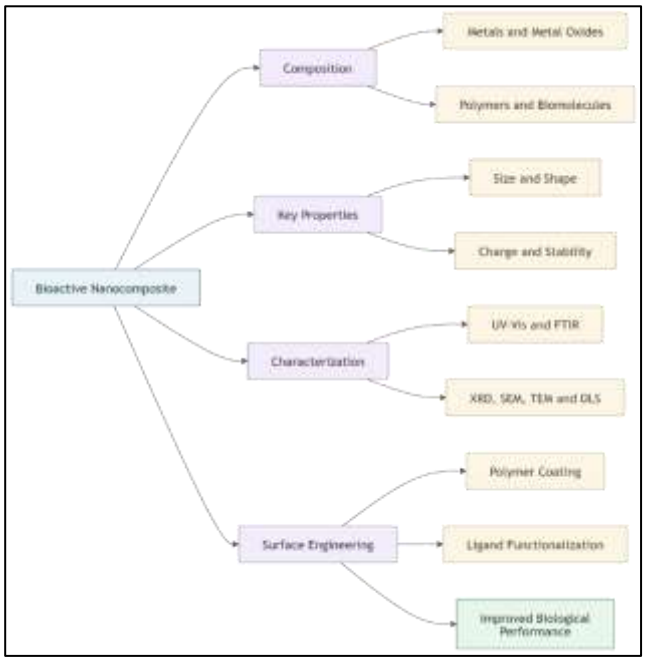


Figure 1. Composition, characterization, and functional properties of bioactive nanocomposites

4. Antioxidant Mechanisms of Green-Synthesized Bioactive Nanocomposites

The therapeutic efficiency of green-synthesized bioactive nanocomposites is mainly due to their capacity of regulating the oxidative stress by controlling the production of Reactive Oxygen Species (ROS) and activation of the endogenous antioxidant defense systems. Although ROS are involved in normal physiological processes for cellular signaling and regulation, excessive ROS production can lead to oxidative damage to lipids, proteins, nucleic acids and cellular membranes. Continuous oxidative stress is believed to contribute to the pathogenesis of inflammatory diseases, defective tissue repair, metabolic disorders and many chronic diseases, thus highlighting the need for efficient antioxidant strategies to preserve cellular homeostasis [22,23].

Bioactive nanocomposites prepared by green methods have been proven to have antioxidant activity via several molecular mechanisms. One of the main mechanisms is the direct removal of free radicals through the transfer of an electron or a hydrogen atom to the reactive and unstable species, which is the termination of the oxidative chain reaction. Moreover, a number of nanocomposites have metal-chelating properties which prevent the generation of highly reactive hydroxyl radicals by catalysis via transition metals. In addition, surface bound phytochemicals derived from plant extracts, can further optimize the antioxidant activity, by stabilizing the reactive intermediates and maintaining the cellular redox balance. All these synergistic mechanisms together decrease the oxidative damage and prevent the irreversible damage of the cellular components [24].

Many of the physicochemical properties of the nanocomposites such as particle size, morphology, surface area, crystallinity and surface functional groups play an important role in determining their antioxidant activity at the molecular level. The larger the surface area to volume ratio of the smaller nanoparticles the more surface area that is available to neutralize free radicals. Similarly, functional groups generated by

biological reducing agents, help to promote electron transfer reactions as well as enhancing radical scavenging efficiency. Antioxidant mechanisms have also been shown to highly depend on the molecular structure, electronic configuration, and surface chemistry of these nanocomposites through computational investigations, thereby emphasizing the need for a rational design of these nanocomposites to optimize their therapeutic performance [24,25].

To assess the antioxidant activity, standardized experimental assays which are able to measure various mechanisms of radical inhibition are necessary. The commonly used assays are 2,2-diphenyl-1-picrylhydrazyl (DPPH) for hydrogen atom or electron donation capacity, 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) for both hydrophilic and lipophilic antioxidant activity, and ferric reducing antioxidant power (FRAP) for reducing power. Other assays such as oxygen radical absorbance capacity (ORAC), nitric oxide scavenging assays and lipid peroxidation inhibition assays supplement the data obtained on antioxidant activity under varying circumstances. Since different assays relate to different antioxidant activity mechanisms, the use of various techniques to measure antioxidant activity provides a better picture of biological activity of the green-synthesized nanocomposites [26].

