BIONANOTECHNOLOGY IN AGRICULTURE: A COMPREHENSIVE REVIEW REGARDING GRAPHENE-BASED NANOMATERIALS

Renato D. Matosinhos[1*], Isabela K. Della-Flora[1], Hállen D. R. Calado[2], Cristiano J. de Andrade[1]

[1] *Department of Chemical and Food Engineering, Federal University of Santa Catarina, Florianopolis, Brazil.*
[2]*Department of Chemistry, Federal University of Minas Gerais, Minas Gerais, Brazil*
* *Corresponding author's email address: rd.matosinhos@gmail.com*

ABSTRACT

In order to meet the increasing demand for food, challenges such as land and water scarcity, climate instability, and diseases, poses a significant global dilemma. Researchers explore various technological approaches, including fertilizers, pesticides, hybrid seeds, and genetically modified crops, enhancing global agricultural sustainability. By 2050, with the world's population projected to exceed 9 billion, a significant 70% escalation in global food production is needed, exacerbated by global warming. In this context, bionanotechnology emerges as an alternative, offering transformative potential in revitalizing the agricultural and food industries, for example, offer physicochemical properties that improve nutrient absorption and gradual nutrient release. Bioanotechnology, particularly the use of graphene-based nanomaterials, manipulates materials on the nanoscale, with implications for agriculture such as enhanced fertilizer efficacy, increased crop productivity, and improved pathogen detection in food. Thus, this research explores the current diversity of bionanotechnology applications in agriculture, specifically focusing on graphene-based nanomaterials. **Keywords:** Nanomaterials 1. Graphene 2. Agriculture 3. Bionanotechnology 4.

1 INTRODUCTION

One of the main emerging challenges is meeting the growing demand for food in the context of resource scarcity, climate instability, and pests. Innovations such as fertilizers, pesticides, and genetically modified crops are crucial for agricultural sustainability, especially with the population expected to exceed 9 billion by 2050, necessitating a 70% increase in food production [1,2].

Bionanotechnology emerges as a multidisciplinary and transdisciplinary science combining biotechnology and nanotechnology [3,4]. A primary challenge in this emerging area is understanding the interaction of nanoscale materials with biological systems, with the aim to produce functionalized nanomaterials for applications in many fields, such as health, agriculture, and the environment [3]. Bionanotechnology, with its transformative potential, offers hope for revitalizing the agricultural and food industries, benefiting resource-scarce populations [5]. By manipulating materials at the nanoscale (1-100 nm) [6,7], nanotechnology can enhance fertilizer efficacy, crop yields, and pathogen detection, while reducing pesticide reliance [1,8]. Despite limited applications in agriculture compared to other sectors, the promise of nanomaterials in addressing global food production challenges is undeniable.

This research explores the current diversity of bionanotechnology applications in agriculture, with a specific focus on graphene-based nanomaterials. The aim of this work was to investigate the feasibility of employing these materials in agriculture and to examine their potential implications for plants, soil, and human health. Additionally, the current potentials and challenges associated with the use of these nanomaterials in agricultural settings will be analyzed.

2 MATERIAL & METHODS

In April 2024, research was conducted using the Scopus and Web of Science databases, employing the keywords "nanomaterials", "graphene-based", "agriculture", and "bionanotechnology". Articles identified through these searches were critically evaluated and discussed within this review.

3 BIONANOTECHNOLOGY REVOLUTIONIZING AGRICULTURE: OVERVIEW AND CONTEXT

Bionanotechnology in agriculture represents a dynamic and cutting-edge area of study to augment crop productivity and nutrient efficiency by utilizing nanoscale agrochemicals. NMs possess at least one dimension falling within the nanometer range and, are categorized into 0D (e.g., nanoparticles), 1D (e.g., nanowires or nanotubes), 2D (e.g., nanosheets or nanocoatings), and 3D structures (e.g., bundles of nanowires or nanotubes). These minute materials enable the application of reduced dosages compared to conventional agrochemicals, offering a potentially more effective and less environmentally harmful solution for agricultural practices [9]. Bionanotechnology's applications in agriculture are broad and multifaceted, encompassing nano-fertilizers, nano-pesticides, nano-carriers, and nano-sensors. Each of these applications aims to enhance soil health, facilitate nutrient absorption, stimulate crop growth, improve crop traits, safeguard against pests, and bolster stress resilience.

Table 1 provides a comprehensive overview of various bionanomaterials used in agricultural applications, highlighting their types, specific uses, and the outcomes of their applications.

