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Chapter 2

Agricultural waste-driven Nanoemulsions and Microemulsions: A novel Bio-circular economic approaches for climate-resilient agriculture and combating hunger

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Abstract

The increasing menace of global warming, food insecurity, and hidden hunger necessitates a paradigm shift in agriculture. In this chapter, we critically analyze the viability of utilizing nanoemulsions/microemulsions developed through agricultural/food waste resources in creating a sustainable agricultural system. These colloidal carriers, developed through the conversion of different biobased materials like lignocellulosic biomass, fruit peels, and oilseed waste into bio-based surfactants, offer precise delivery of agrochemicals, thereby increasing climate resilience in crops while reducing environmental impacts. This chapter critically discusses their mode of action in increasing nutrient uptake, pest resistance, and abiotic stress tolerance, creating climate-resistant crops that increase food security on a global scale. More importantly, this chapter critically discusses issues of scalability, regulatory frameworks, and ecotoxicological concerns, emphasizing the need for integrated life cycles in creating a sustainable agricultural system through waste resources. Using schematic illustrations of formulation pathways and application matrices, this chapter outlines a high-impact pathway of utilizing waste resources in creating nanoemulsions/microemulsions in reducing hunger, including micronutrient hunger, in a warming world.

Keywords: Agricultural, Waste, Nanoemulsion, Microemulsion, Circular agriculture, Climate resilience, Hidden hunger, Global warming,

1. Introduction

The integration of agricultural and food waste into nanotechnological and biomolecular platforms, specifically through the creation of nanoemulsions and/or microemulsions, presents a multifaceted strategy to address critical global challenges including climate change, food insecurity, and the widespread issue of hidden hunger (Shah et al., 2024; Bamisaye et al., 2023). This approach aligns with the principles of a circular bioeconomy and aims to foster climate-resilient agricultural systems (Saxena et al., 2024; Mungwari et al., 2025). The increasing global population, projected to exceed 9 billion by 2050, necessitates a revolution in food production, distribution, storage, and consumption to ensure food security amidst a changing climate and declining arable land (Vaidya et al., 2024). Nanotechnology offers transformative solutions by improving plant nutrition, enhancing stress resistance, and optimizing agricultural efficiency (Shoukat et al., 2024, Shah et al., 2024, Otari et al., 2024, Ur Rahim et al., 2021; Patel and Patel, 2022a).

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Nanoemulsions and microemulsions, which are thermodynamically stable, among which nanostructured fluids of oil and water, are particularly promising for encapsulating and delivering various active agents (Yi et al., 2025, Mohammed et al., 2021). These systems are characterized by their small droplet sizes, typically less than 200 nm, and their ability to enhance the solubility, stability, and bioavailability of encapsulated compounds (Zuccari and Alfei, 2023; Mohammed et al., 2021; Chaudhary et al., 2024). The unique properties of these nano-delivery systems make them ideal for sustainable agricultural applications, including the precise delivery of agrochemicals, nutrients, and phytochemicals (Gupta et al., 2024; Gallucci et al., 2025; Lowry et al., 2024; Singh et al., 2023; Patel and Patel, 2022b).

The valorization of agricultural and food waste through nanotechnology addresses significant environmental challenges posed by traditional disposal methods, such as crop burning, which contribute to air pollution and ecological degradation (Saxena et al., 2024). By transforming these residues into valuable resources, such as nutrient-rich nanofertilizers or bio-pesticides, nanotechnology supports a circular economy model (Saxena et al., 2024; Mungwari et al., 2025; Preethi et al., 2024). This conversion mitigates waste and offers sustainable alternatives to synthetic inputs that often have negative environmental and health effects (Mungwari et al., 2025, Younis et al., 2021). For instance, waste-derived nanofertilizers can improve nutrient use efficiency, reduce environmental pollution, and augment plant productivity (Mungwari et al., 2025).

Climate change is a primary driver of agricultural instability, causing abiotic stresses such as drought, salinity, heat, and heavy metal toxicity, which collectively lead to significant annual yield losses, ranging from 20% to 50% globally (Rehman et al., 2024; Singh et al., 2025; Raza et al., 2023; Ahmad et al., 2024). Nanomaterials and nano-enabled strategies have demonstrated remarkable potential in enhancing plant resilience to these stressors (Rehman et al., 2024, Shoukat et al., 2024, Ochoa et al., 2025, Azameti and Imoro, 2023). Nanomaterials can modulate heavy metal and arsenic stress in food crops, offering a pathway to improve food safety and public health (Rai et al., 2023). They can also improve nutrient uptake and utilization, particularly of micronutrients, which are often scarce in degraded soils (Shoukat et al., 2024; Singh et al., 2024). The ability of nanomaterials to deliver these crucial elements efficiently helps plants maintain physiological processes like photosynthesis and water absorption under adverse conditions (Singh et al., 2025).

A key application of nanoemulsions in agriculture is the enhanced delivery of pesticides and other agrochemicals, leading to broad-spectrum effectiveness with minimal environmental impact (Gupta et al., 2024). Nanoemulsions and nanoencapsulation enable the controlled release of active ingredients, reducing the required dosage and minimizing off-target effects and environmental contamination (Ashaq et al., 2025, Gallucci et al., 2025, Kumar et al., 2023, Patil et al., 2024). This precision delivery is crucial for developing ”stress-smart” crops that can withstand the increasingly severe and volatile weather patterns associated with climate change (Raza et al., 2023, Singh et al., 2023).

Furthermore, nanotechnology can integrate with plant hormones and plant-associated microbiomes, forming a ”Nano–Phyto–Micro Triad” for climate-resilient agriculture (Oluwole et al., 2025). The plant-associated microbiome is vital for crop growth, nutrient acquisition, and resistance to pathogens and abiotic stress (Ahmed et al., 2023). Nanocarriers can improve the delivery and stability of natural hormones and compounds compatible with the microbiome, overcoming issues of low bioavailability and environmental degradation (Oluwole et al., 2025). Nano-enabled agrochemicals can dynamically interact with this microbiome, potentially improving plant performance without the collateral negative impacts often seen with conventional approaches (Ahmed et al., 2023).

