



Oleosin-coated nanocarriers enhance mycorrhizal-mediated pollinator forage and sunflower productivity under neonicotinoid stress

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Abstract

Global pollinator decline, driven by neonicotinoid insecticides and agricultural intensification, poses a critical threat to sunflower (*Helianthus annuus*) oilseed yields. Even in self-fertile sunflower varieties, yield losses of up to 30% occur in the absence of pollination, underscoring the vital role of insect pollinators in determining seed and oil quality. This review synthesizes recent advancements in arbuscular mycorrhizal fungi (AMF) symbiosis and proposes a novel framework utilizing oleosin-stabilized nanocarriers. These nanocarriers are designed to mitigate neonicotinoid degradation while serving as a synergistic approach to restoring pollen nutritional quality and safeguarding bee health in contaminated agricultural environments. We examine the role of hybrid-specific oleosin isoforms (*HaOL1* and *HaOL2*) in stabilizing AMF inoculants, enabling targeted delivery to the rhizosphere, and optimizing nutrient mobilization, pollen amino acid composition, and overall plant health. Although AMF demonstrates potential for enhancing seed set and pollen value through improved phosphorus and micronutrient uptake, the widespread presence of persistent neonicotinoids (e.g., imidacloprid) continues to impede pollinator recovery. This review identifies a critical research gap: the lack of large-scale field validation for these nano-biotechnological tools and the insufficient monitoring of wild bee populations. We present a conceptual model combining AMF-mediated stress alleviation with precision oleosin-based delivery systems to address the “Pollinator-Forage Paradox,” wherein the ecological benefits of floral resources are undermined by pesticide contamination. Through predictive modeling, this framework aims to reduce chemical residues in plant tissues, thereby protecting pollinator health. Ultimately, this approach promotes sustainable agriculture via climate-resilient sunflower systems (SDG 2, 13), the conservation of pollinator biodiversity (SDG 15), and innovation in nanobiotechnology (SDG 9, 12).

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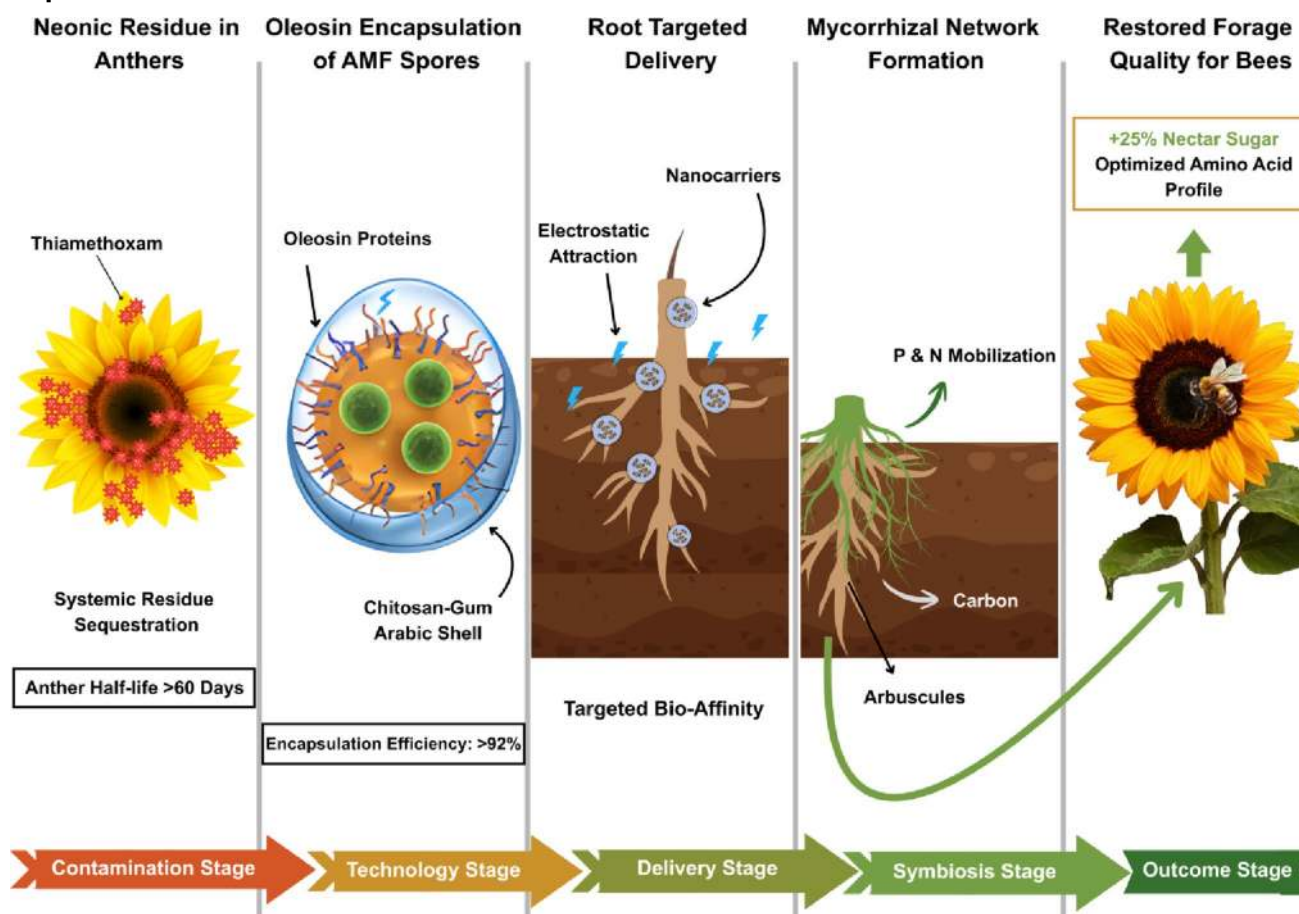
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Graphical abstract



