Proceedings of the Pakistan Academy of Sciences: B
Life and Environmental Sciences 62(1): 1-18 (2025)

ISSN (Print): 2518-4261; ISSN (Online): 2518-427X
http://doi.org/10.53560/PPASB(62-1)1071

Pakistan Academy of Sciences

Review Article

Advances in Nanocomposite-Based Fertilizers for Sustainable Agricultural Practices

Nadeem Ullah[1], Amjid Khan[1,2], Tahira Younis[1], Haris Maqbool[1], Mehwish Iqbal[1], Muhammad Ali[3], and Zabta Khan Shinwari[1,4*]

[1]Molecular Systematics and Applied Ethnobotany Laboratory (MoSAEL), Department of Plant Sciences, Quaid-i-Azam University, Islamabad-45320, Pakistan
[2]Department of Botany, University of Mianwali, Mianwali-42200, Punjab, Pakistan
[3]Department of Biotechnology, Quaid-i-Azam University, Islamabad-45320, Pakistan
[4]Federal Urdu University of Arts, Science and Technology, Karachi-75300, Pakistan

Abstract: Nanotechnology is having a significant impact in the field of agriculture, providing solutions to increase agricultural output to solve environmental issues. It promotes sustainable agriculture and successfully solves the current crisis of global food security. Sustainable agriculture is vital for securing food deliveries, maintaining resources, and combating environmental impact. The objective of this review is the recent development of nanocomposites based fertilizers in promoting agricultural sustainability. The use of traditional agricultural fertilizers indicates high nutrient losses of 80-90% of phosphorus and 50-70% of nitrogen contributing to environmental pollution. To cope with these demands, advancement in nanotechnology, such as nanocomposites-based fertilizers, is a substitute. Prominent trials in field scale indicate that zinc oxide nanocomposites enhanced crop yields by 25-30% though reducing fertilizer application rates up to 50%. Chitosan based nanocomposites demonstrated dual benefits of improved nutrient uptake and disease resistance, increasing plant biomass by 15-20%. The Nanocomposites based fertilizers are ecologically friendly, reduce environmental issues, provide sustainability to agriculture and agronomy, promote crop productivity, reduce the wastage of traditional fertilizers, and improve soil health. This review is estimated to cheapen and transform agricultural practices, increasing sustainability and productivity for shareholders and all associates for upcoming generations.

Keywords: Nanocomposites Fertilizers, Sustainable Agriculture, Controlled Nutrient Release, Eco-friendly Farming Solutions.

1. INTRODUCTION

The term "nanotechnology" originates from the Greek word "nano", which means to "extremely small". It covers a billion meters [1]. So, we know nanotechnology is a term used to understand and organize the substances ranging from 1-1000 nm which is an emerging technology of the 21st century [2]. Nanotechnology is a technology that we implement at the nanoscale and has a lot of applications worldwide. Nowadays nanotechnology has turned out to have a general purpose representing a megatrend that benefits the public [3]. Currently, in agriculture nanotechnology applications improve soil health, plant mineral nutrition (uptake of minerals), reduce fertilizer waste, enhance crop products, and micro-flora with soil, leading to sustainable solutions to replace bulk fertilizers [4]. Nanotechnology based management of crops is a very vital tool for improving agricultural yields. Quantum dots, nanofibers and carbon nanotubes of nanostructure and nanomaterials are used in agricultural research as biosensors to check the distribution of fertilizers and quality of the soil. In improving quality of crops, the carbon nanotubes and nanomaterials of TiO_2, ZnO, SiO_2, and gold are used [5, 6]. Additionally, nanotechnology specifically biogenic silver nanoparticles, holds

Received: June 2024; Revised: January 2025; Accepted: March 2025
* Corresponding Author: Zabta Khan Shinwari <shinwari@qau.edu.pk>

immense promise across various fields, their distinct physiochemical attributes for potential applications as potent antimicrobial and anticancer agents [7, 8]. Agriculture is a significant growth drive all over the area, contributing to local increase of production [9]. For the survival of the rapidly growing global population, plant species treated with nano fertilizer must exhibit tolerance towards climate change [10]. In the growth of the economy, agriculture may contribute in major proportions which means that somehow 40-60% of the countrywide income is produced by agriculture and 50-60% of people are doing job in the production of agriculture [11]. In agriculture, nanotechnology is forwarding step in the direction of tolerance and agricultural products through solubility enhancement, control release and targeted delivery while also lowering the damage [12]. Agricultural crops are prime food sources and vital fields of our living organisms which feed our increasing populations. Plant diseases have currently become a major factor in the deterioration of food quality and production, so to overcome this problem, nanotechnology is a promising area in agriculture from seed sowing in soil the cultivation of plants [13]. Nanotechnology presents promising avenues for sustainable agricultural practices, wherein nanochemicals play a pivotal role in enhancing plant growth and managing pests. Nanomaterials, like silver nanoparticles, are also used in food packaging to keep microbes from getting into the food. However, they need to be carefully studied to see how they might affect plant growth before they can be used legally [14, 15]. Amidst the challenges posed by climate change, advanced nano-engineering emerges as a crucial ally in enhancing crop production and securing agricultural sustainability.

Nanotechnology contributes to agricultural efficiency by optimizing input utilization and minimizing losses, particularly by leveraging nanomaterials to enhance fertilizer and pesticide delivery. Moreover, nano biosensors enable precise management and control of agricultural inputs, facilitating the adoption of high-tech farming methods [16]. Nanotechnology, which uses nanomaterials as carriers, facilitates a variety of applications in plant growth and crop management, including nanofertilizers, nanopesticides, nanosensors, and nanobiotechnology. Nanotechnology enhances the effectiveness and durability of agro-chemicals by harnessing distinctive structural properties, fostering plant growth and resilience to environmental stressors [17].

In the burgeoning era of nanotechnology's integration into agriculture, a rich tapestry emerges, illuminating the intricate interplay between nanomaterials and the soil-plant interface. From the artistry of synthesis to the orchestration of metabolic pathways, nano fertilizers hold promises for enhancing crop physiology while potentially reducing dependency on pesticides through heightened reactivity. As attention turns to nanoparticles used in pesticides and soil restoration, new areas are opening that haven't been explored yet. This is made even more important by the need to quickly figure out how soil nanomaterials move and what effects they have on farming systems [18]. It increases the ability of plants to resist abiotic and biotic stress by improving yield and quality of crops through the process of gene editing, and nanotechnology also contributes to the connotation of CRISPR/Cas [19]. Elimination of pollutants has become a major problem worldwide so to combat this issue nanotechnology is used to boost up the process of bioremediation. Nano remediation is a promising solution to this manmade disaster [20]. Nanotechnology can also modify the genome of the mitochondria and plastid as well as edit germ lines [21].

Agricultural lands are facing various critical challenges that threaten their productivity and sustainability. The primary and major problem is low resource use efficiency, specifically for fertilizers and water. The use of conventional fertilizers often displays poor nutrient use efficiency due to runoff, leaching, and volatilization with more than 50% of applied nutrients being lost [22]. This contributes to environmental pollution, i.e. increased greenhouse gas emissions; eutrophication of water bodies and results in significant economic losses. Moreover, overuse of chemical fertilizer has led to degradation of soil, lowering organic matter in soil, disrupt diversity of microbes, and deteriorating soil fertility for long term. Scarcity of water is another pressing problem, as agriculture consumes the largest share of global water, and ineffective irrigation practices. Likewise, over dependency on chemical pesticides has faster pest development and disease resistance, requiring the rising production costs and higher inputs [23]. These challenges are compounded by the impacts of climate change, comprising of droughts, floods, and unpredictable weather patterns that decrease crop productivity and increase the risk of food insecurity. The rapidly growing population of the world is expected to reach 10 billion by 2050, guaranteeing sufficient production of food and protecting environmental health has become an urgent priority [24]. This study aims to investigate advancements in nanocomposite-based fertilizers recently, increased nutrient use efficacy, directing on nutrient release mechanism, and possibility of environmental benefits. In addition, it also seeks to promote awareness among researchers, farmers, and experts to emphasize the need for commercialization and Environmental Impact Assessment for sustainable agricultural practices.

2. METHODOLOGY FOR SEARCHING

2.1. Information Retrieval Approach

We conducted a detailed search on electronic databases such as Google Scholar, Science Direct, PubMed, and Scopus to find the most relevant literature related to our review topic. We used specific phrases and keywords like "nanotechnology", "nanofertilizers", "nanomaterials", "traditional fertilizers", "smart fertilizers", "nanocomposite materials-based fertilizers", and "agricultural sustainability" during present search. This approach ensured that we gathered comprehensive data from 2000 to 2024 information for this study.

2.2. Inclusion Criteria

- Articles that target nanocomposite fertilizers and their applications in agricultural sustainability.
- Examines environmental benefits of nanocomposites and controlled nutrient release mechanisms.
- Research exploring synthesis sources and bio nanocomposites in agricultural applications.

2.3. Exclusion Criteria

Research articles not related to nanocomposites applications in agricultural and only on traditional fertilizers without nanocomposite.