One of the most pressing global health issues, hidden hunger, affects nearly 2 billion people due to deficiencies in essential micronutrients like iron, zinc, iodine, and vitamin A (Vignesh et al., 2025; Mandal et al., 2023; Li et al., 2024). Climate change exacerbates this problem through the ”nutrient dilution effect,” where elevated atmospheric CO_2 can boost crop calorie counts but dilute essential nutrients, leading to less nutritious food despite increased biomass. Biofortification, a strategy to enhance the nutrient content of crops, is a sustainable solution to combat hidden hunger (Vignesh et al., 2025; Kolpakova et al., 2024; Li et al., 2024). Nanotechnology can significantly contribute to biofortification by enabling targeted delivery of micronutrients to plants, thereby increasing their concentration in edible parts (Balusamy et al., 2023; Mandal et al., 2023). For instance, zinc fortification, supported by nano-delivery systems, can play a crucial role in mitigating micronutrient deficiencies (Rana et al., 2024, Patel et al., 2024a). The development of nanoemulsion-based edible coatings also offers solutions for post-harvest losses, particularly for fruits and vegetables which are highly perishable (Patel and Patel., 2024). These coatings can restrict losses and boost quality retention, contributing to food security and economic stability (Panwar et al., 2024, Patel et al., 2024b).

The successful implementation of nanotechnology in agriculture requires a comprehensive understanding of how nanocarriers interact with plants at the cellular and molecular levels (Lowry et al., 2024; Allará et al., 2025). Insights from mammalian nanomedicine can inform the design of efficient and effective nano-delivery systems for plants (Lowry et al., 2024). Electronic nanomaterials, for instance, can encapsulate bioactive substances and enhance photosynthesis and stress tolerance, thereby boosting crop yields (Allará et al., 2025).

The agricultural sector is a significant contributor to greenhouse gas emissions, particularly methane from livestock and nitrous oxide from fertilizers. The nitrogen surplus, resulting from excessive synthetic fertilizer application, leads to environmental nitrogen losses, including nitrous oxide emissions. By improving nutrient use efficiency through nanofertilizers and optimizing delivery, nanotechnology can help mitigate these emissions, supporting climate change mitigation efforts (Mungwari et al., 2025; Younis et al., 2021).

2. Fundamentals of Nanoemulsions and Microemulsions

Nanoemulsions (NEs) and microemulsions (MEs) represent advanced colloidal systems that are increasingly pivotal in sustainable agriculture, particularly through the valorization of waste-derived components to enhance food security and mitigate climate change impacts (Xu et al., 2023; Shelar et al., 2023; Gupta et al., 2024; Shawky et al., 2025; Jiang et al., 2021; Preethi et al., 2024; Hafez and Khalil, 2024). These systems, characterized by their nanoscale droplet sizes, offer superior delivery mechanisms for agrochemicals and nutrients, addressing critical challenges such as nutrient use efficiency, pest management, and climate resilience in crops (Kumar et al., 2025; Shelar et al., 2023; Gupta et al., 2024; Bhaskar et al., 2023; Munir et al., 2023; Hafez and Khalil, 2024).

NEs are kinetically stable, biphasic liquid dispersions where one immiscible liquid is dispersed within another, typically forming oil-in-water (O/W) or water-in-oil (W/O) configurations (Bhushani and Anandharamakrishnan, 2017). Their stability is maintained by surfactants at the oil-water interface, which significantly reduce interfacial tension (often below 10^{-3} N/m) and increase Laplace pressure ($\Delta P = 2\ \gamma/r$), thereby preventing droplet coalescence (McClements, 2012; Koroleva and Yurtov, 2012). NEs generally have droplet diameters ranging from 20 to 200 nm (Aleti et al., 2022). In contrast, MEs are thermodynamically stable, transparent, and spontaneously forming systems that self-assemble driven by entropy maximization (Nair, 2024; McClements, 2012). They typically feature droplet radii below one-quarter of the wavelength of light, resulting in their optical clarity, and exhibit ultra-low viscosity. The fundamental distinction lies in their thermodynamic stability: MEs are thermodynamically stable, while NEs are kinetically stable, requiring energy input for their formation (McClements, 2012).

The development of NEs and MEs is significantly advanced by the incorporation of waste-derived components, promoting a circular economy approach in agriculture (Xu et al., 2023; Shawky et al., 2025; Kaur, 2024; Preethi et al., 2024; Xiong et al., 2019). For instance, pectin extracted from apple pomace, lecithin from oilseed cakes, and phenolics from onion skins can function as green surfactants and co-stabilizers (Shawky et al., 2025). Pectin typically has a Hydrophile-Lipophile Balance (HLB) value of 10–12, while lecithin exhibits a critical micelle concentration (CMC) between 0.1–1% w/v (Manzoor et al., 2023). These waste-derived surfactants contribute to the biocompatibility and functionality of the nanoformulations. For example, rice bran oil nanoemulsions have demonstrated an impressive 95% encapsulation efficiency for hydrophobic pesticides such as chlorpyrifos and can reduce their photodegradation by 70% (Guanghui et al., 2023). The thermodynamic favorability (Gibbs free energy Δ G <0) for ME formation is rooted in the amphiphilicity of surfactants, which can also enable phase inversion temperature (PIT) tuning for temperature-responsive release in heat-stressed agricultural fields (Liu et al., 2021).

3. Fabrication Pathways and Waste Valorization

The preparation of NEs and MEs involves various high-energy and low-energy methods (Sadeq, 2020; Koroleva and Yurtov, 2012). High-energy methods include ultrasonication, high-pressure homogenization, and microfluidization, while low-energy methods encompass spontaneous emulsification and phase inversion methods (Sadeq, 2020; Cholakova et al., 2022; Koroleva and Yurtov, 2012).

