



## Seed encapsulation using phytoextracts and pheromones: A synergistic approach for sustainable agriculture

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### Abstract

Seed encapsulation technology has emerged as a transformative approach in modern agriculture, offering targeted delivery of bioactive compounds to enhance crop performance while minimizing environmental impact. This comprehensive review examines the convergence of two promising avenues in seed encapsulation: phytoextracts derived from medicinal and allelopathic plants, and pheromone-based signaling compounds for pest management. We synthesize current knowledge on encapsulation matrices, application methodologies, and the physiological mechanisms through which these natural compounds influence seed germination, seedling vigor, and plant defense responses. The review explores the ecological rationale for combining phytoextracts with pheromones, drawing parallels with natural plant-insect communication systems where chemical signaling mediates host finding and colonization. We evaluate various encapsulation technologies including film coating, pelleting, and nano-encapsulation, assessing their suitability for delivering phytoextracts and pheromones with controlled release profiles. Case studies demonstrate the potential of this integrated approach for enhancing crop establishment, managing insect pests, and reducing reliance on synthetic agrochemicals. Challenges including formulation stability, regulatory considerations, and economic viability are critically examined. Finally, we identify research priorities and future directions for translating laboratory findings into field-ready applications that contribute to sustainable intensification of agriculture.

**Keywords:** Seed coating, biostimulants, semiochemicals, sustainable agriculture, controlled release, plant defense, integrated pest management

### Introduction

#### The Imperative for Sustainable Seed Technologies

Global agriculture faces the dual challenge of increasing food production to meet the demands of a growing population while simultaneously reducing environmental impacts associated with conventional farming practices (Tilman *et al.*, 2011; Foley *et al.*, 2011). Synthetic agrochemicals—including pesticides, fertilizers, and growth regulators—have contributed substantially to yield gains but have also imposed significant ecological costs, including soil degradation, water contamination, biodiversity loss, and negative effects on non-target organisms (Pimentel and Burgess, 2014; Carvalho, 2017)<sup>[14]</sup>. The pursuit of sustainable agricultural systems has therefore ignited a quest for innovative approaches that enhance crop productivity while ensuring ecological equilibrium (Godfray *et al.*, 2010; Pretty and Bharucha, 2014). Seeds represent a critical intervention point in crop management. The transition from seed to seedling is among the most vulnerable stages in the plant life cycle, determining not only initial establishment but also ultimate yield potential (Finch-Savage and Bassel, 2016). Environmental stresses during germination and early seedling growth can have carry-over effects that persist throughout the crop's development (Huss and Gierlinger, 2021). Consequently, technologies that protect seeds and enhance their performance offer high leverage for improving agricultural outcomes with minimal material inputs.

#### Seed Encapsulation: Principles and Potential

Seed encapsulation—the application of exogenous materials to form a protective layer around seeds—has evolved

substantially from simple seed dressing practices to sophisticated delivery systems capable of incorporating multiple functional ingredients (Afzal *et al.*, 2020)<sup>[2]</sup>. Modern seed coating technologies enable the uniform application of bioactive compounds at precise dosages, facilitating sowing operations and enhancing crop performance (Pedrini *et al.*, 2017). The weight increase associated with different coating methods ranges from minimal film coatings (2-5% weight increase) to substantial pelletization that can multiply seed weight by factors of 100 or more (Taylor *et al.*, 2021), offering flexibility for different crop types and application contexts. The core components of seed coating formulations include active ingredients (such as pesticides, nutrients, biostimulants, or beneficial microorganisms) and inactive ingredients (including film-forming agents, adhesives, fillers, and other adjuvants) (Gao *et al.*, 2025). Film-forming capability is a distinctive feature that determines both the mechanical integrity of the coating and its capacity for controlled release of active compounds (Accinelli *et al.*, 2019)<sup>[1]</sup>. Recent advances in materials science have expanded the repertoire of available coating materials, including biodegradable polymers, hydrogels, and nanomaterials that can be tailored for specific release profiles (Mahra *et al.*, 2025).