2.4. Detailed Analysis Taken Articles

One of the authors conducted an individual revision to the full articles acquired through electronic search. Relevant data from these articles were extracted, and any discrepancies were resolved through discussion and then referred to the second reviewer (another author) for a final decision. The extracted data were then summarized and organized in (Table 1) showing diverse nanocomposites material synthesized from plants, used primarily for antimicrobial activity, catalysis, plant growth enhancement, and environmental remediation and (Table 2) showing nanocomposites material synthesized from various plants source for antimicrobial, growth enhancement, and photocatalytic applications in agriculture for comprehensive analysis. The details from the extracted data were explained under corresponding headings and shown in Figure 1 focus on the role of nanocomposite materials in sustainable agriculture by improving fertilizers, soil management, pesticides, stress management and food security and classifies nanofertilizers on the basis nutrient content, release mechanisms, and special coatings for controlled nutrient delivery to provide a clear demonstration (Figure 2).

3. RESULTS AND DISCUSSION

3.1. Nanocomposites Material

Nanocomposites are materials that are composed of nanosized standard substances. It is characterized by chemical composition, physical characteristics, resource, external appearance, and size [25]. Bio nanocomposites are minute in size, ranging from 1 to 100 nm in the large amount of similar elements, but have the same nano characteristics. Bio-nanocomposites are minute in size, ranging from 1 to 100 nm in the large amount of similar elements, but have the same nano characteristics. Bio-nanocomposites in agriculture have a lot of applications, including plant growth, crop production, pest protection, and providing good nanoparticles or agricultural chemicals [26]. Nanocomposites are solid substances comprising multiple phases, with each phase exhibiting dimensions that may span one, two, or three proportions in the size of a nanometer [27]. Agriculture is facing challenges in terms of sustainability and population growth which prompt innovation such as polymeric films using the non-biodegradable polyethylene. Bio-nanocomposites play a key role by improving the mechanical properties and allowing the controlled release of

Table 1. Nanocomposites-based material synthesized from plant sources and their multifaceted roles across various applications.

S. No.	Nanocomposites material	Source of Synthesis	Size/wt	Roles	References
1	ZnO-rGO	*Avicennia marina* and *Polycladia myrica*	28.1 nm	Fouling resistant activity.	[31]
2	CdS/CQDs	*Aegle marmelos*	73 nm	Photocatalytic activity.	[32]
3	Fe_3O_4/HAP/ZnO	*Falcaria Vulgaris Bernh*	500 nm	High porosity level. Separation of substances from aqueous solution.	[33]
4	Ag/Bhm NC and Ag/Bhm/Chit NC	*Rosmarinus officinalis*	72.3 and 60.8 nm	Apoptotic and sporicidal agents.	[34]
5	ZnO-Chitosan	*Azadirachta indica*	39 nm	Antibacterial activity and UV protection.	[35]
6	Mn-ZnO	*Withania somniferum*	11-14 nm	Reduce environmental pollution.	[36, 37]
7	Ag-doped ZnO/MgO	*Caccinia macranthera*	88 nm	Use for detection lead ions.	[38]
8	Ag and ZnO, Silver-peptide	*Trigonella foenumgraecum*	75 nm	Antimicrobial activity against *Staphylococcus aureus* and *E. coli*. Antifungal activity against *Candida albicans.* Also act as photo catalyst and antioxidant agent.	[39, 40]
9	ZnO and TiO_2	*Hibiscus*	10/90 and 50/50 wt	Used as protecting agent in lime mortars and stones coating.	[41, 42]
10	Ag and ZnO	*Silybum marianum*		Biomedical	[43]
11	$BiVO_4$	*Hyphaene thebaica*	75 nm	Biomedical	[44]
12	BCN	*Saccharum officinarum*	2-100 nm	Increase mechanical vigor and pure type of NC.	[45]
13	Au and Ag alloy	*Azadirachta indica*	50-100 nm	Help in remediation of heavy metals.	[46]
14	CNF	*Elaeis guineensis Beta vulgaris* L. and *Gossypium* species	3-60 nm	Used in packaging, foams, paints films and coating.	[47]
15	Bimetallic Ag and Au	*Punica granatum*	12 nm	Reduction of nitrogen compound into aromatic amines. Act as antioxidant agent.	[48]
16	ZnO and CeO_2	*Acacia nilotica*	12 nm	*S. aureus* and *K. aerogenes* shown antibacterial activity. Help in degradation of methylene blue dyes.	[49]
17	MgO and Cu	*Cassytha filiformis* L.	12 nm	Reduce methylene blue, nitrogen compounds and Congo red by catalytic activity.	[50]

18	CuO and C	*Adhatoda vasica Neea*	7-11nm	*Candida albicans and Aspergilus niger* showing antifungal activity. *S. aureus, K. pneumoniae, E. coli*, and *P. aeruginosa* showing antimicrobial activity.	[51]
19	SiO-TiO_2	*E. coli*	0.8 × 5 mg	Role in microbial activity, osteogenesis, and LED (Light emitting diode).	[52]
20	ZnO and FeO BNC	*Anethum graveolens*	15/15 wt	Enhance seed biomass, vegetative growth and inflorescence and improve stress tolerance in plants.	[53]
21	Ag-ZnO	*Tetradenia riperia*	200-600 μg/m	Antibacterial activity	[54]
22	Alginate/Chitosan with CuO	*Fortunella margarita*	300 nm	Enhances the germination of seed.	[55]
23	Vinasse Biochar dolomite	*Sectaria viridis*	41 nm	Phosphorus fertilizer substitute and enhance growth.	[56]
24	Bentonite/ Acrylate acid-co-acryl amide	*Oryza sativa*	34.6 nm	Use in agriculture for water absorption and nitrogenous (urea) fertilizers.	[57]
25	CNCs (Alginate coated cellulose nanocrystals)	*Gossypium arboreum*	5% wt	Increase Hydrogel property. Improve water retention Help in sustainability of fertilizers.	[58]

agricultural chemicals, promoting cultivation, and decreasing pollution by facing obstacles in commercialization such as production costs and nontoxicity [28]. Nanocomposites lessen the pesticide and fertilizer burden, offering promising solutions for sustainable agricultural practices [29]. Nanocomposites have significant properties that are related to native polymers formed by the addition of nanoparticles to polymers. Primarily, it controls the spatial distribution of nanoparticles. Secondly, predicting the spreading of particles and the condition of organization can optimize many properties of nanocomposite and lastly, we must look at the function that particle nature (form) affects dispersion therefore controlling the property. Nanocomposite has achieved good attention in advancement of agriculture products that are based on nanotechnology [30].

3.2. Agricultural Fertilizers and their Importance

Agricultural fertilizers are compounds that are composed of a mixture of elements and essential mineral substances used for plant nourishment and growth [59]. Currently, to make agriculture sustainable and productive, fertilizers are among the most significant [60]. To cope with the demand for food due to the increase in population, fertilizers are essential agricultural inputs. Complications of human health problems and many environmental issues have resulted from the application of careless use [61].

3.2.1. Smart fertilizers

Smart fertilizers are used in top, which is applied for the management of interval, time, and speed of nutrient release and absorption by plants for improving crop growth and reducing the impact of other environmental issues [62]. In smart fertilizers, one is slow-release fertilizers (SRF), which refers to the spreading of nutrients that are available to plant life through the processes of solubility reduction, biodegradation, and hydrolysis as compared to products that are reference soluble,

Table 2. Applications of Nanocomposites material in agriculture.

S. No.	Nanocomposites material	Source	Size	Roles	References
1	Ag-chitosan	*Solanum lycopersicum*	87 nm	Control bacterial wilt	[73]
2	Ag-Starch	*Punica granatum*	1-54 nm	Antimicrobial activity	[74]
3	Carboxymethyl Cellulose/Silver (CMC-AgNPs)	*Syzygium aromaticum*	30-70 nm	Antibacterial activity	[75]
4	Mt-Ag	*Zea mays*	10.52 nm	Wastewater treatment	[76]
5	Ag-chitosan	*Cissus arnottiana*	23 nm	Antibacterial activity	[77]
6	AgNP/MCC/starch/whey protein	*Azadirachta indica*	20 nm	Antibacterial and food preservation activity	[78]
7	Ag-Chitosan	*Aloe vera*	20 nm	Improve physiochemical properties	[79]
8	Zinc oxide/carbon nanofiber	*Thymus daenensis and Stachys pilifera Benth*	45 nm	Efficient Antibacterial and photocatalytic activity	[80]
9	Zinc oxide–silver Zinc oxide–copper	*Bridelia ferruginea*	18.98 and 18.90 nm	Improve phenolic and terpenoids	[81]
10	Zno-GO	*Sonchus Oleraceus*	5 nm	Generation of Reactive Oxygen Species	[82]
11	ZnO-Ag	*Thymus vulgaris*	75 nm	Antioxidant, photocatalytic and antimicrobial activity	[83]
12	$Mg0.5Zn0.5FeMnO_4$	*Astragalus gummifer*	20 nm	Photocatalytic activity	[84]
13	ZnO-NiO	*Sterculia foetida*	30-35 nm	Antibacterial activity	[85]
14	Chitosan-ZnO	*Beta vulgaris*	20-80 nm	Antibacterial activity	[86]
15	Ag-ZnO	*Ocimum tenuiflorum*	30-40 nm	Dye degradation and antibacterial	[87]
16	Ag-ZnO	*Trigonella foenum-graecum*	75 nm	Antioxidant and antifungal	[88]
17	TiO_2-PN	*Ageratina altissima*	60-100 nm	Increase catalytic activity	[89]
18	Ag-TiO_2	*Cymbopogon citratus*	41.8 nm	Catalytic and antimicrobial activity	[90]
19	TiO2–ZnO	*Allium sativum*	4.58 nm	Improve growth parameters	[91]
20	Ag-TiO_2	*Vitis vinifera*	10 - 30 nm	Bactericidal, Antioxidant, Photocatalytic, and Activities	[92]
21	Ag-TiO_2	*Cymbopogon citratus*	49 nm	Metal Degradation	[93]
22	Cu-Chitosan	*Zea mays*	37 nm	Increase seedling growth	[94]
23	Chitosan-Zn Chitosan-Cu	*Oryza sativa*	56 nm	Protective agent and improve plant growth	[95]
24	Cur-Chitosan	*Pyricularia grisea*	34.6 nm	Biocontrol agent against blast disease and increase plant growth	[96]
25	K-Chitosan	*Zea mays*	39 - 79 nm	Improve overall growth and act as soil conditioner	[97]
26	Se-Chitosan	*Raphanus sativus*	50 nm	Enhance uptake of essential nutrients	[98]
27	Cu-Chitosan	*Zea mays*	36 nm	Act as fungicide	[99]
28	Chitosan-Ag	*Capsicum annuum*	4 nm	Antifungal agent against *Colletotrichum truncatum* causing anthracnose	[100]
29	Chitosan-Metal	*Prunus avium*	76 nm	Agro fungicides	[101]
30	Graphene-tinO	*Cocos nucifera*	3 nm	Antibacterial activity	[102]