In conclusion, the antioxidant activity of green-synthesized bioactive nanocomposites is attributed to a concerted interplay of structural attributes, surface phytochemicals and the molecular activity of free radical neutralization. It is crucial to understand these mechanisms in order to create multifunctional nanocomposites with improved antioxidant effects and great potential in future biomedical and adolescent health applications. The most frequently used analytical assays to assess green-synthesized bioactive nanocomposites along with the most important antioxidant mechanisms are presented in Table 2.

Table 2. Antioxidant mechanisms and evaluation methods

Mechanism/Assay	Biological principle	Major outcome	Application	References
Free radical scavenging	Electron/Hydrogen donation	Neutralization of ROS	Cellular protection	[24,25]
Metal ion chelation	Inhibits ROS generation	Reduced oxidative damage	Antioxidant therapy	[24]
DPPH assay	Radical scavenging activity	Antioxidant capacity	Initial antioxidant screening	[26]

ABTS assay	Radical cation reduction	Hydrophilic/lipophilic antioxidant evaluation	Comparative antioxidant analysis	[26]
FRAP assay	Ferric ion reduction	Reducing power	Quantification of antioxidant potential	[26]

5. Applications of Green-Synthesized Bioactive Nanocomposites in Adolescent Health

The synthesis of bioactive nanocomposites using green technology has proved to be a promising approach for creating a multifunctional material to be used in solving adolescent health problems. These antioxidant, antimicrobial, anti-inflammatory, and regenerative attributes make them suitable for various applications such as nutrition, wound care, oral care, dermatology, and targeted drug delivery. Due to the high biocompatibility and environmentally-friendly synthesis, these nanocomposites can be used as safe alternatives to the conventional synthesis of nanomaterials and can be used for the prevention and treatment of oxidative stress related diseases [27].

The most promising use is in the development of nutraceuticals and functional foods where bioactive nanocomposites can improve the stability, bioavailability and controlled release of natural antioxidants. The processing and storage of plant derived polyphenols or other phytochemicals is often accompanied by degradation of the compounds, which can be prevented by encapsulation, and gastrointestinal absorption is also improved. These systems not only prolong the functional food's shelf-life but also deliver the antioxidant activity for a long period of time, which is beneficial for adolescents' nutrition and for the reduction of oxidative stress [28,29].

Another crucial role of the green-synthesized nanocomposites is wound healing and tissue regeneration. They not only have the ability to neutralize the harmful ROS, but also have antimicrobial activity, which is conducive to the proliferation of cells, the synthesis of collagen, the formation of blood vessels and the remodeling of tissues. Antioxidant biomaterials in hydrogel, scaffolds and wound dressing could be useful for wound healing and reduce inflammation which can be a problem in acute wounds, burns and chronic wound lesions that may be a problem in the adolescent and could be usefull for therapeutic applications [27].

Oral healthcare has shown significant potential of antioxidant nanocomposites in prevention and treatment of oral infections, dental caries and periodontal diseases. The antimicrobial activity of the biomaterials produced by green methods is broad-spectrum and satisfactory biocompatibility with oral

tissues. These materials can be used in restorative dental products, as implant coatings and in mouth-care products for antimicrobial activity to inhibit bacterial colonization, promote good oral hygiene, and improve long-term clinical results [30].

The dermatological uses have also attracted more interest as oxidative stress is an important factor in acne vulgaris, skin inflammation and early damage of skin. The production of nanocomposites using green synthesis methods and their application in topical formulations enhances antioxidant activity, helps in controlling inflammatory responses, and ensures the controlled release of bioactive agents. The essential oil based and antioxidant enriched formulations are additionally interesting in the field of management of skin disorders in adolescence because they further improve skin barrier function and decrease skin irritation [31].

One of the other fast-growing fields is the use of bioactive nanocomposites as efficient carriers for therapeutic agents in targeted drug delivery. Controlled and site-specific delivery of drugs can be achieved with the help of biopolymer-based encapsulation systems, especially alginate-based nanocomposites, which enhances treatment efficacy and reduce systemic toxicity. These types of platforms are particularly useful for the delivery of antioxidants for chronic diseases that need long-term treatment and individualized approaches [32].