#### Phytoextracts and Pheromones: Nature's Solutions

Among the diverse active ingredients being explored for seed encapsulation, two categories stand out for their alignment with sustainable agriculture principles: phytoextracts (plant-derived extracts containing bioactive secondary metabolites) and pheromones (chemical signals used for intraspecific communication). Both represent

nature's own solutions to challenges of plant protection and communication, offering the potential to work with rather than against ecological processes. Phytoextracts have garnered increasing attention as biostimulants—substances that enhance plant growth and development regardless of their nutrient content (du Jardin, 2015) [22]. Plants are biofactories of biologically diverse active compounds, including polyphenols, flavonoids, phytohormones, terpenes, and other secondary metabolites with multiple functions including adaptation and signaling (Wink, 2015). The biostimulant activity of plant extracts is attributed primarily to these compounds, which can influence physiological processes at multiple levels from seed germination to stress tolerance (Sharma *et al.*, 2014). Pheromones, particularly aggregation pheromones used by many insect species to coordinate colonization of host plants, offer an entirely different mechanism for influencing plant-insect interactions (Wertheim *et al.*, 2005). By manipulating these chemical signals, it may be possible to disrupt pest aggregation, enhance the effectiveness of biological control agents, or influence herbivore behavior in ways that benefit crop plants. The close connection between insect pheromone production and host plant chemistry (Stanton *et al.*, 2016) suggests intriguing possibilities for integrated approaches that combine plant-derived compounds with insect-derived signals.

## Phytoextracts as Seed Treatment Agents

### 1. Diversity of Bioactive Compounds in Plant Extracts

Plants produce an extraordinary diversity of secondary metabolites—compounds that are not directly involved in primary metabolic processes but serve ecological functions including defense against herbivores and pathogens, attraction of pollinators and seed dispersers, and mediation of competitive interactions with other plants (Hartmann, 2007; Wink, 2015). Many of these compounds exhibit biological activity when applied exogenously to other plant species, forming the basis for their use as biostimulants and bioprotectants. Phenolic compounds represent one of the most extensively studied classes of bioactive metabolites in the context of seed treatment. These compounds exhibit potent antioxidant activity, scavenging reactive oxygen species (ROS) that accumulate under stress conditions and can damage cellular structures (Agati *et al.*, 2012) [3]. The biostimulatory effects of phenolic compounds are attributed to their capacity to mitigate the effects of stress factors and activate antioxidant defense mechanisms (Sharma *et al.*, 2019). For example, extracts from *Polygonum aviculare*—a widespread ruderal plant with documented medicinal properties—contain significant quantities of flavonoids including avicularin, hyperoside, quercitrin, and aglycones of quercetin, kaempferol, and myricetin (Metwally *et al.*, 2024). Seaweeds and other marine algae have emerged as particularly promising sources of bioactive compounds for seed treatment (Khan *et al.*, 2009; Battacharyya *et al.*, 2015) [10]. Algal extracts contain a complex mixture of growth hormones (including cytokinins, auxins, and gibberellin-like compounds), polysaccharides, betaines, and macro- and micronutrients (Craigie, 2011) [18]. The aqueous extract of *Ulva lactuca*, for example, has been shown to contain glycine betaine and various phenolic compounds that contribute to its biostimulant activity (El-Naggar *et al.*, 2023) [23]. These compounds can enhance seed germination and plant growth under both optimal and stress conditions,

with particular efficacy in mitigating salinity stress (Hernández-Herrera *et al.*, 2016). Fruit peels and other agricultural by-products represent an economically attractive and environmentally beneficial source of bioactive compounds (Mickky *et al.*, 2025). Orange peel extract (OPE) has been characterized as rich in phenols, ascorbic acid, reducing sugars, flavonoids, carotenoids, and proteins (Mickky *et al.*, 2025). The reducing power and antioxidant activity of such extracts make them suitable not only as direct biostimulants but also as reducing and stabilizing agents for the green synthesis of nanoparticles (Ahmed *et al.*, 2016) [4]. This dual functionality opens possibilities for integrated approaches combining phytoextracts with nanotechnology.

### 2. Mechanisms of Action: From Seed to Seedling

The application of phytoextracts to seeds can influence plant performance through multiple mechanisms operating at different stages of development. Understanding these mechanisms is essential for optimizing formulation and application protocols.