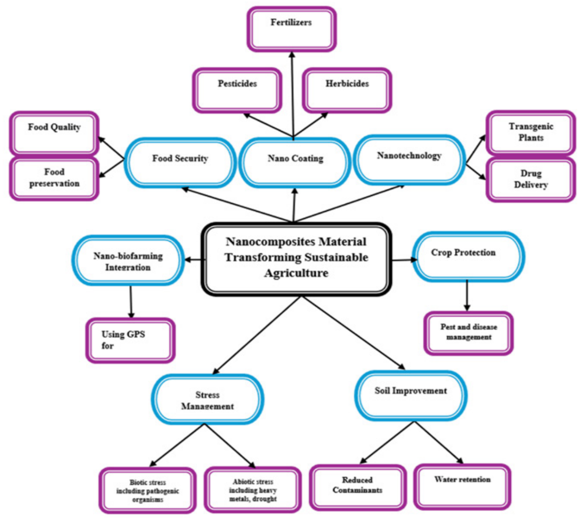

Fig. 1. Flow chart of Nanocomposites-Based-Material Transforming Sustainable Agriculture. This flowchart is obtained by using Bio render software.

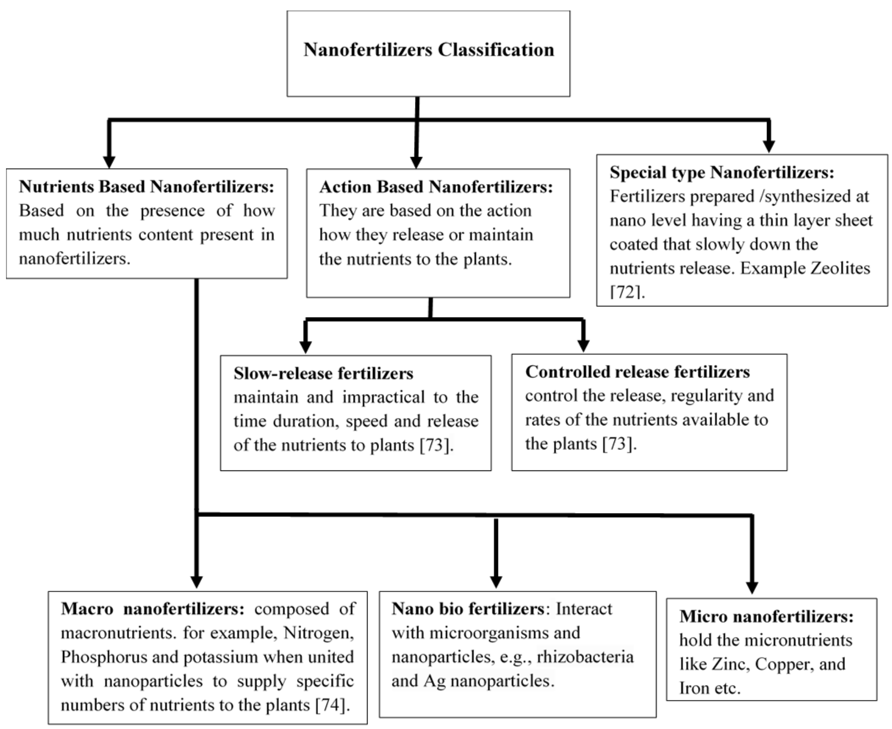

Fig. 2. Classification of the nanofertilizers on different basis like nutrients based, action based, and special type are categorized above.

like urea, ammonium nitrate, and ammonium sulfate. These fertilizers are commonly used for nitrogen containing compounds that participate in the breakdown of bacteria, e.g., manure which is available to us naturally, but we cannot synthesize in controlled conditions. SRF can be in two forms of either organic or inorganic, which release nutrients slowly over time. Conclusively, SRF are traditionally used fertilizers that progressively release nutrients for a long period of time and are not that environmentally destructive [63]. The other one is controlled release fertilizers (CRF) that refers to fertilizers which release nutrients when met with necessary factors like rate and period of nutrients and temperature. CRF holds nutrients that are not readily absorbed by the plants. We use organic or inorganic compound coatings on CRF to regulate the duration, pattern, and rate of nutrient liberation for the plants [64].

3.2.2. Nano fertilizers and their classification

Nano fertilizers have led to research for eco-friendly fertilizers, specifically with having high nutrient use efficiency whose alternative promise is emerging nanotechnology. Application of these nutrients either separately or collectively bound to nano based adsorbents, which will release the nutrients deliberately compared to other fertilizers. Through this approach, we can reduce the leaching of nutrients in ground water and enhance nutrient use efficiency [65]. The overuse of chemical fertilizers and pesticides nowadays has led to severe human health problems and environmental pollution. Nowadays, nanoscience might solve these problems by providing nanofertilizers, i.e., nitrogen, phosphorus, potassium, zinc etc., [66].

3.3. Mechanism of Nanocomposites Root Delivery Improving Nutrient Uptake Efficiency

Nanocomposites material is made to measure nutrients that are delivered precisely to plant roots. Their tiny size and roomy surface area allow them to penetrate inside the roots effectively, ensuring direct access to the root zone where nutrients are highly required. This targeted delivery system ensures plants receive nutrients exactly where and when they need them, promoting optimal growth. In terms of nutrients efficiency, nanocomposites play a key role in improving how plants absorb nutrients. The special characteristics of these materials is that they increase the solubility and availability of nutrients, making them easier for plant roots to access. Moreover, the large surface area of nanoparticles facilitates better interaction with root surfaces, leading to enhanced nutrient absorption. This improved efficiency means plants can make the most of available nutrients, resulting in healthier growth and development [71].

The exact mechanism for slow-release fertilizers works in two steps: Firstly, through photo degradation, where exposure to sunlight, soil temperature changes, and cultivation practices cause the fertilizer to crash, releasing nutrients. Secondly, in biodegradation, soil microbes break down the fertilizer, converting it into forms that plants can readily absorb, ensuring nutrient availability for plant growth. While controlled release fertilizers utilize various mechanisms to release nutrients effectively where nutrients gradually permeate the coating material, maintaining a stable release when the water potential stabilizes. This process guarantees a consistent supply of nutrients, with coating permeability and temperature playing pivotal roles. Secondly, osmotic pumps and fertilizers couple osmotic pressure alterations, influenced by variations in hydrostatic pressure and osmotic gradients for nutrient release. Pressure accumulation causes the coating to become semi permeable and develop cracks, releasing solutes and delivering nutrients to the plant as needed. Lastly, convective releasing under higher hydrostatic pressure, the coating can rupture, resulting in a swift release of nutrients. This phenomenon is commonly seen in fertilizers such as sulfur coated urea, primarily stems from coating breakdown, guaranteeing prompt nutrient availability for plants [72].

3.4. Nanocomposite-Base Fertilizers as the Future Frontier of Sustainable Agriculture

The efficiency of nutrient based fertilizers is low because of the various pathways of losses: runoff, fixation, immobilization of microbes, denitrification, and leaching. Estimations of these nutrients are that more than 95% of micronutrients, 80-90% of phosphorus, 50-70% of potassium, and 40-70% of nitrogen are lost in our environment, which alternatively results in pollution. Smart fertilizers like bio formulated fertilizers such as nanofertilizers and slow-release fertilizers are advanced technologies that increase the efficiency of using nutrients and improve crop production in a sustainable way. To make use of slow, controlled release fertilizers, it reduces eutrophication, contaminants in water, leaf burn risk and the efficiency of nutrient use [103]. Nanofertilizers are vital in reducing the use of agrochemical fertilizers and minimizing their aggressive effects on the environment. Nanofertilizers can penetrate the epidermal layer of plants because of their reactive nature, which increases the efficiency of nutrients and decreases the excess nutrients, leading to productive crops [104]. Chitosan is an amino polysaccharide that is regarded as the next generation of fertilizers that enhance the immune systems of plants by delivering nutrients in a controlled, slow, and targeted way. It can help researchers in the agricultural system and is applied in multiple fields as an effective and ideal preference [104]. Nanofertilizers also improve the health of soil by releasing bounce nutrients, improving the improving the structure of soil, and increasing the activity of valuable microbes [105]. Silicon, which is a metalloid element, affects the growth of plants, manages stress, and improves crops. The application of Si (available to plants in Orthosillicic acid) helps with soil fertility, moisture content and nutrient uptake, resulting in improved growth, yields and defense against stress [106].