Waste valorization efforts integrate these methods effectively. For example, ultrasonication of banana peel extracts, which can yield 15–20% dry weight of surfactants (saponins), combined with clove oil, produces NEs with a polydispersity index (PDI) typically below 0.2 (Martin-Piñero et al., 2019). This PDI indicates a narrow size distribution of droplets, crucial for effective delivery (Guanghui et al., 2023). ME formation via alcohol-mediated co-surfactancy, where ethanol derived from molasses, a food waste product, can lower interfacial tension to 10^{-4} N/m, facilitating spontaneous emulsification (Tong et al., 2015).

The process of waste valorization for NE/ME synthesis generally involves several steps (Xiong et al., 2024). These include waste pre-treatment (e.g., hydrolysis or enzymatic extraction), isolation of surfactants, emulsification with agro-actives, and subsequent characterization using techniques like Dynamic Light Scattering (DLS) and Transmission Electron Microscopy (TEM) (Xiong et al., 2024). These steps ensure the quality and efficacy of the nanoformulations.

4. Waste Streams as Nanoplatform Precursors

Agricultural and food processing waste streams are abundant sources for producing nanoplatform precursors (Xu et al., 2023; Shawky et al., 2025; Preethi et al., 2024; Xiong et al., 2019). Rice bran, produced at approximately 70 million tons globally per year, provides γ-oryzanol-rich oils suitable for O/W NEs (Shawky et al., 2025). These NEs stabilize droplets through steric hindrance, often exhibiting a [zeta potential] of around -35 mV, which contributes to their colloidal stability (Guanghui et al., 2023; Du et al., 2016). Nanocellulose derived from sugarcane bagasse can reinforce emulsion gels, extending the shelf-life of biofertilizers by up to 6 months (Qiao et al., 2022). Life-cycle analyses (LCA) have affirmed a significant 60% reduction in carbon footprint when using these waste-derived surfactants compared to synthetic alternatives (Preethi et al., 2024).

Citrus peels, with a global production of about 30 million tons per year, are a source of limonene (serving as an oil phase) and flavonoids (natural antioxidants) (Xu et al., 2023; Medeleanu et al., 2023). These components can be formulated into NEs containing essential oils for antifungal coatings, with droplet sizes typically around 50 nm, facilitating transcuticular penetration in plants (Baldassarre et al., 2023; Medeleanu et al., 2023). Spent coffee grounds yield caffeic acid surfactants, enabling the creation of ME-based zinc nanofertilizers that boost zinc bioavailability four-fold in alkaline soils (Saikia et al., 2023). Comparative yields and properties of various waste-derived surfactants are summarized in Table 1, showcasing their potential in terms of yield, HLB values, and optimal droplet sizes.

Table 1: Exmples of succesful NEs

Waste Source	Surfactant Type	Yield (% dw)	HLB	Droplet Size (nm)	Ref.
Citrus Peel	Limonene/Pectin	18-22	11	40-80	Xu et al. 2023; Medeleanu et al., 2023
Rice Bran	Oryzanol/Lecithin	12-15	9-10	30-60	Shawky et al. 2025, Guanghui et al. 2023
Onion Skin	Quercetin	8-12	12	50-100	Shawky et al. 2025
Banana Peel	Saponins	15-20	13	20-50	Shawky et al. 2025

5. Applications in Sustainable Agriculture

Nanoemulsions and microemulsions offer promising applications across various facets of sustainable agriculture, including nutrient delivery, pest and disease management, and enhancing climate resilience (Shelar et al., 2023; Gupta et al., 2024; Bhaskar et al., 2023; Munir et al., 2023; Jiang et al., 2021; Hafez and Khalil, 2024).

5.1. Nutrient Delivery and Fertilizer Efficiency

NEs are highly effective in encapsulating essential micronutrients like iron (Fe), zinc (Zn), and manganese (Mn), thereby addressing nutrient deficiencies and ”hidden hunger” in crops (Hafez and Khalil, 2024; Gohari et al., 2024). Also, NE can help to improve efficiency of crucial diverse molecules to easily transport from cell to cell. For example, Soybean protein isolate (SPI)-stabilized nanoemulsions (NEs) were formulated to encapsulate diosgenin (DIO) that demonstrated improving transport efficiency across $CaCo_2$ cells (Guanghui et al., 2023). MEs can facilitate the slow release of urea, which can significantly reduce nitrous oxide (N_2O) emissions from agriculture by 50%. Agriculture is a major contributor to N_2O emissions, accounting for 60% of the total (Hafez and Khalil, 2024). Critically, foliar application of NEs bypasses soil fixation mechanisms, elevating nutrient use efficiency (NUE) from a typical 40% to 85% (Hafez and Khalil, 2024; Mungwari et al., 2025). The mechanism of NE-mediated foliar uptake involves endocytosis and apoplastic transport, with waste-stabilized droplets enhancing adhesion and penetration, especially under drought stress conditions (Ochoa, et al., 2025).