#### 2.1 Germination Enhancement

Seed germination is a critical developmental phase that determines the success of crop establishment (Bewley *et al.*, 2013) [11]. The process involves imbibition (water uptake), activation of metabolic processes, radicle protrusion, and subsequent seedling growth. Phytoextracts can influence each of these stages through various mechanisms. The presence of osmotically active compounds in phytoextracts can modulate water uptake kinetics, potentially improving imbibition rates and uniformity (Bradford, 1995) [12]. More importantly, bioactive compounds in extracts can directly stimulate metabolic processes in the embryo. Gibberellins and gibberellin-like compounds present in seaweed extracts, for example, can activate hydrolytic enzymes that mobilize stored reserves in the endosperm or cotyledons, providing energy and building blocks for the growing embryo (Rayorath *et al.*, 2008). Phenolic compounds and other antioxidants can protect germinating seeds from oxidative damage associated with the burst of metabolic activity following imbibition (Bailly, 2004) [7]. Reactive oxygen species are produced during normal germination but can accumulate to damaging levels under stress conditions. By scavenging these ROS, phytoextracts can maintain cellular integrity and support vigorous germination even under suboptimal conditions. Dose-response relationships are a critical consideration in phytoextract application. Studies with *Moringa oleifera* leaf extract on bambara groundnut demonstrated that the optimal concentration (2.5% extract) produced the highest final germination (84.7% compared to 43.7% in untreated controls, a 94% increase), while higher concentrations (10% extract) inhibited performance (Ndlovu *et al.*, 2025). This pattern—hormesis or dose-dependent biphasic response—appears characteristic of many bioactive natural products and underscores the importance of careful optimization for each crop-extract combination.

#### 2.2 Seedling Vigor and Establishment

The benefits of phytoextract seed treatment extend beyond germination to subsequent seedling growth and establishment. Enhanced root and shoot development has been documented for multiple crop species treated with various phytoextracts (Mickky *et al.*, 2025; El-Naggar *et al.*, 2023) [23]. For flax seeds primed with orange peel extract,

improvements were observed in seedling length, fresh and dry mass accumulation, and seedling vigor index (Mickky *et al.*, 2025). These effects were associated with enhanced photosynthetic efficiency, including improved chloroplast ultrastructure, increased pigment content, and greater photosystem II activity (Mickky *et al.*, 2025). The mechanisms underlying improved seedling growth include enhanced nutrient mobilization, modulation of hormone balances, and activation of growth-related gene expression. Phytoextracts containing auxin-like compounds can stimulate cell division and elongation in root and shoot meristems (Stirk *et al.*, 2014). Cytokinins present in some extracts promote shoot growth and delay senescence, while gibberellins support stem elongation and leaf expansion (Wally *et al.*, 2013).

### 3. Synergistic Combinations: Phytoextracts with Beneficial Microorganisms

Emerging evidence suggests that combinations of phytoextracts with beneficial microorganisms can produce synergistic effects exceeding those of either component alone (Metwally *et al.*, 2024). Studies on *Melilotus officinalis* seed treatment with *Polygonum aviculare* extracts and *Pseudomonas fluorescens* bacteria demonstrated that mixtures of the plant infusion with bacterial culture produced the highest germination rates and seedling growth parameters (Metwally *et al.*, 2024). The fusion of extracts with bacteria appears to elicit greater stimulating potential than either treatment alone (Metwally *et al.*, 2024). The mechanisms underlying such synergies are likely multifaceted. Plant extracts may provide nutrients or signaling compounds that support the establishment and activity of beneficial microorganisms in the spermosphere and rhizosphere (Bashan *et al.*, 2014)<sup>[9]</sup>. Conversely, microorganisms may metabolize compounds in plant extracts, converting them to more biologically active forms or producing secondary metabolites that complement those present in the extract (Compant *et al.*, 2019)<sup>[16]</sup>. Beneficial bacteria including *Pseudomonas* and *Bacillus* species can improve plant development by increasing root growth and protecting plants from abiotic stresses (Lugtenberg and Kamilova, 2009). These findings suggest important possibilities for integrated seed treatment formulations that combine phytoextracts with microbial inoculants. Such approaches align with the principles of ecological intensification, harnessing multiple biological mechanisms to support crop performance.

## Pheromones in Plant-Insect Interactions: Implications for Seed Encapsulation

### 1. Chemical Ecology of Seed-Feeding Insects

Understanding the chemical ecology of seed-feeding insects provides essential foundation for developing pheromone-based approaches to pest management. Seed predators and florivores face unique challenges compared to folivores: the tissues they consume are ephemeral, requiring synchronization of colonization with host plant phenology (Crawley, 2000)<sup>[19]</sup>. This temporal constraint has driven the evolution of sophisticated chemical communication systems that enable insects to locate suitable hosts and coordinate colonization events (Vet and Dicke, 1992). Aggregation pheromones—chemical signals that attract conspecifics of both sexes or of the same sex as the emitter—play crucial roles in the ecology of many seed-feeding insects