For increasing food production mineral fertilizers are key despite heavy losses and low uptake of nutrients, yet nanofertilizers can lead to increased crop production and a reduction of nutrient loss. This increases the attention given to nano based fertilizers, which is the concept of nanotechnology. So marketable nanofertilizers can lead to the sustainability of agricultural trade [107]. The limits of conservative products which are biodiversity loss, human diseases and environmental issues are overcome by the applications of controlled release systems (nanocarriers). Nano carriers are ecofriendly and sustainable strategies for agriculture, ecosystem and human fitness [108]. Synthetic NFs are an essential input and demanding for current agriculture [109]. Nanofertilizers revealed the ability to add to the production of food materials, civilizing nutritional food and tumbling waste substances to strengthen the sustainability of agriculture products [110, 111]. Nanofertilizers are intended for specific targets and do not cause disturbances in the environment. It can help to enhance crop production, increase the use of nutrients and lessen the use of unwarranted synthetically prepared fertilizers [112]. Agronomical applications of nanocomposite material are used as nano-sensor, nano-pesticides and nanofertilizers which facilitate the release of pesticides and smart fertilizers to lessen the discharge of toxic substances into our surroundings [113].

3.5. Navigating the Challenges of Traditional Fertilizer Usage

The usage of traditional fertilizers poses a challenge to eco efficient agriculture because of its involvement in environmental degradation, resource inefficiencies, and economic burdens. To address these challenges, it requires a transference towards sustainable practices that optimize nutrient management, embracing precision agriculture, and incorporating organic fertilizers to increase soil health and decrease the environmental impact. Holistic approaches encompassing social, economic, and institutional dimensions are essential for fostering eco efficient agricultural systems, and crucial for long term food security amidst global demands and environmental pressures [114]. Also, traditional fertilizer usage presents a dual challenge: significant ammonia emissions contribute to environmental pollution and health risks. To tackle this, we must boost fertilizer efficiency, curb environmental impact, and navigate the delicate balance between food production and biofuel needs on available arable land. Engaging policymakers and stakeholders in a thorough discussion is vital to setting targets that foster sustainable agricultural practices, ensuring food security while safeguarding the environment [115].

Dealing with the problems of conventional fertilizer application for boosting agricultural output, the traditional fertilizers use substantially contributes to nitrous oxide emissions and global warming [116]. The widespread utilization of conventional nitrogen fertilizers poses significant hurdles, as around 50% of the nitrogen input escapes into the environment, leading to air and water contamination and posing risks to food and environmental safety. Forecasts suggest a 150% rise in nitrogen pollution by 2050, with agriculture exerting a notable influence. [117]. Both inorganic and organic fertilizers play critical roles in nourishing crops and improving soil quality, but they also carry substantial pollution risks from potential contaminants and mishandling. Nitrogenous and phosphate fertilizers are major contributors to soil, water, and air pollution, which in turn affects human health and worsens climate change by releasing greenhouse gases. Moreover, fertilizer misuse leads to water bodies becoming eutrophic and heavy metals accumulating in the soil [118].

3.6. Transforming Agriculture with Smart Fertilizers

Agricultural challenges feeding a highly growing population and fighting against climate change, stress the importance of efficient, affordable, and environmentally friendly fertilizers. It delves into the concept of smart fertilizers and nanocomposites material, which control nutrient release, particularly by examining field scale studies on herbaceous plants. Smart fertilizers are formulations that adjust nutrient release timing to meet plant needs, ultimately enhancing yields and sustainability in contrast to traditional fertilizers [119]. As climate change poses a growing threat, there is a pressing call for inventive ways to tackle its impact on agriculture. Smart fertilizers emerge as a key solution, helping to counteract nutrient shortages worsened by shifting environmental patterns. Using precision agriculture methods, these fertilizers finely tune distribution using precision agriculture methods, boosting crop strength, and reducing environmental harm. This blend of technology with sustainable farming methods holds great promise for addressing the agricultural challenges brought on by climate change [120].

3.7. Nanocomposite for Improved Nutrient Delivery and Crop Yield

Nanotechnology modernizations deliver sustainable and robust agricultural solutions, promoting both crop yield and quality while protecting food security. Despite progress in nano fertilizers, pesticides, and delivery systems, ongoing study is vital to creating biodegradable, affordable, and safe nanomaterials, underscoring the need for systematic studies and public awareness campaigns to protect food production systems [121]. Adding nanocomposite materials to smart fertilizers addresses discourses the challenges impersonated by excessive usage of traditional fertilizer, which promotes soil health and optimizes nutrient absorption in plants. Engineered nanocomposites facilitate precise, controlled release delivery of agrochemicals, catering to specific crop requirements. These strategies will sustain and target the release, emphasizing their significance in boosting plant growth and defense which would prioritize scalability, cost efficiency, field testing, and environmental safety as imperatives for the wider adoption of nanocomposite-based smart fertilizers [122]. This integration of nanocomposites material offers a hopeful path toward sustainable agriculture, undertaking ecological issues and stimulating food security. These cutting-edge nano formulations elevate nutrient delivery, soil vitality, and crop productivity, all while curbing environmental harm [123].

3.8. Nanocomposites in Disease Management

Nanocomposites revolutionize agriculture by combating crop diseases through smart fertilizers. These fertilizers utilize nanotechnology for precise nutrient delivery and real time disease detection, ensuring targeted efficacy. By continuously monitoring plant health and adjusting nutrient delivery, they offer a proactive approach to disease management, promising sustainable agricultural productivity [124]. Bio-nanocomposites (BNCs) and endophytes showcase unique nanoproperties and have various applications, notably in agriculture, where they bolster plant defense against pests, growth, and crop yield [125, 126]. Nanocomposites are key to fighting against plant diseases with cutting edge methods. By merging nanotechnology with biopolymers, these hybrids boast improved mechanical and thermal attributes, proving invaluable in disease control particularly silver nanoparticles, graphene oxide, and chitosan-based blends that display strong antifungal properties against pathogens like *Rhizoctonia solani, Fusarium graminearum,* and *Botrytis cinerea,* presenting hopeful avenues for agricultural disease management [127]. It also controls the disease by providing dual benefits including nanopesticides that protect plants from phytopathogens, while nano fertilizers enhance plant growth, which is crucial for global food production [128]. Nanocomposite-based smart fertilizers transform crop disease management by delivering nutrients precisely and detecting threats promptly. Through the incorporation of nanoparticles with high surface to volume ratios, these fertilizers ensure targeted delivery of disease fighting agents. Integrated nanosensors enable real time disease detection, facilitating swift intervention. Moreover, the engineered release of bioactive compounds triggers plant defense mechanisms, providing comprehensive protection against crop diseases [129].

Chitosan, known for its versatility, is widely utilized in pharmaceuticals, biomedicine, and agriculture due to its cost effectiveness and advantageous properties. Acting as a carrier for diverse active substances, including nanomaterials and essential oils, aids in improving plant nutrient absorption and bolstering defense mechanisms against pathogens. Through various production techniques, chitosan-based nanocomposites offer solutions like controlled release of nutrients and pesticides, along with antimicrobial effects against bacteria, fungi, and viruses [130, 131]. These fertilizers ensure optimal nutrient and disease-fighting agent delivery to plant roots, maximizing absorption. Antimicrobial agents embedded within the nanocomposites are released gradually, curbing pathogen growth and lessening disease impact [132].

3.9. Future Perspective of Nanocomposites-Based Fertilizers

Fertilizers made from nanocomposites offer hopeful remedies for the sustainability issues in agriculture. However, their broad acceptance faces obstacles due to worries about scaling up production and ensuring their durability over the long term. Carbon based and metal/metal oxide nanoparticles show promise in enhancing membrane functionality, particularly in preventing fouling and enhancing permeability. Future research ought to prioritize optimizing nanoparticle concentration to prevent aggregation, tackling scalability hurdles for real world application, and thoroughly examining the long-term durability of these membranes [133]. Intensive research on two dimensional nanomaterials like MXenes, metal dichalcogenides and graphene is driven by their exceptional properties, which offer promise in agriculture and food solutions. Potential applications include sustainable water management, advanced agrochemicals, nanosensors, and packaging, with significant benefits such as enhanced purification and sensitive contamination detection [134]. The potential of nanostructured graphene materials to enhance PV efficiency is due to their high electron mobility and conductivity. Incorporating semiconductor metal oxides with graphene further enhances efficiency by facilitating photon absorption and reducing recombination centers. The synthesis of high-quality graphene and graphene/metal oxide materials is crucial for advancing PV technology and stimulating innovation in sustainable energy solutions [135]. Chitosan based nanocomposites, which combine chitosan (CS) with metal oxide nanoparticles, show great promise in identifying hazardous metal ions (HMIs) in water. These materials trigger detectable changes in either the light they reflect or their ability to conduct electricity due to chemical interactions called chelation. CS brings advantages like being friendly to living tissues and easy to squeeze, making these nanocomposites potentially affordable for spotting HMIs effectively. Despite these benefits, challenges like needing to be very sensitive, staying stable, avoiding interference from other substances, and consistently giving the same results need to be addressed. Take, for example, an innovative electrochemical sensor that utilizes a blend of CS, reduced graphene oxide (rGO), and titanium dioxide (TiO_2) to spot lead (Pb (II)) with precision. This sensor has an impressively low limit for detecting lead and works well in various situations, from checking environmental and biological samples to even testing food, showcasing its adaptability [136].