In recent times, technological progress has allowed the use of antioxidant nanocomposites with wearable healthcare devices, which further extend the application field of antioxidant nanocomposites. New opportunities arise for personalized healthcare for adolescents with smart biosensors and non-invasive wearable systems that can track physiological parameters and oxidative stress biomarkers. In addition to precision therapeutic interventions, nanotechnology could enable early detection of disease, continuous monitoring of health, and precision therapeutics, and is an important area for future biomedical innovation [33]. The major applications of the green-synthesized bioactive nanocomposites in adolescent healthcare such as nutritional support, skin care, oral health, wound management, drug delivery, health monitoring, etc. are presented in the figure 2.

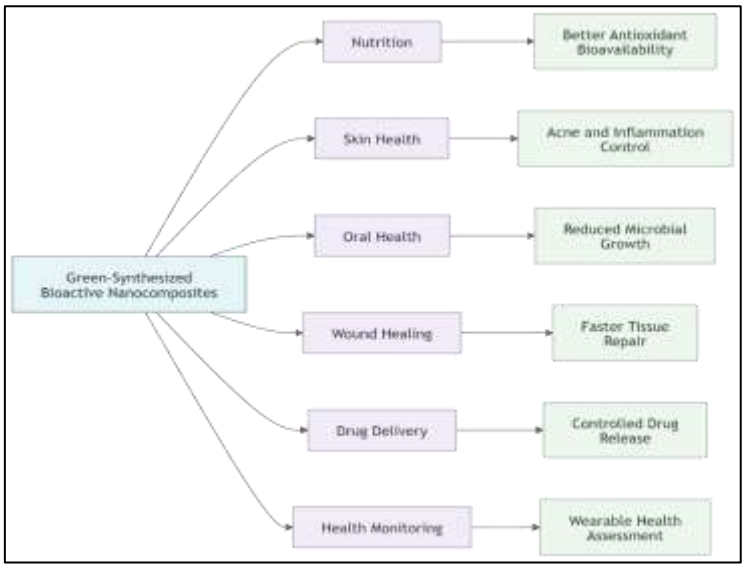


Figure 2. Major applications of green-synthesized bioactive nanocomposites in adolescent health

6. Safety, Toxicity, Biocompatibility, and Regulatory Considerations

However, for the successful transfer of green-synthesized bioactive nanocomposites from the lab to the clinic, it is essential that they are safe for long-term use, biocompatible, and accepted by regulatory bodies. While green synthesis, in general, is expected to lead to the use of fewer harmful chemicals and provide a more biologically compatible nanomaterial, full safety testing is still necessary before use on a large scale in the biomedical field. Biological responses, and the overall risk profile of nanocomposites, can be highly affected by their composition, size, surface chemistry, dose and duration of exposure [34].

Biocompatibility is one of the main criteria for the biomedical nanocomposites as they come directly in contact with cells, tissues and physiological fluids. A normal cell function should be maintained while the biocompatible nanocomposite causes no exaggerated inflammation, oxidative damage or immune reactions. The usual biological tests which are performed are cytotoxicity assays, cell viability studies, hemocompatibility tests, inflammatory marker analysis, and cell uptake investigations. Recent studies have shown that appropriate surface engineering and controlled synthesis conditions significantly enhance the cells' compatibility, and reduce the undesirable biological response, which will significantly boost the clinical potential of green-synthesized nanocomposites [34,35].

Although the biomedicine properties of the nanocomposites are encouraging, there are potential toxicological issues that need to be addressed as a function of their physical-chemical properties and biological activity. Biodistribution, tissue accumulation, cellular internalization and elimination mechanisms are dependent of particle size, morphology, surface charge, chemical composition, and degradation product(s). A buildup in organs like the liver, spleen, kidneys or lungs can cause oxidative stress, inflammatory reactions or organ toxicity. Therefore, there is a need to investigate biodistribution, pharmacokinetics, biodegradation and long term biosafety in detail to determine safe dosage ranges and to reduce any possible adverse effects [35,36].

Understanding the impact of nanomaterials on biological safety through manipulation of their designs has become an important research field; called precision nanotoxicology. Advanced methods use molecular toxicology, computational modeling and personal risk assessment to model the behavior of nanocomposites in a variety of biological settings. These approaches can help realize multifunctional nanocomposites that display enhanced therapeutic functions and minimized toxicity and undesirable biological interactions, thereby aiding in their rational design. However, questions about chronic exposure, repeated dosing and long-term environmental effects remain major challenges to clinical translation [36-38].