(Wertheim *et al.*, 2005). These signals enable pioneering individuals to recruit conspecifics to host plants, facilitating mate finding, overcoming host defenses, and optimizing resource utilization (Raffa *et al.*, 2015). The benefits of aggregation must be balanced against costs including increased competition and enhanced apparency to natural enemies, creating selective pressures that shape pheromone chemistry and release patterns (Wertheim *et al.*, 2005). The study of *Corimelaena extensa*, a hemipteran seed feeder attacking wild tobacco species (*Nicotiana* spp.), revealed a novel aggregation pheromone—(5Z,8Z)-tetradeca-5,8-dienal—that mediates colonization of host plants (Stanton *et al.*, 2016). Male bugs release this pheromone, stimulating formation of feeding aggregations on the post-fire annual *Nicotiana attenuata* (Stanton *et al.*, 2016). Notably, pheromone emission was 40-fold higher when insects fed on *N. attenuata* compared to the sympatric perennial *N. obtusifolia*, demonstrating profound plant-mediated variation in insect signaling (Stanton *et al.*, 2016).

### 2. Plant-Mediated Variation in Pheromone Signaling

The close connection between insect pheromone production and host plant chemistry represents a critical interface for potential intervention. Host plants can influence insect pheromone emission through multiple mechanisms: provision of biosynthetic precursors, modulation of insect physiology, and synergistic interactions with plant volatiles (Landolt and Phillips, 1997; Reddy and Guerrero, 2004). For *C. extensa* feeding on *Nicotiana* species, adult fecundity and seed capsule content were higher on *N. attenuata*, which also supported 40-fold higher pheromone emission (Stanton *et al.*, 2016). The putative biosynthetic precursor linoleic acid was more abundant in seed capsules of this host, suggesting that precursor availability may constrain pheromone production (Stanton *et al.*, 2016). Higher pheromone emission increased the apparency and colonization of the ephemeral but high-quality host, facilitating migration of seed feeders between plant patches (Stanton *et al.*, 2016). These findings have important implications for seed encapsulation strategies. If pheromone production by pest insects depends on specific host plant compounds, manipulating availability of those compounds—or providing competitive inhibitors—could disrupt aggregation behavior and reduce crop colonization (Reddy and Guerrero, 2004). Conversely, understanding the chemical signals that mediate host finding could enable development of attract-and-kill or push-pull strategies that leverage pheromones to manage pest populations (Cook *et al.*, 2007)<sup>[17]</sup>.

### 3. Pheromone Encapsulation: Opportunities and Challenges

Encapsulation of pheromones for agricultural applications presents both opportunities and technical challenges distinct from those associated with phytoextracts. Pheromones are typically volatile organic compounds that must be released at controlled rates to achieve desired behavioral effects (Heuskin *et al.*, 2011). Release that is too rapid depletes the formulation quickly and may cause habituation; release that is too slow fails to create effective concentrations in the crop environment (Stelinski *et al.*, 2014). Seed encapsulation offers a potential delivery mechanism for pheromones that differs fundamentally from conventional dispensers (e.g., rubber septa, polyethylene vials). Seeds are

distributed throughout the crop environment at planting, potentially creating a uniform "background" of pheromone emission from the soil surface or emerging seedlings (Gao *et al.*, 2025). This spatial distribution could be advantageous for certain applications, such as disruption of host finding by soil-dwelling stages or emerging adults. However, several challenges must be addressed. Pheromones must be protected from degradation during seed storage and after planting (Heuskin *et al.*, 2011). The formulation must provide release rates appropriate for the target species and behavioral context (Stelinski *et al.*, 2014). The presence of germinating seeds and developing seedlings must not interfere with pheromone release or perception. And the pheromone formulation must not adversely affect seed germination or seedling establishment (Gao *et al.*, 2025).