4. CONCLUSIONS

Nanofertilizers are used the aim of improving agricultural sustainability and increasing crop yields. Nanocomposite-Based Fertilizers propose substantial potential for increasing agricultural sustainability by improving crop yields and nutrient use efficiency whereas reducing fertilizer application. This approach also encourages the use of environmentally friendly methods in modern agriculture. The combined use of nanotechnology and nanocomposites with agronomy, particularly in the application of nano smart fertilizers, promises an attractive pathway to improving agricultural productivity and mitigating environmental problems. Nanofertilizers are available in various forms, including nano biofertilizers, micro nanofertilizers, and macro nanofertilizers. Each type provides nutrients to support plant growth. Furthermore, smart fertilizers such as controlled release fertilizers (CRF) and slow released fertilizers (SRF) contribute to effectively regulating nutrient levels and minimizing environmental impacts compared to conventional fertilizers. In addition, nanofertilizers are designed to target specific areas, resulting in limited damage to the environment and the most beneficial production of crops. They are involved in the development of agronomic technology, which contributes to solving food security issues, promotes ecological sustainability, and resolves the challenges faced by modern agriculture.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

6. REFERENCES

1. S. Rahman, L. Rahman, A.T. Khalil, N. Ali, D.

Zia, M. Ali, and Z.K. Shinwari. Endophyte-mediated synthesis of silver nanoparticles and their biological applications. *Applied Microbiology and Biotechnology* 103(2): 2551-2569 (2019).
2. Y. Wang, Y. Fei, T. Yang, Z. Luo, Y. Xu, B. Su, and X. Lin. Nanotechnology for ultrafast nucleic acid amplification. *Nano Today* 48(11): 101749 (2023).
3. B. Bhushan. Introduction to nanotechnology. In: Springer Handbook of Nanotechnology. B. Bhushan (Ed.). *Springer* pp. 1-19 (2017).
4. T. Adhikari and S. Ramana. Nano Fertilizer: Its impact on crop growth and soil health. *The Journal of Research PJTSAU* 47(3): 1-70 (2019).
5. A. Osherov, R. Prasad, W. Chrzanowski, E.J. New, L. Brazaca, O. Sadik, C.L. Haynes, and E. Maine. Responsible nanotechnology for a sustainable future. *One Earth* 6(7): 763-766 (2023).
6. A. Khattak, F. Ullah, Z.K. Shinwari, and S. Mehmood. The effect of titanium dioxide nanoparticles and salicylic acid on growth and biodiesel production potential of sunflower (*Helianthus annuus* L.) Under water stress. *Pakistan Journal of Botany* 53(6): 1987-1995 (2021).
7. F. Bibi, A. Khan, I. Iqrar, M. Iqbal, and Z.K. Shinwari. Therapeutic applications and mechanism of action of plant-mediated silver nanoparticles. *Pakistan Journal of Botany* 56(2): 531-540 (2024).
8. M. Almas, S. Jan, and Z.K. Shinwari. Assessment of antimicrobial and antioxidant properties of silver nanoparticles from nepeta laevigata (d. Don) hand.-mazz. And nepeta kurramensis rech. F. *Pakistan Journal of Botany* 56(1): 277-282 (2024).
9. G. Pandey, S. Tripathi, S. Bajpai, and M. Kamboj. Approaches, Challenges, and Prospects of Nanotechnology for Sustainable Agriculture. *Agricultural and Environmental Nanotechnology* 46(3): 83-103 (2023).
10. A. Khan, F. Bibi, S.A. Jan, and Z.K. Shinwari. Role of Dof Transcription Factors under Abiotic Stresses. *Proceedings of the Pakistan Academy of Sciences* 60(3): 367-376 (2023).
11. D. Gollin. Getting income shares right. *Journal of Political Economy* 110(2): 458-474 (2002).
12. E. Loizou, C. Karelakis, K. Galanopoulos, and K. Mattas. The role of agriculture as a development tool for a regional economy. *Agricultural Systems* 173(5): 482-490 (2019).
13. A. Raza, S. Charagh, H. Salehi, S. Abbas, F. Saeed, G.E. Poinern, K.H. Siddique, and R.K. Varshney. Nano-enabled stress-smart agriculture: Can nanotechnology deliver drought and salinity-smart crops? *Journal of Sustainable Agriculture and Environment* 2(3): 189-214 (2023).
14. H. Chhipa. Nanofertilizers and nanopesticides for agriculture. *Environmental Chemistry Letters* 15(2): 15-22 (2017).
15. A. Khan, R.A. Khan, M. Ali, and Z.K. Shinwari. Impact of plant growth promoting rhizobacteria biofertilzers on biochemical attributes, antioxidant activities, nutritional values and productivity of maize. *Pakistan Journal of Botany* 55(6): 2057-2066 (2023).
16. Y. Shang, M.K. Hasan, G.J. Ahammed, M. Li, H. Yin, and J. Zhou. Applications of nanotechnology in plant growth and crop protection. *Molecules* 24(14): 2558 (2019).
17. C. Liu, H. Zhou, and J. Zhou. The applications of nanotechnology in crop production. *Molecules* 26(23): 7070 (2021).
18. F.A. Igiebor, B. Ikhajiagbe, and M. Asia. Green nanotechnology: A modern tool for sustainable agriculture in Nigeria–A review. *International Journal of Horticultural Science and Technology* 10(3): 269-286 (2023).
19. M. Bala, S.K. Bansal, and F. Fatima. Nanotechnology: A boon for agriculture. *Materials Today* 73(4): 267-270 (2023).
20. O.P. Singh and R.M. Nehru. Nanotechnology and cancer treatment. *Asian Journal Experimental Sciences* 22(2): 6 (2008).
21. F. Javed, S. Hayat, B. Aslam, M. Saqalein, M. Waseem, A. Meklat, and S. Muzammil. Agricultural applications of Bionanocomposites. *Advances in Bionanocomposites* 6(1): 327-350 (2024).
22. T. Muyesaier, H.D. Ruan, L. Wang, J. Lyu, R. Sadler, D. Connell, C. Chu, and D.T. Phung. Agriculture development, pesticide application and its impact on the environment. *International Journal of Environmental Research and Public Health* 18(5): 1112 (2021).
23. Z. Wei, M. Li, and V. Achal. A comprehensive review on environmental and human health impacts of chemical pesticide usage. *Emerging Contaminants* 11(1): 100410 (2024).
24. H.M. Agha, A.A. Alkamil, R.T. Yahya, A.A. Mohammed, Z.T. Ali, and M.M.S. Alsayadi. Consequences of global climate change on biodiversity and food security: a mini review. *AUIQ Complementary Biological System* 1(1): 43-51 (2024).
25. V.R. Umapathy, P.M. Natarajan, and B. Swamikannu. Review of the role of nanotechnology in overcoming the challenges faced in oral cancer

diagnosis and treatment. *Molecules* 28(14): 5395 (2023).