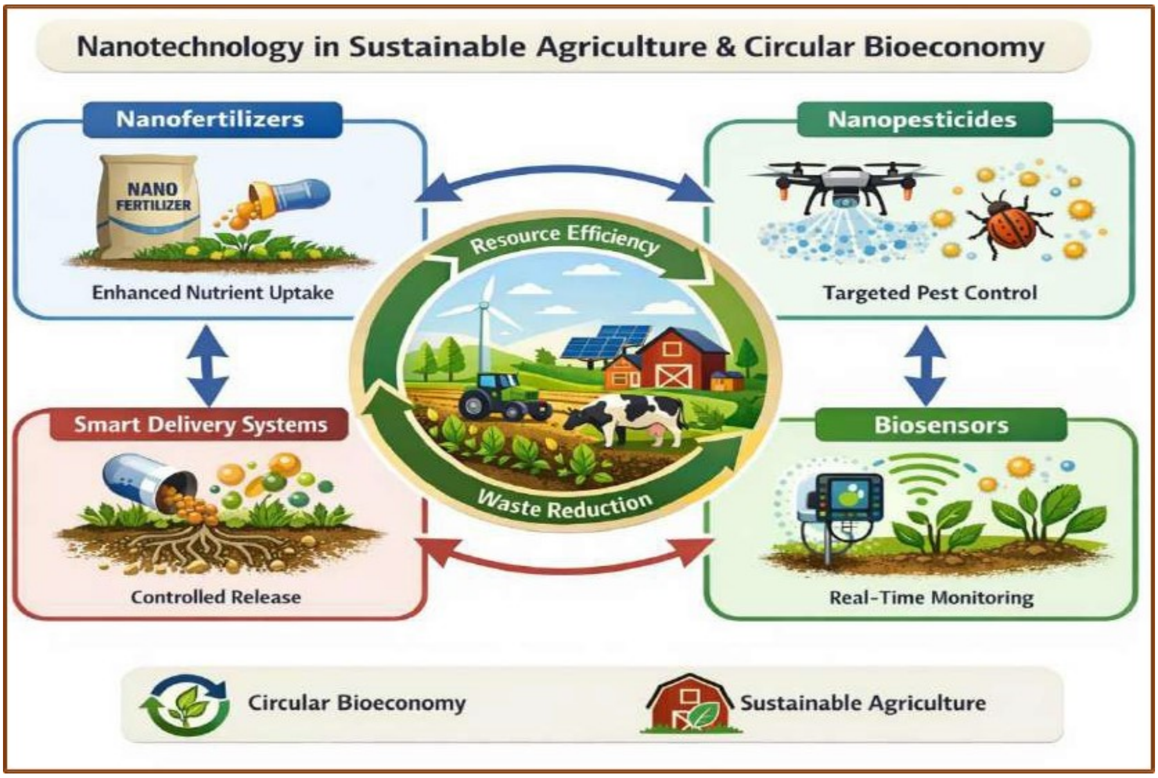

Figure 1: Application of Nanotechnology in Agriculture

The above Figure 1 illustrates the broad applications of nanotechnology in agriculture, encompassing areas such as nanofertilizers, nanopesticides, smart delivery systems, and biosensors, all of which can be contribute to sustainable agriculture (Shah et al., 2024). These applications are central to the vision of a circular bioeconomy where waste is minimized and resources are efficiently utilized. Moreover, the multifaceted role of agri-nanotechnology in optimizing crop protection and production for sustainable agriculture, emphasizing its importance in addressing climate change impacts and ensuring long-lasting crop yields (Singh et al., 2023).

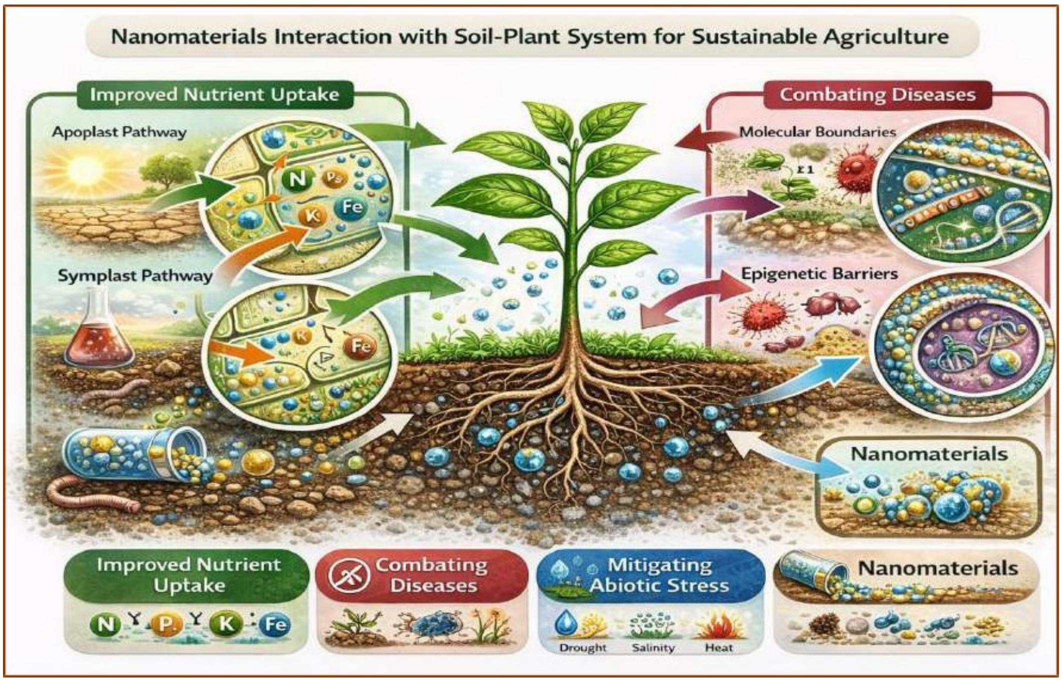

Figure 2: Interactions of Nanomaterials in the Soil-Plant System

The above Figure 2 depicts the complex interactions of nanomaterials within the soil-plant system, highlighting their potential to improve nutrient delivery, combat diseases, and mitigate abiotic stresses. These interactions are fundamental to achieving sustainable agricultural outcomes (Balusamy et al., 2023). Moreover, through a seed priming and soil amendment, to mitigate heavy metal and arsenic-induced oxidative stress in edible crops, thereby supporting food security. This can combat heavy metal and arsenic stress in food crops. This is critical for ensuring food safety and public health, especially in contaminated areas (Rai et al., 2023).