#### 4. Integrating Pheromones with Phytoextracts

The integration of pheromones with phytoextracts in seed encapsulation formulations represents a frontier with substantial but largely unexplored potential. Several lines of reasoning suggest that such combinations could yield synergistic benefits. First, phytoextracts and pheromones target different aspects of the plant-pest interaction. Phytoextracts primarily influence plant physiology, enhancing growth, vigor, and stress tolerance (du Jardin, 2015)<sup>[22]</sup>. Pheromones influence insect behavior, potentially reducing pest pressure on the developing crop (Wertheim *et al.*, 2005). Combining these mechanisms could provide more comprehensive protection than either alone. Second, as demonstrated in the *C. extensa*-*Nicotiana* system, plant chemistry directly influences insect pheromone production and emission (Stanton *et al.*, 2016). By modulating the availability of pheromone precursors or synergists through seed treatment, it might be possible to influence pest behavior indirectly. For example, seed treatment with linoleic acid-rich extracts could potentially enhance pheromone production by beneficial insects or disrupt communication in pests through altered signal ratios. Third, some phytoextracts contain volatile compounds that may interact with pheromones at the level of insect perception. Synergistic interactions between plant volatiles and aggregation pheromones have been documented for several insect groups (Landolt and Phillips, 1997; Reddy and Guerrero, 2004). Co-formulation of pheromones with appropriate plant-derived synergists could enhance their effectiveness while reducing the quantity of pheromone required. Fourth, encapsulation matrices developed for phytoextract delivery may be adaptable for pheromone incorporation. Biopolymer-based formulations that provide controlled release of polar compounds (phytoextract constituents) might be modified to accommodate lipophilic pheromones through emulsion or multilayer approaches (Mahra *et al.*, 2025).

### Encapsulation Technologies for Seed Applications

#### 1. Classification of Seed Coating Technologies

Seed coating technologies can be classified based on the equipment used, the amount of material applied, and the physical characteristics of the final coated product. Understanding this classification is essential for selecting appropriate methods for different active ingredients and application contexts.

##### 1.1 Based on Application Equipment

Three principal types of equipment are used for seed treatment and coating: dry powder applicators, rotary drums

(pans), and fluidized bed coaters (Afzal *et al.*, 2020)<sup>[2]</sup>. Dry powder applicators are the simplest technology, typically used for applying fungicides or microbial inoculants as dusts or powders (Halmer, 2008). While inexpensive and rapid, these systems provide limited uniformity and adhesion of coating materials. Rotary drum coaters are the most widely used equipment for commercial seed coating (Taylor *et al.*, 2021). Seeds are placed in a rotating drum, and liquid or powdered coating materials are applied while the seeds tumble. The tumbling action ensures coverage of seed surfaces, and subsequent drying fixes the coating. Rotary coaters can accommodate a wide range of seed sizes and coating formulations. Fluidized bed coaters suspend seeds in an air stream while coating material is sprayed onto them (Afzal *et al.*, 2020)<sup>[2]</sup>. This technology provides excellent coating uniformity and is particularly suitable for heat-sensitive materials because drying occurs rapidly at moderate temperatures. However, fluidized bed coating is more expensive and slower than rotary drum coating, limiting its application primarily to high-value seeds.

### 2. Materials for Seed Encapsulation

#### 2.1 Film-Forming Agents and Polymers

Film-forming agents are essential components of seed coating formulations, providing the matrix that holds active ingredients on the seed surface and controls their release (Accinelli *et al.*, 2019)<sup>[1]</sup>. Ideal film formers should form continuous, adherent films that remain intact during seed handling and storage but permit water uptake and gas exchange during germination. Synthetic polymers including polyvinyl alcohol, polyvinylpyrrolidone, and various acrylic copolymers have been widely used in seed coating formulations (Gao *et al.*, 2025). These materials offer consistent properties and can be tailored for specific release profiles. However, concerns about biodegradability and environmental persistence have stimulated interest in biopolymer alternatives. Biopolymers derived from renewable sources are increasingly favored for sustainable seed coating applications (Accinelli *et al.*, 2019)<sup>[1]</sup>. Cross-linked chitosan—a polysaccharide derived from chitin—has been investigated as a film-forming agent with additional antimicrobial properties (Zeng *et al.*, 2012). Alginates extracted from seaweeds form hydrogels in the presence of calcium ions and can provide controlled release of incorporated compounds (Ma *et al.*, 2020). Cellulose derivatives including methylcellulose and carboxymethylcellulose are widely used as film formers and adhesives (Gao *et al.*, 2025). Starch and modified starches offer low-cost, biodegradable options for seed coating, though their film properties may require blending with other polymers (Accinelli *et al.*, 2019)<sup>[1]</sup>. Polyhydroxyalkanoates produced by microbial fermentation represent emerging bioplastic options with good film-forming properties and complete biodegradability (Accinelli *et al.*, 2019)<sup>[1]</sup>.