To receive approval from the regulators, nanomedicines must be thoroughly tested for quality, safety, efficacy, consistency of manufacture and environmental impact. International regulatory agencies are still busy working on guidelines to accommodate the specific features of nanomaterials, such as harmonised methods for the physicochemical characterisation, toxicity evaluation, quality control and post-marketing surveillance. But, the lack of globally consistent regulatory frameworks can be a barrier to commercialization and clinical uptake. Therefore, it will be vital to develop standardized synthesis protocol, which can be accepted by regulatory bodies and validated safety assessment methods for green-synthesized bioactive nanocomposites to accelerate their responsible development and clinical implementation in healthcare [38,39]. The key parameters that will be relevant for safe clinical translation

of bioactive nanocomposites such as toxicity and regulatory factors are given in Table 3.

Table 3. Safety and regulatory considerations for bioactive nanocomposites

Assessment parameter	Purpose	Major concern	Clinical implication	References
Cytotoxicity evaluation	Cell compatibility	Cellular damage	Safe biomedical application	[34,36]
Biodistribution analysis	Organ distribution	Tissue accumulation	Dose optimization	[35,36]
Long-term toxicity	Chronic safety	Organ toxicity	Clinical risk assessment	[36–38]
Biocompatibility testing	Host response	Inflammation and immune reaction	Improved therapeutic efficacy	[34,35]
Regulatory compliance	Quality and safety standards	Lack of harmonized guidelines	Clinical translation and commercialization	[37–39]

7. Current Research Trends, Challenges, and Future Perspectives

With the incorporation of Artificial Intelligence (AI), cutting-edge manufacturing methods, and precision materials engineering, the field of green-synthesized bioactive nanocomposites is advancing with great speed. Recent studies have moved beyond the traditional trial-and-error synthesis methods to the data-driven techniques that predict material properties, optimize synthesis parameters and speed up the discovery of multi-functional nanocomposites. Computational models with AI can help to analyze vast amounts of experimental data to find the optimal composition of materials, particle properties, and process conditions, optimizing the process to improve its repeatability while minimizing the use of resources and development time [40,41].

AI is also reshaping the landscape of designing future generation of nanomaterials by facilitating the prediction of their physicochemical properties, biological interactions, and functionality. Machine learning algorithms help in the selection of appropriate precursor materials, and predict the stability of nanoparticles, the antioxidant efficiency and intelligent optimization of green synthesis protocols. These computational tools greatly decrease experimental complexity and offer a more systematic approach for

highly efficient nanocomposite design for specific biomedical applications. Hence, AI in materials science is likely to become an integral part of future research and innovation in nanotechnology [40,41].

Even with these technological advancements, a number of issues remain to be addressed for the clinical and commercial translation of these green-synthesized bioactive nanocomposites in the future. A major challenge is to be able to scale up laboratory synthesis with consistent quality of particles, reproducibly, and biological performance to an industrial level of production. The batch to batch variation of biological reducing agents and the variation in composition of plant extract and lack of standardization in process often leads to product variability and hence reliability. Besides that, purification, quality assurance, storage stability and large scale manufacturing are still tremendous technical challenges that need to be solved by multidisciplinary approaches [42,43].

Another challenge is that of manufacturing nanocomposites, which should be integrated to actual healthcare systems while complying with strict regulations and quality standards. Commercial translation involves well established manufacturing procedures, effective quality control measures, the use of validated analytical tools, and an effective supply chain management system. In addition, there is a need for interdisciplinary interaction between materials scientists, biomedical researchers, clinicians, regulators, and industry, which will be key in the transition from laboratory findings to clinical use. It is expected that data analytics and digital manufacturing will enhance process optimization and compliance with regulations, throughout the product development process [42,43].

In the future, green-synthesized bioactive nanocomposites are likely to be more and more important in personalized medicine, precision nutrition and next generation functional healthcare products. Nanotechnology, biotechnology, AI, and sustainable manufacturing are expected to be involved in the creation of intelligent antioxidant delivery systems, smart biomaterials, and functional nutraceuticals tailored for combating oxidative stress-related disorders. However, continued research is needed in the design of new nanomaterials, computational material design and scalable green manufacturing technologies to translate these innovative nanocomposites to safe, effective and sustainable healthcare solutions for future generations [44]. The future development of green-synthesized bioactive nanocomposites needs to be integrated with sustainable synthesis, artificial intelligence, quality assurance, clinical validation and personalized healthcare as shown in Figure 3.