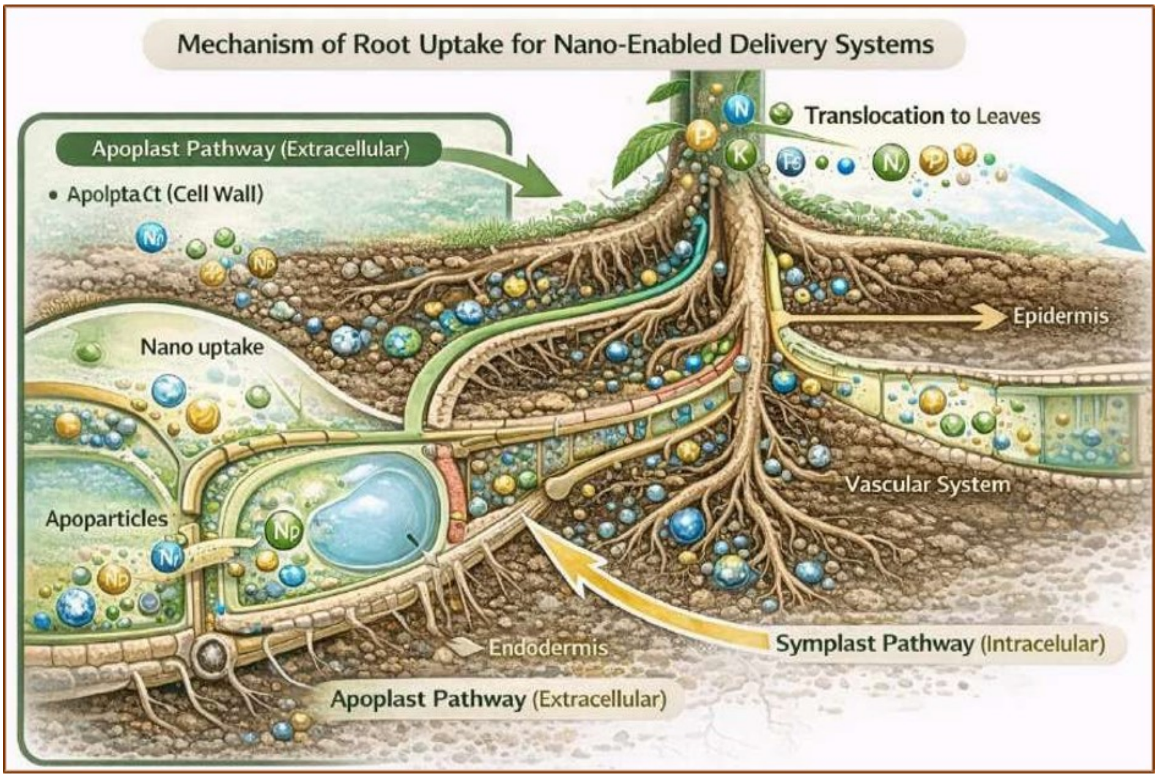

Figure 3: Two important pathways to responsible for nanomaterials transportation in the plant

Also, nanocarriers can facilitate chemical priming in plants, enhancing their tolerance to various stress factors. By the two pathways (Apoplast and Symplast) of nutrient transportation from root to leaves are common to deliver such a nanomaterial or nanocarrier in the entire plant system Figure 3. Understanding these mechanisms is crucial for optimizing nanotechnology applications in agriculture and plant physiology as well as plant molecular biology and biotechnology (Lowry et al., 2024).

5.2. Pest and Disease Management

Essential oil NEs, such as those derived from garlic waste (containing allicin), achieve up to 90% mortality against aphids (Ali et al., 2017). Their efficacy is superior to conventional emulsions, with a 10-fold lower LC_{50} (lethal concentration 50%) due to enhanced cuticular permeation (Gupta et al., 2024; Pandey et al., 2021; He et al., 2023; Ali et al., 2017). ME-based fungicides, like azoxystrobin encapsulated in coffee waste MEs, effectively suppress Fusarium wilt in climate-stressed bananas, reducing the required dosage by 70% (Baldassarre et al., 2023; Zaharioudakis et al., 2023). Environmentally, these biopesticides are advantageous as they typically degrade by 90% within 7 days, thereby averting significant bioaccumulation (Gupta et al., 2024; Mustafa and Hussein, 2020).

5.3. Climate Resilience Engineering

This Figure 4 illustrates various bionanotechnological applications aimed at improving productivity and resilience in agriculture, contributing to climate-smart food production systems (Otari et al., 2024). The delivery of active agents, nutrients, and genetic materials through nanotechnology is a critical advancement for developing climate-resilient crops (Gohari et al., 2024).

Global warming exacerbates environmental stressors such as droughts, floods, and heatwaves, leading to significant yield reductions of 10–25% for every 1°C rise in temperature (Munir et al., 2023). Waste-derived NEs can prime seeds with osmoprotectants, such as trehalose from potato waste, which upregulate aquaporins and Heat Shock Proteins (HSPs) in plants (Munir et al., 2023; Lowry, et al., 2024). This leads to enhanced drought tolerance of up to 35% in crops like wheat. In saline soils, potassium (K^+)-loaded MEs mitigate sodium (Na^+) toxicity in rice, helping to preserve yields in regions affected by sea-level rise (Munir et al., 2023).