26. S. Naaz, S. Sachdev, R. Husain, V. Pandey, and M.I. Ansari. Nanomaterials and Nanocomposites: Significant Uses in Plant Performance, Production, and Toxicity Response. *Nanomaterials and Nanocomposites Exposures to Plants* 7(2): 1-18 (2023).
27. M. Menossi, C. Casalongué, and V.A. Alvarez. Bio-nanocomposites for modern agricultural applications. In *Handbook of consumer nanoproducts* 4(1): 1201-1237 (2022).
28. S.K. Kumar and R. Krishnamoorti. Nanocomposites: structure, phase behavior, and properties. *Annual review of chemical and biomolecular engineering* 1(1): 37-58 (2010).
29. S. Soleimani, A. Jannesari, M. Yousefzadi, A. Ghaderi, and A. Shahdadi. Fouling-Resistant Behavior of Hydrophobic Surfaces Based on Poly (dimethylsiloxane) Modified by Green rGO@ ZnO Nanocomposites. *American Chemicla Society Applied Bio Materials* 7(5): 2794- 2808 (2024).
30. P.M. Gawal and A.K. Golder. Vegetal route for synthesis of CQDs/CdS nanocomposites for photocatalytic reduction of CO_2 to methanol under visible light. *Colloids and Surfaces* 683(22): 133068 (2024).
31. M. Rashtiani, E. Ghasemi, S. Hallajian, and H. Ziyadi. Green synthesis of Nanocomposite-Based on magnetic hydroxyapatite using Falcaria vulgaris Bernh leaf extract to remove tartrazine dye from aqueous solution. *Inorganic Chemistry Communications,* 31(8): 112361 (2024).
32. A. Bagherivand, S. Jafarirad, R. Norouzi, and A. Karimi. Scolicidal and apoptotic effects of phyto-and chemically synthesized silver/boehmite nanocomposites on Echinococcus granulosus protoscoleces. *Biomaterials Advances* 157(15): 213723 (2024).
33. K. Subramani and A. Incharoensakdi. Physicochemical and photocatalytic properties of biogenic ZnO and its chitosan nanocomposites for UV-protection and antibacterial activity on coated textiles. *International Journal of Biological Macromolecules* 15(3): 130391 (2024).
34. I.A. Vagena, M.A. Gatou, G. Theocharous, P. Pantelis, M. Gazouli, N. Pippa, and N. Lagopati. Functionalized ZnO-Based Nanocomposites for Diverse Biological Applications: Current Trends and Future Perspectives. *Nanomaterials* 14(5): 397 (2024).
35. Z. Sabouri, S. Sabouri, S.S.T.H. Moghaddas, A. Mostafapour, S.M. Gheibihayat, and M. Darroudi. Plant-based synthesis of Ag-doped ZnO/MgO nanocomposites using Caccinia macranthera extract and evaluation of their photocatalytic activity, cytotoxicity, and potential application as a novel sensor for detection of Pb2+ ions. *Biomass Conversion and Biorefinery* 14(7): 8293-8305 (2024).
36. A. Kalia, S.P. Sharma, H. Kaur, and H. Kaur. Novel nanocomposite-based controlled-release fertilizer and pesticide formulations: Prospects and challenges. *Multifunctional Hybrid Nanomaterials for Sustainable Agri-food and Acosystems* 15(6): 99-134 (2020).
37. M. Anas, S. Bibi, U. Farwa, A. Khan, and U.M. Quraishi, Manganese oxide nanoparticles elicit cadmium tolerance in wheat seedlings by ionomic and phenomic adjustment, regulation of AsA–GSH pathway, cellular thickness recovery, and antioxidant modulation. *Environmental Science: Nano* 11(11): 4588-4605 (2024).
38. M. Ovais, A. Ali, S. Ullah, A.T. Khalil, A. Atiq, M. Atiq, N. Dogan, Z.K. Shinwari and M. Abbas. Fabrication of colloidal silver-peptide nanocomposites for bacterial wound healing. *Colloids and Surfaces* 651(73): 129708 (2022).
39. A.P. Kanth and A.K. Soni. Application of nanocomposites for conservation of materials of cultural heritage. *Journal of Cultural Heritage* 59(1): 120-130 (2023).
40. Z. Noohpisheh, H. Amiri, S. Farhadi, and A. Mohammadi-Gholami. Green synthesis of Ag-ZnO nanocomposites using Trigonella foenum-graecum leaf extract and their antibacterial, antifungal, antioxidant and photocatalytic properties. *Spectrochimica Acta* 240(73): 118595 (2020).
41. S. Hameed, A.T. Khalil, M. Ali, M. Numan, S. Khamlich, Z.K. Shinwari, and M. Maaza. Greener synthesis of ZnO and Ag–ZnO nanoparticles using Silybum marianum for diverse biomedical applications. *Nanomedicine* 14(6): 655-673 (2019).
42. H.E.A. Mohamed, S. Afridi, A.T. Khalil, T. Zohra, M.M. Alam, A. Ikram, Z.K. Shinwari and M. Maaza. Phytosynthesis of bivo 4 nanorods using Hyphaene thebaica for diverse biomedical applications. *AMB Express* 9(2): 200 (2019).
43. A.P. Kanth and A.K. Soni. Application of nanocomposites for conservation of materials of cultural heritage. *Journal of Cultural Heritage* 59(23): 120-130 (2023).
44. A. Shahzad, M.W. Ullah, J. Ali, K. Aziz, M.A.

Javed, Z. Shi, S. Manan, M. Ul-Islam, M. Nazar, and G. Yang. The versatility of nanocellulose, modification strategies, and its current progress in wastewater treatment and environmental remediation. *Science of the Total Environment* 858(97): 159937 (2023).

45. S.S. Shankar, A. Rai, A. Ahmad, and M. Sastry. Rapid synthesis of Au, Ag, and bimetallic Au core–Ag shell nanoparticles using Neem (Azadirachta indica) leaf broth. *Journal of Colloid and Interface Science* 275(2): 496-502 (2004).

46. T. Mai, D.D. Li, L. Chen, and M.G. Ma. Collaboration of two-star nanomaterials: The applications of nanocellulose-based metal organic frameworks composites. *Carbohydrate Polymers* 302(65): 120359 (2023).

47. M.M. Kumari, J. Jacob, and D. Philip. Green synthesis and applications of Au–Ag bimetallic nanoparticles. *Molecular and Biomolecular Spectroscopy* 137(51): 185-192 (2015).

48. A. Syed, L.S.R. Yadav, A.H. Bahkali, A.M. Elgorban, D. Abdul Hakeem, and N. Ganganagappa. Effect of CeO2-ZnO nanocomposite for photocatalytic and antibacterial activities. *Crystals* 10(9): 817 2020).

49. M. Nasrollahzadeh, Z. Issaabadi, and S.M. Sajadi. Green synthesis of a Cu/MgO nanocomposite by Cassytha filiformis L. extract and investigation of its catalytic activity in the reduction of methylene blue, congo red and nitro combpounds in aqueous media. *RSC Advances* 8(7): 3723-3735 (2018).

50. A.H. Anwer, M. Shoeb, F. Mashkoor, A. Ali, S. Kareem, M.Z. Ansari, J.M. Park and C. Jeong. Simultaneous reduction of carbon dioxide and energy harvesting using RGO-based SiO_2-TiO_2 nanocomposite for supercapacitor and microbial electrosynthesis. *Applied Catalysis* 339(17): 123091 (2023).

51. P. Bhavyasree and T. Xavier. Green synthesis of Copper Oxide/Carbon nanocomposites using the leaf extract of Adhatoda vasica Nees, their characterization and antimicrobial activity. *Heliyon* 6(2): e-03323(2020).

52. K. Ghassemi-Golezani and S. Rahimzadeh. Biochar-based nutritional nanocomposites: a superior treatment for alleviating salt toxicity and improving physiological performance of dill (Anethum graveolens). *Environmental Geochemistry and Health* 45(6): 3089-3111 (2023).

53. I. Matai, A. Sachdev, P. Dubey, S.U. Kumar, B. Bhushan, and P. Gopinath. Antibacterial activity and mechanism of Ag–ZnO nanocomposite on *S. aureus* and GFP-expressing antibiotic resistant *E. coli*. *Biointerfaces* 115(11): 359-367 (2014).

54. M. Leonardi, G.M. Caruso, S.C. Carroccio, S. Boninelli, G. Curcuruto, M. Zimbone, M. Allegra, B. Torrisi, F. Ferlito, and M. Miritello. Smart nanocomposites of chitosan/alginate nanoparticles loaded with copper oxide as alternative nanofertilizers. *Environmental Science* 8(1): 174-187 (2021).

55. N. Kamali, A.R. Mehrabadi, M. Mirabi, and M.A. Zahed. Synthesis of vinasse-dolomite nanocomposite biochar via a novel developed functionalization method to recover phosphate as a potential fertilizer substitute. *Frontiers of Environmental Science and Engineering* 14(1): 70 (2020).

56. G. Abbas and S. Kurniawan. Superabsorbent nanocomposite synthesis of cellulose from rice husk grafted poly (acrylate acid-co-acrylamide)/bentonite. *Materials Science and Engineering* 188(33): 175 (2017).

57. D.M. do Nascimento, Y.L. Nunes, J.P. Feitosa, A. Dufresne, and M.D.F. Rosa. Cellulose nanocrystals-reinforced core-shell hydrogels for sustained release of fertilizer and water retention. *International Journal of Biological Macromolecules* 216(57): 24-31 (2022).

58. G. Hazra. Different types of eco-friendly fertilizers: An overview. *Sustainability in Environment* 1(1): 54 (2016).

59. İ. Karagöz. Fertilization and Fertilizer Types. *Applied Soil Chemistry* 1(1): 123-148 (2021).

60. R. Chakraborty, A. Mukhopadhyay, S. Paul, S. Sarkar, and R. Mukhopadhyay. Nanocomposite-based smart fertilizers: A boon to agricultural and environmental sustainability. *Science of the Total Environment* 863(73): 160859 (2023).

61. R. Tayade, A. Ghimire, W. Khan, L. Lay, J.Q. Attipoe, and Y. Kim. Silicon as a smart fertilizer for sustainability and crop improvement. *Biomolecules* 12(8): 1027 (2022).

62. S. Divya, I. Rusyn, O. Solorza-Feria, and K. Sathish-Kumar. Sustainable smart fertilizers in agriculture systems: A review on fundamentals to in-field applications. *Science of the Total Environment* 904: 166729 (2023).

63. L. Li, Y. Sun, B. Cao, H. Song, Q. Xiao, and W. Yi. Preparation and performance of polyurethane/mesoporous silica composites for coated urea. *Materials and Design* 99(13): 21-25 (2016).

64. F. Zulfiqar, M. Navarro, M. Ashraf, N.A. Akram, and S. Munné-Bosch. Nanofertilizer use for sustainable agriculture: Advantages and

limitations. *Plant Science* 289(81): 110270 (2019).