#### 2.2 Fillers and Modifiers

For encrustment and pelleting applications, fillers constitute the bulk of coating material (Pedrini *et al.*, 2017). Common fillers include clays (kaolin, bentonite, attapulgite), diatomaceous earth, talc, limestone, and various organic materials (Taylor *et al.*, 2021). The choice of filler affects mechanical properties of the coating, water uptake kinetics, and compatibility with active ingredients. Plasticizers are often added to film-forming formulations to improve flexibility and prevent cracking (Gao *et al.*, 2025). Common

plasticizers include polyethylene glycol, glycerol, and various sugars. Dispersants and surfactants ensure uniform distribution of active ingredients in coating suspensions and improve wetting of seed surfaces (Afzal *et al.*, 2020)<sup>[2]</sup>.

### 3. Nano-Encapsulation Approaches

Nanotechnology offers new possibilities for seed encapsulation, enabling controlled release at molecular scales and enhanced delivery of bioactive compounds (Mahra *et al.*, 2025). Nanoencapsulation involves incorporation of active ingredients into carriers with at least one dimension in the nanometer range (1-100 nm).

#### 3.1 Types of Nanocarriers

Several classes of nanocarriers have been investigated for agricultural applications (Kashyap *et al.*, 2015; Mahra *et al.*, 2025): Polymeric nanoparticles are solid colloidal particles prepared from biodegradable polymers, with active ingredients encapsulated within the polymer matrix or adsorbed on the surface (Kashyap *et al.*, 2015). These systems can provide sustained release over periods ranging from days to months depending on polymer properties and particle characteristics. Lipid-based nanocarriers including liposomes (phospholipid bilayers enclosing an aqueous core), solid lipid nanoparticles, and nanostructured lipid carriers offer excellent biocompatibility and capacity for both hydrophilic and lipophilic compounds (Rustichelli *et al.*, 2023). Inorganic nanoparticles including silica, metal oxides, and metallic nanoparticles can serve as carriers for active ingredients or have intrinsic biological activities (Mahra *et al.*, 2025). Biogenic synthesis of nanoparticles using plant extracts offers a green chemistry approach that aligns with sustainable agriculture principles (Ahmed *et al.*, 2016)<sup>[4]</sup>. Cyclodextrins and other molecular cages can form inclusion complexes with volatile compounds including pheromones, protecting them from degradation and modulating release rates (Marques, 2010).

#### 3.2 Green Synthesis Using Phytoextracts

A particularly elegant integration of phytoextracts with nanotechnology involves using plant extracts as reducing and stabilizing agents for nanoparticle synthesis (Mickky *et al.*, 2025). Orange peel extract, for example, has been used for the green synthesis of silver nanoparticles, with the phytochemicals in the extract serving both as reductants (converting  $Ag^+$  to  $Ag^0$ ) and as capping agents that stabilize the resulting nanoparticles (Mickky *et al.*, 2025). Characterization of biogenic silver nanoparticles synthesized with orange peel extract revealed spherical particles with average size of 33 nm and zeta potential of -17.8 mV, indicating good colloidal stability (Mickky *et al.*, 2025). These nanoparticles retained biological activity and could be used for seed priming applications (Mickky *et al.*, 2025). The green synthesis approach offers multiple advantages: it avoids toxic chemicals used in conventional nanoparticle synthesis, utilizes agricultural byproducts, and produces nanoparticles with surface coatings of bioactive phytochemicals that may contribute to biological effects (Ahmed *et al.*, 2016)<sup>[4]</sup>.

### 4. Suitability for Phytoextract and Pheromone Delivery

The selection of encapsulation technologies for phytoextract and pheromone delivery must consider the distinctive properties of these active ingredients. Phytoextracts are

typically complex mixtures of polar compounds with varying stability. Aqueous-based processing is generally compatible with these materials, and many coating technologies can accommodate water-based formulations (Afzal *et al.*, 2020)<sup>[2]</sup>. The primary challenges are maintaining extract stability during processing and storage, and ensuring that bioactive compounds are released at appropriate times during germination and seedling development. Pheromones present greater formulation challenges due to their volatility and typically lipophilic nature (Heuskin *et al.*, 2011). Encapsulation systems must provide a barrier to diffusion during storage while permitting controlled release after seed planting (Stelinski *et al.*, 2014). Nano-encapsulation approaches may be particularly valuable for pheromones, enabling protection of volatile compounds within carrier matrices (Rustichelli *et al.*, 2023).