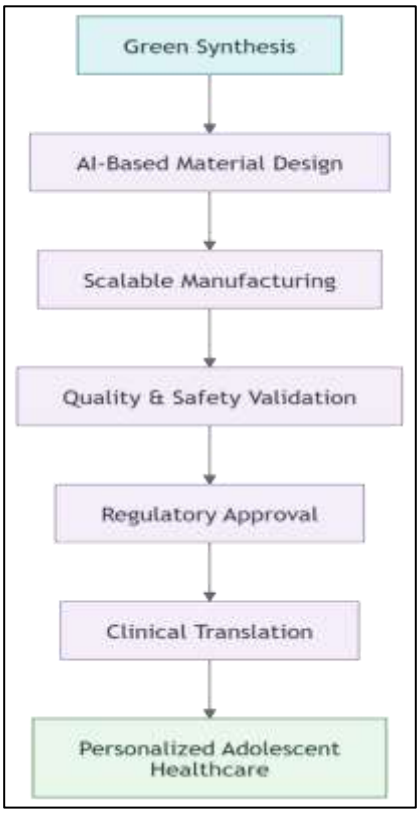


Figure 3. Future roadmap for the clinical translation of green-synthesized bioactive nanocomposites

8. Research Gaps and Opportunities

Despite significant advances in the green synthesis of bioactive nanocomposites, there are still several issues related to the scientific and translation ideas of these nanocomposites that remain unsolved. The majority of published studies highlight the synthesis, physicochemical characterization, and in vitro antioxidant assessment of materials, while the evaluation of their long-term biological performance, clinical efficacy, and age-specific therapeutic outcomes is less frequently reported. Specifically, there is a lack of evidence justification for the use of antioxidant nanocomposites in the health of adolescents, and well-designed preclinical and clinical studies are needed to assess safety, efficacy, and therapeutic benefits based on diseases [45,46].

Still another significant research gap is the lack of standardization for green synthesis, green characterization and antioxidant evaluation. The biological reducing agents, synthesis conditions, and analytical techniques vary between studies making it hard to compare results from different studies and making reproducibility difficult. Future investigations should be directed towards harmonising experimental procedures and validated quality-control strategies to enhance consistency and aid in regulatory approval for biomedical use [46].

The advancements in digital technologies open great prospects in the rapid development of the newer generation of bioactive nanocomposites. Data-driven modeling with artificial intelligence can be used to

optimize synthesis parameters and predict biological performance, as well as identify promising biomaterial combinations, and reduce experimental complexity. Moreover, the combination of multi-omics technologies and AI could uncover molecular mechanisms associated with oxidative stress, biomaterial–host interactions, and individualized responses to therapy, which could pave the way for precision nanomedicine and personalized healthcare [47].

Future studies should also focus on interdisciplinary efforts of materials scientists, biotechnologists, clinicians, computational research, and regulatory experts to enable clinical translation. The use of sustainable green synthesis in conjunction with AI, systems biology and precision medicine will help the development of safer, more effective, patient-specific antioxidant nanocomposites. These combined strategies are anticipated to fill the gaps in knowledge and speed up the transformation of novel nanoscale materials into clinically significant solutions for adolescent health care and other biomedical applications

9. Conclusion

In the context of sustainable nanotechnology, green-synthesized bioactive nanocomposites are a promising direction for research and development, as they are not only synthesized in an environmentally friendly manner but are also multifunctional antioxidants. Biological reducing agents not only promote the biocompatibility of the materials but also reduce the amount of hazardous chemicals, thus these nanocomposites are good candidates for biomedical applications. They possess several properties related to the reduction of oxidative stress, enhancing therapeutic delivery, aiding tissue regeneration, and supporting dermatological, oral, and nutritional health, which underscore their potential value in promoting adolescent health. However, existing data are still limited to laboratory studies, and there are significant gaps in the areas of long-term safety, standardized synthesis procedures and clinical validation. Large-scale clinical translation remains limited due to the variability of biological raw materials, manufacturing reproducibility and the lack of harmonized regulatory frameworks. The use of novel technologies, specifically artificial intelligence, multi-omics and precision manufacturing can provide new opportunities to optimize material design, quality control and to speed up the development of personalized antioxidant therapy. Future interdisciplinary research works involving the materials science and biotechnology along with clinical medicine and regulatory science will play a pivotal role in translating the green synthesized bioactive nanocomposites to safe, effective, and clinically viable healthcare solutions. These sustainable nanomaterials could become a key player in preventive and therapeutic approaches to adolescent health and more broadly in the biomedical field, as a result of such advances..

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