Table 1 Nanomaterials in Agricultural Applications

	Nanomaterial	Type	Application	Outcome	References
Inorganic	Silver nanoparticles (AgNPs)	Metallic	Electrochemical sensor for detecting cadmium and lead in bee pollen	Effective cadmium and lead detection with low limits, high sensitivity, good reproducibility, suitable for bee pollen analysis.	10
	Iron Oxide (Fe_3O_4NPs)	Metal Oxide	Alleviation of salinity stress and promotion of plant growth in agroforestry (specifically *Eucalyptus tereticornis*)	Enhanced salt stress tolerance and growth in *Eucalyptus tereticornis* by boosting antioxidant activities, shoot length, chlorophyll, and salt-responsive genes.	11
	Graphene Oxide (GO)	Carbon	Rapid detection of groundnut bud *necrosis orthotospovirus* (GBNV) in agricultural crops	Highly sensitive and specific detection of GBNV, offering a rapid and cost-effective alternative to traditional methods.	12
	Reduced graphene oxide (rGO)	Carbon	Electrochemical sensor for detecting imidacloprid in brown rice.	Highly sensitive imidacloprid associated with good long-term stability.	13
Inorganic	MeSiNPs@bPEI	Silica	Pesticide carriers (biopesticide citridiol) and soil improvers	Effective controlled and slow release of citridiol with potential to improve soil nutrient content by providing nitrogen and silicon.	14
	Chitosan (CNPs)	Polymeric	Insect pest management	Chitosan nanoparticles loaded with agrochemicals are more effective than free ones, reducing *Drosophila egg-laying* at lower doses.	15

4 APPLICATIONS OF GRAPHENE-BASED BIONANOTECHNOLOGICAL STRUCTURES IN AGRICULTURE: NANOPESTICIDES, NANOFERTILIZERS AND NANOSENSORS

Culture media are vulnerable to various pests, including insects, bacteria, and fungi, typically managed through conventional pesticides. However, these formulations often experience premature degradation, evaporation, or runoff upon spraying, leading to inadequate targeting of the intended organisms. In response to these challenges, nanopesticides present a promising strategy with the potential to prolong the chemical's persistence, augment the efficacy of the active ingredient, and reduce the quantity of pesticide required for pathogen control [16].

To address this issue, nanofertilizers offer physicochemical properties that improve nutrient absorption and gradual nutrient release, providing an alternative solution to nutrient deficiencies in plants. These attributes position nanofertilizers as promising replacements for conventional fertilizers due to their lower environmental risks and ability to penetrate plants, reaching organs or tissues [17].

Sensors derived from carbon nanomaterials, particularly graphene derivatives, emerge as highly prospective contenders for electrode modification, attributed to their expansive surface area, abundance of functional groups, and exceptional conductivity [18]. Within the spectrum of nanosensors, those designed for pesticide detection specialize in identifying minute traces of these substances across diverse mediums, including culture media, fruits, vegetables, rivers, reservoirs, and living organisms.

5 LIMITATIONS, CHALLENGES, AND OPPORTUNITIES OF BIONANOTECHNOLOGY APPLICATIONS IN AGRICULTURE

Graphene-based nanomaterials have attracted significant interest for applications in agriculture due to their unique properties, such as high electrical and thermal conductivity, superior mechanical strength, and large surface area. The integration of nanobiotechnology using graphene-based materials in agriculture encounters constraints and hurdles that necessitate resolution to fully capitalize on its prospects. Figure 1 shows the main topics addressed in this section.

Figure 1 Limitations, challenges, opportunities, and essential investment

Different forms of graphene-based nanomaterials can have adverse effects on the growth and development of various plant species. Therefore, the main concern regarding the use of graphene in agriculture is the potential toxicity to plants, soil and microorganisms, which depends on factors such as concentration, physicochemical properties, exposure time and plant species [19]. However, these nanomaterials promote more sustainable and environmentally friendly agricultural practices. They can reduce dependence on agrochemicals and synthetic fertilizers, improve biodiversity, soil health, human health and food security, and minimize environmental pollution and waste [20].

6 CONCLUSION

In summary, to advance the application of graphene-based nanomaterials in agriculture, fostering collaboration among researchers, industry stakeholders, and regulatory agencies is paramount. This collaboration is essential to overcome existing challenges and explore the opportunities offered by these materials. It involves investments in research and development, the establishment of strategic partnerships, and the creation of specific guidelines to promote innovation and responsible use. With these efforts and a comprehensive understanding of their applications, graphene-based nanomaterials have the potential to enhance agricultural practices and make resources more productive, sustainable, and economically viable.

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