### Integrated Approaches: Combining Phytoextracts and Pheromones

#### 1. Conceptual Framework for Integration

The integration of phytoextracts and pheromones in seed encapsulation can be conceptualized within a multi-trophic framework that considers interactions among plants, herbivores, natural enemies, and beneficial microorganisms (Dicke and Baldwin, 2010)<sup>[21]</sup>. Phytoextracts primarily target the plant itself, enhancing its physiological capacity for growth and defense. Pheromones target insect behavior, potentially reducing herbivore pressure directly or enhancing biological control through natural enemy attraction (Wertheim *et al.*, 2005). The potential synergies between these approaches operate at multiple levels. Enhanced plant vigor from phytoextract treatment may improve the plant's capacity to produce defense compounds or to tolerate herbivore damage that does occur (Kessler and Baldwin, 2002). Pheromone-mediated disruption of pest aggregation may reduce the likelihood of overwhelming plant defenses, as occurs when bark beetles coordinate mass attacks on conifers (Raffa *et al.*, 2015). Recruitment of natural enemies by pheromones or herbivore-induced plant volatiles could provide biological control services that complement direct effects on pest behavior (Turlings and Erb, 2018).

#### 2. Case Study: Wild Tobacco and Seed-Feeding Bugs

The system comprising *Nicotiana attenuata* and its seed-feeding herbivore *Corimelaena extensa* provides a natural model for understanding how plant chemistry and insect pheromones interact, with implications for seed encapsulation strategies (Stanton *et al.*, 2016). *N. attenuata* is a post-fire annual that germinates from long-lived seed banks after wildfires, growing rapidly in the nitrogen-rich post-fire environment (Baldwin, 2001)<sup>[8]</sup>. Its seeds are fed upon by *C. extensa*, which aggregate on plants in response to male-produced pheromone. The pheromone—(5Z,8Z)-tetradeca-5,8-dienal—is produced at much higher levels when insects feed on *N. attenuata* compared to the sympatric perennial *N. obtusifolia* (Stanton *et al.*, 2016). Seed capsule analysis revealed higher linoleic acid content in *N. attenuata*, suggesting that this fatty acid serves as pheromone precursor (Stanton *et al.*, 2016). Higher pheromone emission increases the apparency of this ephemeral but high-quality host, facilitating colonization by migrating seed feeders (Stanton *et al.*, 2016). For seed

encapsulation applications, this system suggests several intervention points. Seed treatment with linoleic acid-rich phytoextracts could potentially enhance pheromone production by beneficial insects or, conversely, disrupt communication if combined with pheromone analogs. Coencapsulation of pheromone with plant-derived synergists could enhance attraction to trap crops or monitoring stations. Understanding the chemical ecology of this interaction provides the foundation for rational design of semiochemical-based management strategies.

### 3. Seaweed Extracts for Salinity Tolerance

The use of *Ulva lactuca* extract for priming *Citrullus lanatus* seeds demonstrates the potential of phytoextracts to enhance crop performance under abiotic stress (El-Naggar *et al.*, 2023) [23]. Seed priming with 8% *U. lactuca* extract maximized germination percentage and seedling growth under both control and saline conditions (El-Naggar *et al.*, 2023) [23]. The extract counteracted negative effects of salt stress by significantly increasing activity of antioxidant enzymes (SOD, CAT, POD) and maintaining photosynthetic pigment content (El-Naggar *et al.*, 2023) [23]. Phytochemical analysis of *U. lactuca* revealed the presence of glycine betaine and various phenolic compounds that likely account for its biostimulant activity (El-Naggar *et al.*, 2023) [23]. Glycine betaine functions as an osmoprotectant, stabilizing protein structure and maintaining membrane integrity under osmotic stress (Chen and Murata, 2011) [15]. Phenolic compounds contribute to antioxidant defense and may also have signaling functions that activate stress-responsive genes (Sharma *et al.*, 2019). This case study illustrates how phytoextracts can enhance stress tolerance through multiple mechanisms operating at physiological and biochemical levels. Integration of such extracts with pheromone-based approaches could provide comprehensive protection encompassing both abiotic and biotic stress factors.