5.4. Synergies with Circular Economy and Global Warming Mitigation

Circular agriculture, integrating waste-mediated NEs and MEs, repurposes approximately 95% of agricultural waste into valuable precursors, closing material loops and generating significant economic value, estimated at $100–150 per ton of waste (Xu et al., 2023; Preethi et al., 2024; Xiong et al., 2019). NE-treated fields contribute to soil carbon [sequestration], enhancing it by 15–20% through improved mycorrhizal associations, which could offset 1.2 Gt CO_2 equivalent annually if widely adopted (Saikia et al., 2023). Furthermore, blockchain-tracked

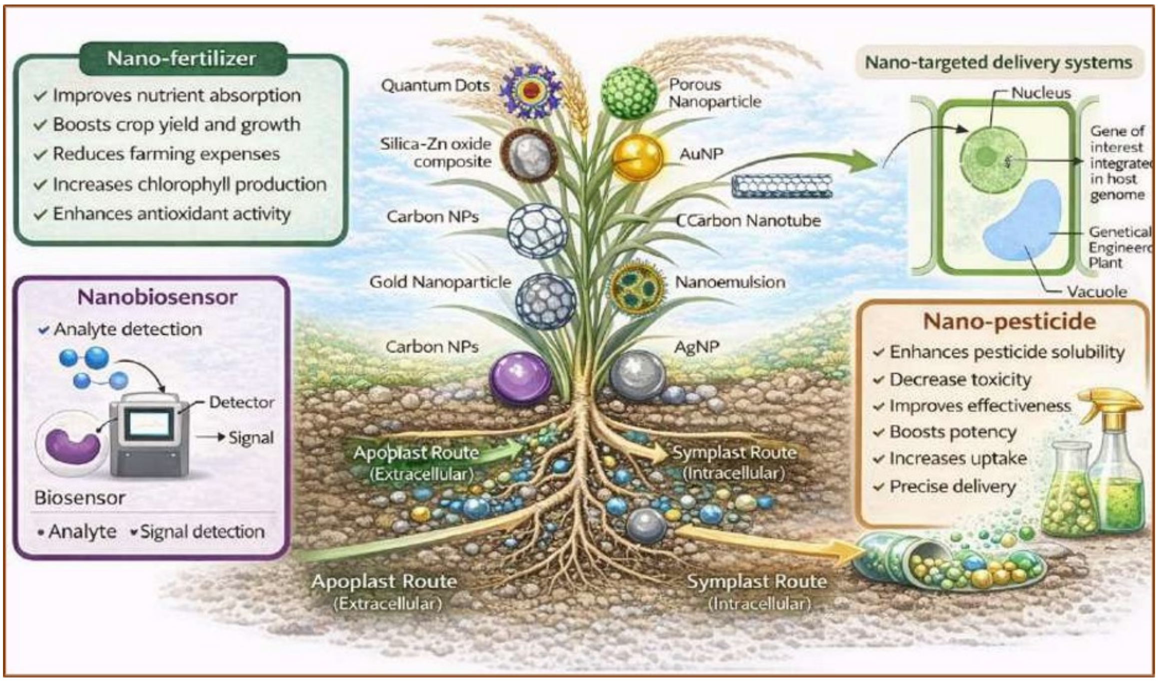

Figure 4: Bionanotechnological Applications for Climate-Smart Agriculture (Revised from Source: Otari et al., 2024)

waste-NE supply chains can ensure transparency and align with United Nations Sustainable Development Goal (SDG) 12, promoting responsible consumption and production (Preethi et al., 2024).

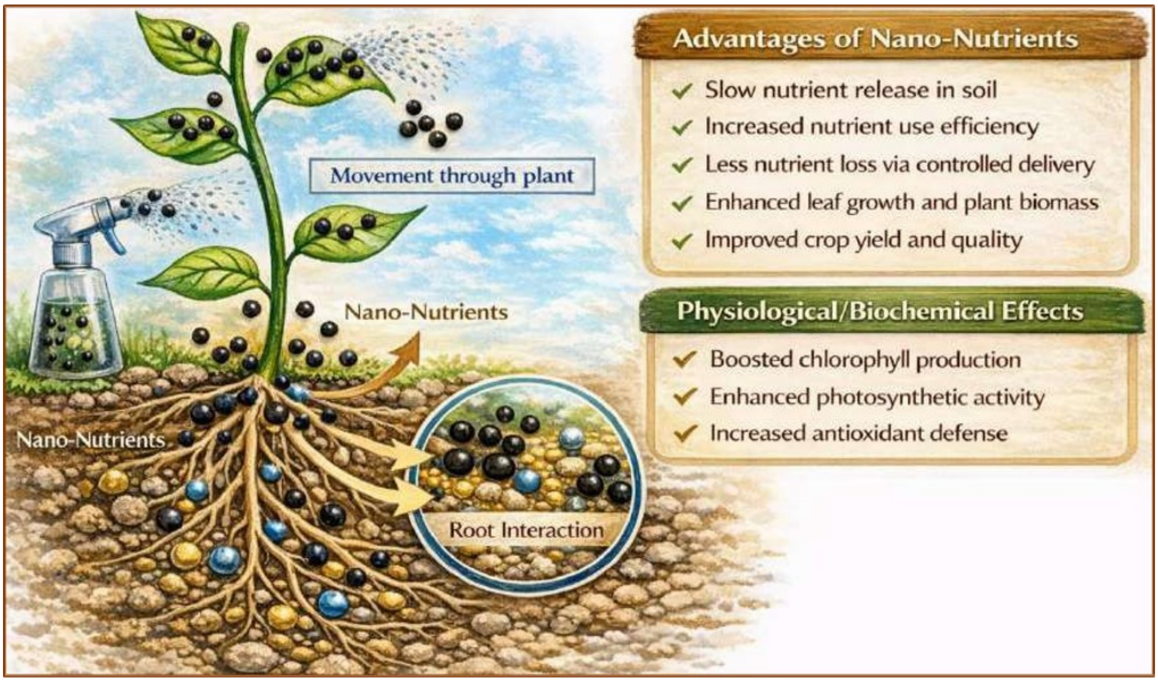

Figure 5: Nanotechnology Interventions for Plant Nutrition and Bio-sensing (Revised from Source: Singh et al., 2024)

The Figure 5 presents an overview of Nanobiotechnology interventions for sustainable plant nutrition and bio-sensing, demonstrating how nanoparticles can optimize nutrient utilization and resource management in farming practices. The application through spray liquid phase of NPs on aerial parts are effectively able to penetrate the plant tissues via stomata. There is direct physiological and metabolic activity influenced by this approach such many important energy dependent and light harvesting system are able to facilitate their role in development of plants. This can be alternatively affected to the yield and yield attributed factors (Singh et al., 2024; Guanghui, et al., 2023).