65. S. Sharma, V.S. Rana, R. Pawar, J. Lakra, and V. Racchapannavar. Nanofertilizers for sustainable fruit production: a review. *Environmental Chemistry Letters* 19(1): 1693-1714 (2021).
66. C. Jia, P. Lu, and M. Zhang. Preparation and characterization of environmentally friendly controlled release fertilizers coated by leftovers-based polymer. *Processes* 8(4): 417 (2020).
67. M. Negi, S. Sharma, U. Sharma, P. Kumar, U. Sharma and Kapil Sharma. Aspects of the Current and Prospective Sustainable Usage of Nanofertilizers in Agriculture and Their Effects on Health of the Soil: an Updated Review. *Soil Science and Plant Nutrition* 23(7): 594-611 (2022).
68. M.S. Haydar, D. Ghosh, and S. Roy. Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. *Plant Nano Biology* 41(2): 100058 (2024).
69. S.S. Patil. Controlled and Slow-Release Fertilizers. In: Emerging Trends in Agriculture Sciences. Volume 13. Y.V. Singh (Ed.). *Integrated Publications, New Delhi, India* (2023).
70. H. Chhipa. Nanofertilizers and nanopesticides for agriculture. *Environmental Chemistry Letters* 15(2): 15-22 (2017).
71. A. Karthik and M.U. Maheswari. Smart fertilizer strategy for better crop production. *Agricultural Reviews* 42(1): 12-21 (2021).
72. O.R. Devi, N. Ojha, B. Laishram, S. Dutta, and P. Kalita. Roles of Nano-Fertilizers in Sustainable Agriculture and Biosafety. *Environment and Ecology* 41(1B): 457-463 (2023).
73. T.R. Santiago, C.C. Bonatto, M. Rossato, C.A. Lopes, C.A. Lopes, E.S. Mizubuti, and L.P. Silva. Green synthesis of silver nanoparticles using tomato leaf extract and their entrapment in chitosan nanoparticles to control bacterial wilt. *Journal of the Science of Food and Agriculture* 99(9): 4248-4259 (2019).
74. M.S. Mohseni, M.A. Khalilzadeh, M. Mohseni, F.Z. Hargalani, M.I. Getso, V. Raissi, and O. Raiesi. Green synthesis of Ag nanoparticles from pomegranate seeds extract and synthesis of Ag-Starch nanocomposite and characterization of mechanical properties of the films. *Biocatalysis and Agricultural Biotechnology* 25(4): 101569 (2020).
75. M.A. Asghar, R.I. Yousuf, M.H. Shoaib, M.A. Asghar, M. Zehravi, A.A. Rehman and K. Khan. Green Synthesis and Characterization of Carboxymethyl Cellulose Fabricated Silver-Based Nanocomposite for Various Therapeutic Applications. *International Journal of Nanomedicine* 5(2): 5371-5393 (2021).
76. P.N. Omo-Okoro, C.E. Maepa, A.P. Daso, and J.O. Okonkwo. Microwave-assisted synthesis and characterization of an agriculturally derived silver nanocomposite and its derivatives. *Waste and Biomass Valorization* 11(1): 2247-2259 (2020).
77. S. Rajeshkumar, M. Tharani, V.D. Rajeswari, N.S. Alharbi, S. Kadaikunnan, J.M. Khaled and M. Govindarajan. Synthesis of greener silver nanoparticle-based chitosan nanocomposites and their potential antimicrobial activity against oral pathogens. *Green Processing and Synthesis* 10(1): 658-665 (2021).
78. H. Pandian, K. Senthilkumar, M. Naveenkumar and S. Samraj. Azadirachta indica leaf extract mediated silver nanoparticles impregnated nano composite film (AgNP/MCC/starch/whey protein) for food packaging applications. *Environmental Research* 216(5): 114641 (2023).
79. V.D. Matteis, M. Cascione, D. Costa, S. Martano, D. Manno, A. Cannavale, and R. Rinaldi. Aloe vera silver nanoparticles addition in chitosan films: improvement of physicochemical properties for eco-friendly food packaging material. *Journal of Materials Research and Technology* 24(7): 1015-1033 (2023).
80. P. Arabkhani, N. Saeedi, H. Sadeghi, S. Nouripour-Sisakht, M. Gharaghani, and A. Asfaram. Plant extracts-mediated green synthesis of zinc oxide/carbon nanofiber nanocomposites with highly efficient photocatalytic and antimicrobial properties for wastewater treatment. *Journal of Water Process Engineering* 54(10): 104020 (2023).
81. E. Gurgur, S.S. Oluyamo, A.O.O. Adetuyi, O.I. Omotunde and A.E. Okoronkwo. Green synthesis of zinc oxide nanoparticles and zinc oxide–silver, zinc oxide–copper nanocomposites using Bridelia ferruginea as biotemplate. *Discover Applied Sciences* 2(5): 911 (2020).
82. M. Tariq, A.U. Khan, A.U. Rehman, S. Ullah, A.U. Jan, Z.U.H. Khan and Q. Yuan. Green synthesis of Zno@ GO nanocomposite and its' efficient antibacterial activity. *Photodiagnosis and Photodynamic Therapy* 35(3): 102471 (2021).
83. M. Zare, K. Namratha, S. Alghamdi, Y.H.E. Mohammad, A. Hezam, M. Zare and X. Zhang. Novel green biomimetic approach for synthesis of ZnO-Ag nanocomposite; antimicrobial activity against food-borne pathogen, biocompatibility and

solar photocatalysis. *Scientific Reports* 9(1): 8303 (2019).

84. F. Moradnia, S.T. Fardood, A. Ramazani, B.K. Min, S.W. Joo, and R.S. Varma. Magnetic Mg0. 5Zn0. 5FeMnO4 nanoparticles: green sol-gel synthesis, characterization, and photocatalytic applications. *Journal of Cleaner Production* 288(2): 125632 (2021).
85. K. Subashini, S. Prakash, and V. Sujatha. Biological applications of green synthesized zinc oxide and nickel oxide nanoparticles mediated poly (glutaric acid-co-ethylene glycol-co-acrylic acid) polymer nanocomposites. *Inorganic Chemistry Communications* 139(64): 109314 (2022).
86. D. Bharathi, R. Ranjithkumar, B. Chandarshekar, and V. Bhuvaneshwari. Preparation of chitosan coated zinc oxide nanocomposite for enhanced antibacterial and photocatalytic activity: as a bionanocomposite. *International Journal of Biological Macromolecules* 129(1): 989-996 (2019).
87. P. Panchal, D.R. Paul, A. Sharma, P. Choudhary, P. Meena, and S.P. Nehra. Biogenic mediated Ag/ZnO nanocomposites for photocatalytic and antibacterial activities towards disinfection of water. *Journal of Colloid and Interface Science* 563(3): 370-380 (2020).
88. Z. Noohpisheh, H. Amiri, S. Farhadi, and A. Mohammadi-Gholami. Green synthesis of Ag-ZnO nanocomposites using Trigonella foenum-graecum leaf extract and their antibacterial, antifungal, antioxidant and photocatalytic properties. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 240(4):118595 (2020).
89. S. Ganesan, I.G. Babu, D. Mahendran, P.I. Arulselvi, N. Elangovan, N. Geetha, and P. Venkatachalam. Green engineering of titanium dioxide nanoparticles using Ageratina altissima (L.) King and HE Robines. medicinal plant aqueous leaf extracts for enhanced photocatalytic activity. *Annals of Phytomedicine* 5(2): 69-75 (2016).
90. V. Uthiravel, K. Narayanamurthi, V. Raja, S. Anandhabasker, and K. Kuppusamy. Green synthesis and characterization of TiO_2 and Ag-doped TiO_2 nanoparticles for photocatalytic and antimicrobial applications. *Inorganic Chemistry Communications* 170(8): 113327 (2024).
91. D. Roy and A.K. Yadav. Green TiO_2–ZnO nanocomposite stimulator for the growth of Solanum lycopersicum in aquaculture. *Applied Nanoscience* 12(5): 1403-1423 (2022).
92. M. Skiba, V. Vorobyova, and K. Sorochkina. Bio-Green and Classical Stabilize Agents of Nanoparticles in Silver-Doped Titanium Dioxide: The Influence on Antioxidant, Photocatalytic, and Bactericidal Activities. *Plasmonics* 17(5): 2221-2234 (2022).
93. M. Coronell, G.T. Lucas, R. Solano, and A.H. Barros. Green Synthesis of Silver-Doped Titanium Dioxide Nanostructures for Acetaminophen Degradation Under Solar Radiation. *Ingeniería y Universidad* 26(6): 56-95 (2022).
94. V. Saharan, R.V. Kumaraswamy, R.C. Choudhary, S. Kumari, A. Pal, R. Raliya, and P. Biswas. Cu-chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. *Journal of Agricultural and Food Chemistry* 64(31): 6148-6155 (2016).
95. R.C. Choudhary, R.V. Kumaraswamy, S. Kumari, A. Pal, R. Raliya, P. Biswas, and V. Saharan. Synthesis, characterization, and application of chitosan nanomaterials loaded with zinc and copper for plant growth and protection. *Nanotechnology* 12(5): 227-247 (2017).
96. M. Sathiyabama and A. Manikandan. Application of copper-chitosan nanoparticles stimulate growth and induce resistance in finger millet (Eleusine coracana Gaertn.) plants against blast disease. *Journal of Agricultural and Food Chemistry* 66(8): 1784-1790 (2018).
97. D. Kubavat, K. Trivedi, P. Vaghela, K. Prasad, G.K. Vijay Anand, H. Trivedi, and A. Ghosh. Characterization of a chitosan-based sustained release nanofertilizer formulation used as a soil conditioner while simultaneously improving biomass production of Zea mays L. *Land Degradation & Development* 31(17): 2734-2746 (2020).
98. G. Moreno-Martín, J. Sanz-Landaluze, M.E. León-González, and Y. Madrid. Insights into the accumulation and transformation of Ch-SeNPs by Raphanus sativus and Brassica juncea: Effect on essential elements uptake. *Science of the Total Environment* 725(21): 138453 (2020).
99. R.C. Choudhary, R.V. Kumaraswamy, S. Kumari, S.S. Sharma, A. Pal, R. Raliya, and V. Saharan. Cu-chitosan nanoparticle boost defense responses and plant growth in maize (Zea mays L.). *Scientific Reports* 7(1): 9754 (2017).
100. S. Gowda and S. Sriram. Green synthesis of chitosan silver nanocomposites and their antifungal activity against Colletotrichum truncatum causing

anthracnose in chillies. *Plant Nano Biology* 5(1): 100041 (2023).