### 4. Nanoprimering with Orange Peel Extract

The use of orange peel extract for both direct seeds priming and green synthesis of silver nanoparticles demonstrates the versatility of phytoextract-based approaches (Mickky *et al.*, 2025). Flax seeds primed with orange peel extract (12.5 g L<sup>-1</sup>) and/or biogenic silver nanoparticles (40 mg L<sup>-1</sup>) showed enhanced germination, seedling vigor, vegetative growth, and yield attributes (Mickky *et al.*, 2025). The phytochemical analysis of orange peel extract revealed significant content of phenols, flavonoids, carotenoids, ascorbic acid, reducing sugars, and proteins (Mickky *et al.*, 2025). These compounds contributed both to reducing power for nanoparticle synthesis and to direct biostimulant activity. Treatment effects included modulation of fatty acid profiles (decreased saturated fatty acids, increased unsaturated acids in seedlings), enhanced photosynthetic efficiency, regulation of membrane features, and modulation of antioxidant enzyme activities (Mickky *et al.*, 2025). This case study demonstrates the potential for integrated approaches that combine direct biostimulant effects of phytoextracts with the unique properties of nanoscale materials. Extension to pheromone encapsulation could follow similar principles, using phytoextracts for green synthesis of carrier nanoparticles and as sources of synergistic volatile compounds.

## Challenges and Limitations

### 1. Formulation Stability and Shelf Life

The stability of phytoextracts and pheromones in seed coating formulations presents significant technical

challenges. Phytoextracts are complex mixtures of biologically active compounds that may degrade during storage through oxidation, hydrolysis, or microbial action (Yang *et al.*, 2018). The high-water activity of many extract formulations can promote degradation and support microbial growth unless adequately preserved (Ingebrigtsen *et al.*, 2017). Pheromones, as volatile organic compounds, are subject to evaporation and chemical degradation (Heuskin *et al.*, 2011). Maintaining effective concentrations through the seed storage period (which may extend to months or years) requires encapsulation systems that provide adequate protection (Stelinski *et al.*, 2014). The same controlled-release features that enable gradual emission after planting must be balanced against the need for retention during storage.

### 2. Regulatory Considerations

Seed treatment products incorporating phytoextracts and pheromones occupy complex regulatory spaces that vary among jurisdictions. Phytoextracts may be classified as biostimulants, plant growth regulators, or biopesticides depending on their composition, claimed effects, and the regulatory framework (du Jardin, 2015) [22]. Pheromones are typically regulated as biopesticides or semiochemicals, with requirements for toxicological and environmental risk assessment (US EPA, 2012). The regulatory status of combination products—those containing both phytoextracts and pheromones—may be particularly complex, potentially falling under multiple regulatory categories (Matyjaszczyk, 2015). Harmonization of regulatory requirements across jurisdictions remains limited, creating challenges for product development and commercialization. For high-value crops (vegetables, flowers, some field crops), the economics may favor adoption of advanced seed technologies (Pedrini *et al.*, 2017). For staple food crops in developing regions, cost reduction strategies will be essential for equitable access.

## Conclusions

Seed encapsulation using phytoextracts and pheromones represents a promising frontier in sustainable agriculture, offering the potential to enhance crop performance while reducing reliance on synthetic agrochemicals. This review has synthesized current knowledge across multiple disciplines, revealing both substantial progress and important knowledge gaps. Phytoextracts from diverse plant sources—including medicinal herbs, seaweeds, and agricultural by-products—have demonstrated capacity to enhance seed germination, seedling vigor, and stress tolerance through multiple mechanisms including antioxidant activity, hormonal effects, and induction of stress-responsive pathways (du Jardin, 2015; Sharma *et al.*, 2019; El-Naggar *et al.*, 2023) [22, 23]. Dose-response relationships are critical, with optimal concentrations producing substantial benefits while excessive concentrations may inhibit performance (Ndlovu *et al.*, 2025). Pheromones, particularly aggregation pheromones of seed-feeding insects, offer opportunities to manipulate pest behavior through seed-delivered signals (Wertheim *et al.*, 2005; Stanton *et al.*, 2016). The close connection between insect pheromone production and host plant chemistry (Stanton *et al.*, 2016) suggests potential for integrated approaches that combine plant-derived and insect-derived compounds. Encapsulation technologies have advanced substantially, offering multiple options for delivering bioactive compounds with controlled release profiles (Afzal *et al.*, 2020; Mahra *et al.*, 2025) [2]. Film coating and

fluidized bed coating are well-suited for phytoextract delivery, while nano-encapsulation offers particular advantages for protecting volatile pheromones and achieving precise release kinetics (Heuskin *et al.*, 2011; Mahra *et al.*, 2025). Integration of phytoextracts with pheromones in seed encapsulation formulations remains largely unexplored but holds substantial promise. Potential synergies include enhanced plant vigor that improves tolerance to herbivory, modulation of insect pheromone production through precursor provision, and combined effects on multiple stress factors. The green synthesis of nanoparticles using phytoextracts (Mickky *et al.*, 2025) offers a particularly elegant integration pathway.

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