5.5. Carbon Footprint Analysis

Life cycle assessments demonstrate that waste-NEs have a substantially lower carbon footprint, emitting only nearly 0.2 to 0.5 kg CO_2/kg compared to 5 kg CO_2/kg for synthetic alternatives. This shift also results in an 80% energy saving during production (Preethi et al., 2024; Xiong et al., 2024). Beyond reduced emissions from production, crop resilience fostered by NEs amplifies carbon sinks; for instance, drought-resistant sorghum developed using citrus peel-derived NEs can sequester an additional 3 tons of carbon per hectare per year (Preethi et al., 2024; Xiong et al., 2024; Ur Rahim et al., 2021).

5.6. Tackling Hunger and Hidden Hunger

This Figure 6 presents a conceptual framework for nano-enabled precision delivery in plants, emphasizing the role of nanocarriers in enhancing the resilience of crop agriculture to climate change and promoting sustainability (Lowry et al., 2024). Such systems are vital for future food security.

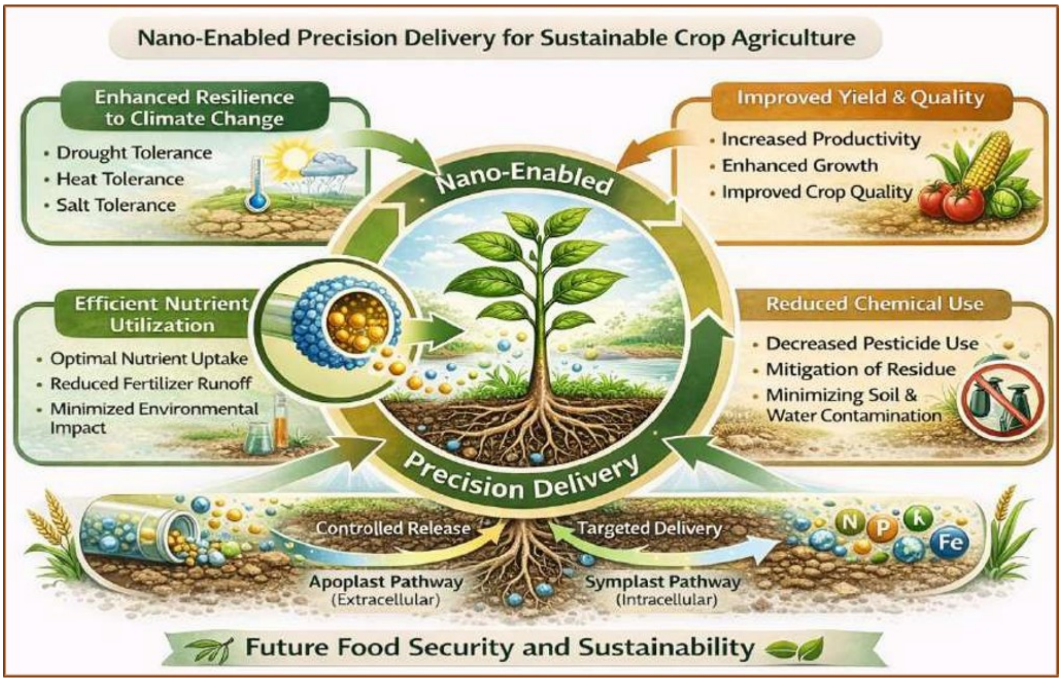

Figure 6: Conceptual Framework of Nanotechnology in Agriculture for food security

The application of NEs and MEs offers significant potential to combat global hunger and hidden hunger. Electrospun nanofibers and nanoemulsions offer distinct advantages for phytochemical delivery in functional foods, with nanofibers excelling in superior encapsulation efficiency and controlled release kinetics for heat-sensitive compounds, particularly under gastrointestinal conditions. Conversely, nanoemulsions are better suited for rapid bioaccessibility of lipophilic phytochemicals, while nanofibers provide enhanced protection against environmental degradation during food processing and storage (Tan et al., 2026; Tong et al., 2015).

5.7. Yield Enhancement

NEs have been shown to boost the yields of staple crops. Maize yields can increase by 25%, and rice yields by 18% under warming scenarios. Scaling this technology to 1 billion hectares globally could potentially yield an additional 300 million tons of grain per year, sufficient to feed an estimated 800 million people (Jiang et al., 2021).

5.8. Biofortification Strategies

Nano-biofortification strategies involve using NEs and MEs to deliver essential micronutrients to crops. Zinc-NEs in wheat can elevate grain zinc content by 50–100 mg/kg, thereby addressing zinc deficiency that affects 17% of the global population. Similarly, iron-protoporphyrin MEs in rice can combat anemia by enhancing iron absorption two-fold. The resolution of hidden hunger through nano-biofortified crops has the potential to avert 1 million child deaths annually (Jiang et al., 2021; Hafez and Khalil, 2024). Some examples of nanobiofotification and its impact on human civilization are compile in Table 2.

Table 2: Some important examples of nanobiofortification

Intervention	Yield Gain (%)	Micronutrient Boost	Hunger Impact (millions affected)	Ref.
Zn-NE Wheat	20-30	Zn +60%	500 (deficiency)	Hafez and Khalil 2024
Fe-ME Rice	15-25	Fe +40%	800 (anemia)	Jiang et al. 2021
Multi-NE Maize	25-35	Zn/Fe/VitA + 50%	300 (hidden hunger)	Jiang et al., 2021

6. Critical Challenges and Regulatory Imperatives

Despite the immense potential, several critical challenges must be addressed for the widespread adoption of waste-mediated NEs and MEs.