101. O. Ejeromedoghene, A. Oladipo, O. Oderinde, E.S. Okeke, S.A. Amolegbe, T.M. Obuotor, and G. Fu. Facile green synthesis of new chitosan-metal nanoparticles as nano-agrofungicide for the preservation of postharvest cherry fruits. *ACS Agricultural Science & Technology* 1(6): 664-673 (2021).
102. A.N. Mohan and S. Panicker. Facile synthesis of graphene-tin oxide nanocomposite derived from agricultural waste for enhanced antibacterial activity against Pseudomonas aeruginosa. *Scientific Reports* 9(1): 4170 (2019).
103. Q. ul Ain, H.A. Hussain, Q. Zhang, A. Rasheed, A. Imran, S. Hussain, and K.S. Ali. Use of nano-fertilizers to improve the nutrient use efficiencies in plants. *Sustainable Plant Nutrition* 71(1): 299-321 (2023).
104. H. Kaur, S.J. Hussain, R.A. Mir, V.C. Verma, B. Naik, P. Kumar, and R. Dubey. Nanofertilizers–emerging smart fertilizers for modern and sustainable agriculture. *Biocatalysis and Agricultural Biotechnology* 23(1): 102921 (2023).
105. R.S. Riseh, M.G. Vazvani, and J.F. Kennedy. The application of chitosan as a carrier for fertilizer: A review. *International Journal of Biological Macromolecules* 72(5): 126483 (2023).
106. C.O. Dimkpa and P.S. Bindraban. Nanofertilizers: new products for the industry? *Journal of Agricultural and Food Chemistry* 66(26): 6462-6473 (2017).
107. P. Fincheira, N.Hoffmann, G. Tortella, A. Ruiz, P. Cornejo, M.C. Diez, A.B. Seabra, A. Benavides-Mendoza, and O. Rubilar. Eco-efficient systems based on nanocarriers for the controlled release of fertilizers and pesticides: Toward smart agriculture. *Nanomaterials* 13(13): 1978 (2023).
108. H. Kaur, S.J. Hussain, R.A. Mir, V.C. Verma, B. Naik, P. Kumar, and R. Dubey. Nanofertilizers–emerging smart fertilizers for modern and sustainable agriculture. *Biocatalysis and Agricultural Biotechnology* 67(3): 102921 (2023).
109. A. Khan, A. Bano, R.A. Khan, and N. Khan. Role of PGPR in suppressing the growth of Macrophomina phaseolina by regulating antioxidant enzymes and secondary metabolites in Vigna radiata L. Wilczek. *South African Journal of Botany* 158(9): 443-451 (2023).
110. B. Borah, P. Parmar, D. Kumar, and S. Pusarla. Nanofertilizers: A Futuristic Approach to Crop Production and Towards a Sustainable Environment. *Nano-Biofortification for Human and Environmental Health* 21(6): 211-235 (2023).
111. R. Mishra, N. Sahu, M. Saha, A. Sarkar, D.K. Yadav, J. Saha, and A. Patra. Nanofertilizers in Agriculture: Futuristic Approach. *Nano-Biofortification for Human and Environmental Health* 1(1): 267-293(2023).
112. B.A. Keating, P.S. Carberry, P.S. Bindraban, S. Asseng, H. Meinke, and J. Dixon. Eco-efficient agriculture: Concepts, challenges, and opportunities. *Crop Science* 50(1): 109-119 (2010).
113. M. Skorupka and A. Nosalewicz. Ammonia volatilization from fertilizer urea—a new challenge for agriculture and industry in view of growing global demand for food and energy crops. *Agriculture* 11(9): 822 (2021).
114. J.P. Aryal, T.B Sapkota,. T.J. Krupnik, D.B. Rahut, M.L. Jat, and C.M. Stirling. Factors affecting farmers' use of organic and inorganic fertilizers in South Asia. *Environmental Science and Pollution Research* 28(37): 51480-51496 (2021).
115. J. Martínez-Dalmau, J. Berbel, and R. Ordóñez-Fernández. Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. *Sustainability* 13(10): 5625 (2021).
116. I. Rashmi, T. Roy, K. Kartika, R. Pal, V. Coumar, S. Kala, and K. Shinoj. Organic and inorganic fertilizer contaminants in agriculture: Impact on soil and water resources. *Contaminants in Agriculture: Sources, Impacts and Management* 76(3): 3-41 (2020).
117. G. Raimondi, C. Maucieri, A. Toffanin, G. Renella, and M. Bori. Smart fertilizers: What should we mean and where should we go? *Italian Journal of Agronomy* 16(2): 68-90 (2021).
118. C. Agrimonti, M. Lauro, and G. Visioli. Smart agriculture for food quality: facing climate change in the 21st century. *Critical Reviews in Food Science and Nutrition* 61(6): 971-981 (2021).
119. X. Xin, J.D. Judy, B.B. Sumerlin, and Z. He. Nano-enabled agriculture: from nanoparticles to smart nanodelivery systems. *Environmental Chemistry* 17(6): 413-425 (2020).
120. B. Toksha, S. Joshi, and A. Chatterjee. The Potential of Nanocomposite Fertilizers for Sustainable Crop Production. *Nanofertilizers for Sustainable Agroecosystems* 7(3): 99-124 (2023).
121. H.U. Rahim, M. Qaswar, M. Uddin, C. Giannini, M.L. Herrera, and G. Rea. Nano-enable materials promoting sustainability and resilience in modern agriculture. *Nanomaterials* 11(8): 2068 (2021).

122. A. Zehra, A. Rai, S.K. Singh, M. Aamir, W.A. Ansari, and R.S. Upadhyay. An overview of nanotechnology in plant disease management, food safety, and sustainable agriculture. *Food Security and Plant Disease Management* 43(1): 193-219 (2021).
123. I. Khan, K. Saeed, and I. Khan. Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry* 12(7): 908-931 (2019).
124. T. Younis, S. Rahman, L. Rehman, I. Iqrar, and Z.K. Shinwari. Exploring the Impact of Endophytic Bacteria on Mitigating Salinity Stress in *Solanum lycopersicum* L. *Plant Stress* 67(12): 100467 (2024).
125. M.A. Alghuthaymi, A. Kalia, K. Bhardwaj, P. Bhardwaj, K.A.A. Abd-Elsalam, M. Valis, and K. Kuca. Nanohybrid antifungals for control of plant diseases: Current status and future perspectives. *Journal of Fungi* 7(1): 48 (2021).
126. N.N. Tran, T.N.Q. Le, H. Q. Pho, T.T. Tran, and V. Hessel. Nanofertilizers and nanopesticides for crop growth. *Plant and Nanoparticles* 12(5): 367-394(2022).
127. D. Maity, U. Gupta, and S. Saha. Biosynthesized metal oxide nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management. *Nanoscale* 14(38): 13950-13989 (2022).
128. A.F. Hashim, S.F. Hamed, H.A.A. Hamid, K.A. Abd-Elsalam, I. Golonka, W. Musiał, and I.M. El-Sherbiny. Antioxidant and antibacterial activities of omega-3 rich oils/curcumin nanoemulsions loaded in chitosan and alginate-based microbeads. *International Journal of Biological Macromolecules* 140(61): 682-696 (2019).
129. A. Shelar, S.H. Nile, A.V. Singh, D. Rothenstein, J. Bill, J. Xiao, M. Chaskar, G. Kai, and R. Patil. Recent advances in nano-enabled seed treatment strategies for sustainable agriculture: challenges, risk assessment, and future perspectives. *Nano-Micro Letters* 15(1): 54 (2023).
130. N.F. Al Harby, M. El-Batouti, and M.M. Elewa. Prospects of polymeric nanocomposite membranes for water purification and scalability and their health and environmental impacts: A review. *Nanomaterials* 12(20): 3637 (2022).
131. M. Anas, A. Falak, A. Khan, W.A. Khattak, S.G. Nisa, Q. Aslam and S. Fahad, Therapeutic potential and agricultural benefits of curcumin: a comprehensive review of health and sustainability applications. *Journal of Umm Al-Qura University for Applied Sciences* (2024). https://doi.org/10.1007/s43994-024-00200-7
132. F.J. Godínez-García, R. Guerrero-Rivera, J.A. Martínez-Rivera, E. Gamero-Inda, and J. Ortiz-Medina. Advances in two-dimensional engineered nanomaterials applications for the agro-and food-industries. *Journal of the Science of Food and Agriculture* 103(11): 5201-5212 (2023).
133. F.W. Low, C.W. Lai, N.A. Samsudin, Y. Yusoff, S.M. Goh, C.F. Chau, and S.K. Tiong. Graphene and its derivatives, synthesis route, and mechanism for photovoltaic solar cell applications. *Sustainable Materials for Next Generation Energy Devices* 42(12): 103-132 (2021).
134. M.D. Shirsat, and T. Hianik. Electrochemical Detection of Heavy Metal Ions Based on Nanocomposite Materials. *Journal of Composites Science* 7(11): 473 (2023).