The integration of waste-mediated nanoemulsions and microemulsions into agricultural practices to combat hidden hunger faces significant hurdles that demand rigorous scientific attention. A fundamental challenge lies in the thermodynamic instability of many waste-derived emulsions, which hinders their consistent performance in diverse agricultural settings due to the variability in interfacial properties conferred by biosurfactants (Ijaz et al., 2024). The inherent risk of residual contaminants, including heavy metals and persistent organic pollutants, from agro-waste feedstocks present a substantial phytotoxicity concern, often exceeding regulatory limits and lacking robust life-cycle assessment validation for purification processes (Ma et al., 2024; Nawaz et al., 2024).

Furthermore, the prevalent polydispersity (PDI >0.3) in these waste-mediated systems compromises uniform uptake and controlled release kinetics in plants, thereby reducing the efficacy of micronutrient delivery and bioavailability essential for biofortification (Rosa et al., 2025). The enzymatic degradation of biodegradable emulsifiers in soil environments also limits the residence time of these nanocarriers, often falling short of the duration required for optimal nutrient chelation and root absorption (Rosa et al., 2025; Sunaina et al., 2024). Regulatory landscapes are presently insufficient, lacking specific guidelines for ”waste-origin” nanocarriers, which impedes their official recognition and commercial deployment (Ma et al., 2024).

The complex interplay between micronutrients, such as the competitive inhibition of Zn^{2+} and Fe^{3+} at plant transporters, is exacerbated by the uncontrolled release profiles from heterogeneous waste matrices, diminishing their potential for effective biofortification (Tamta et al., 2024). Scaling up production is technically challenging, as high-pressure homogenization of viscous waste streams frequently leads to shear-induced coalescence, which is inconsistent with current population balance models (Ijaz et al., 2024). Moreover, non-target effects, such as the disruption of beneficial soil microbiomes by phenolic compounds in waste surfactants, can negatively impact nutrient cycling and plant growth (Sunaina et al., 2024). Economic viability is often questionable, as the energy expenditure for purifying waste feedstocks can counteract the environmental benefits, potentially leading to a net increase in carbon footprint (Wahab, et al., 2024). Finally, the effectiveness of these systems in addressing hidden hunger is limited by the absence of robust pharmacokinetic-pharmacodynamic modeling, which overlooks critical aspects like intestinal epithelial transporter saturation, thereby reducing systemic bioavailability in humans (Choi and McClements, 2020). These challenges underscore the need for advanced material science, stringent regulatory frameworks, and comprehensive environmental impact assessments to unlock the full potential of waste-mediated nanoemulsions and microemulsions (Kadakia et al., 2017; Nawaz et al., 2024; Chaudhary et al., 2025).

7. Scalability and Stability Hurdles

One significant challenge is maintaining stability during large-scale production and storage. Shear-thinning effects in large-scale ultrasonication can lead to the enlargement of droplets, often exceeding 200 nm, which compromises the efficacy of NEs (Liu et al., 2021; Badawy et al., 2017). This necessitates the development of hybrid low-energy methods or optimized high-energy processes (Cholakova et al., 2022; Koroleva and Yurtov, 2012). Furthermore, storage at elevated temperatures, such as 40°C, can induce Ostwald ripening, a process where larger droplets grow at the expense of smaller ones (McClements, 2012). While phenolics can mitigate this by partitioning at the interface and stabilizing the droplets, long-term stability under diverse environmental conditions remains a research focus (Shawky et al., 2025; Wang and Wu, 2021).

8. Ecotoxicology and Risk Assessment

The environmental impact of NEs, particularly concerning non-target organisms and potential long-term effects, requires rigorous evaluation (Xiong et al., 2024; Chidiamassamba et al., 2024). NEs can exhibit dose-dependent phytotoxicity, with an EC_{50} (effective concentration 50%) of 100 mg/L observed for non-target algae (Xiong et al., 2024). Earthworm bioassays for waste-derived NEs generally show an LC_{50} (lethal concentration 50%) greater than 1000 mg/kg, indicating relatively low acute toxicity to these organisms. However, thorough scrutiny of long-term trophic transfer and potential accumulation in ecosystems is essential (Xiong et al., 2024; Ale et al., 2024). Regulatory frameworks analogous to the European Union’s REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) for nanoproducts are still nascent and require development to ensure safe implementation (Xiong et al., 2024; Rasmussen et al., 2023; Sreeja et al., 2025).

9. Future Trajectories and Innovations

The future of waste-mediated NEs and MEs in agriculture is expected to be marked by advanced technological integrations and collaborative efforts. Artificial Intelligence (AI) optimized PIT modeling can predict stability under various climate change scenarios, such as those projected by the Intergovernmental Panel on Climate Change (IPCC) RCP8.5 (Liu et al., 2021). Innovations such as CRISPR-NE hybrids hold promise for editing plant stress genes, potentially leading to 50% gains in resilience against adverse environmental conditions (Jiang et al., 2021). The establishment of global consortia for standardized waste-NE protocols is crucial to facilitate widespread adoption and ensure consistent product quality and safety (Preethi et al., 2024). The phased deployment roadmap from pilot farms to achieving 1 Gt CO_2 abatement signifies a long-term vision for the transformative impact of these technologies on global agriculture and climate mitigation (Liu et al., 2021; Preethi et al., 2024).

10. Conclusion

The application of nanoemulsion and microemulsion technologies derived from agricultural and food waste offers a holistic and sustainable pathway to address interwoven global challenges. These nano-enabled strategies promise to enhance crop resilience against climate change impacts, improve food safety and nutritional quality to combat hidden hunger, and reduce environmental pollution by valorizing waste materials. The integration of these advanced nanotechnological approaches is critical for revolutionizing agricultural practices and building a more secure, sustainable, and resilient global food system. The waste-mediated NEs and MEs represent a significant advancement in circular agriculture, offering a powerful toolkit to develop climate-resistant crops, enhance food security, and alleviate hunger. Rigorous interdisciplinary validation, addressing scalability, stability, and ecotoxicological concerns, is paramount to fully unlock their immense potential.

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