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Introduction

Increased global food demand has driven agricultural intensification, which has led to a sharp reduction in pollinator communities, thereby posing a risk to the stability of oilseed systems. Although modern sunflower (*Helianthus annuus*) breeding programs have prioritized self-fertile breeds to stabilize productivity, the economic and biological benefits of insect pollination remain invaluable. This critical review synthesizes emerging studies on AMF-nanocarrier synergies as regulators of plant growth processes in sunflowers, specifically focusing on mitigating the impact of neonicotinoids on hormonal signaling pathways, reproductive development, and mutualistic interactions. Research in the Iberian Peninsula shows that although self-fertilization can occur, outcrossing by insects significantly enhances seed set by factors of up to 0.341, with individual plant yields increasing between 0.188 and 0.692 (Mota et al. 2024). In

addition, pollination has been demonstrated to increase production by 275 to 382 kg/ha under natural field conditions, depending on the region (Mota et al. 2024). Whereas, Mota et al. (2024) show local yield increases with outcrossing by pollinators, (Amarilla et al. 2025) note that it reduces by 30.4% when pollinators are absent, which shows the variability in the resilience of self-fertile cultivars. This gap indicates that AMF-nanocarrier interventions would help to close such gaps by increasing nutrient mobilization, however field-scale assessments are still scarce as most of the studies are based on greenhouse experiments, not on a variety of agroecosystems. The aggravation of the crisis is based on a 20–40% reduction in the global pollinator populations, which are mainly caused by the isolation of the habitat and the increased use of artificial pesticides. Amarilla et al. (2025) demonstrated the severity of this crisis through field tests in Argentina, where the exclusion of floral visitors resulted in a 30.4% reduction in crop yield and a 5.9%

decline in seed oil content. These results prove that, even within self-fertile cultivars, the protection of pollinators is essential to preserve the quantity and chemical quality of sunflower oil. The objectives of this review are to: (1) examine AMF-nanocarrier mechanisms of growth regulation; (2) critique the impacts of neonicotinoids; and (3) Propose scalable frameworks for sunflower systems under stress. Sunflowers are a versatile keystone of the bio-circular-green economy as they are a crucial source of food, livestock feed, and biodiesel (Puttha et al. 2023). The crop is economical in that it contains high-quality oil that is rich in unsaturated fatty acids (linolenic and linoleic) and vitamins A, D, E, and K. The addition of silage of sunflower (up to 60%) in small-scale dairy systems was also reported to improve the fat-corrected milk (FCM) by 3.5% and to greatly decrease the enteric methane emissions, which proves its productive and environmental effectiveness (Sainz-Ramírez et al. 2021). But to attain maximum economic returns, cultivation must be precise. The variables sowing rates and site-specific management are technological innovations that are essential in reducing the heterogeneity of the fields. Comparisons of the degree of mechanization also show that mechanized farms have much greater technical efficiencies (0.96) than traditional systems (0.88), though also higher Greenhouse Gas (GHG) emissions, between 358 and 438 kg CO₂/ha (Aghili Nategh et al. 2021).

The persistence of neonicotinoids in agricultural ecosystems is a latent risk to non-target organisms. Field runoff in the fields that use treated seeds usually have a high concentration of insecticides such as thiamethoxam. Some sunflowers and buffer crops have also been examined in greenhouse assessments, with some having been found to have varying neonicotinoid sequestration capacities; an example of such is crimson clover, which was capable of hyper-accumulating neonicotinoids up to 50% of applied thiamethoxam, mostly in above-ground tissues (Morrison et al. 2023). Although some seed treatments are not detected in nectar or pollen samples, they nevertheless exert significant pressure on wild bee biodiversity. Studies have shown that the abundance of specialist wild bees, like *Melissodes agilis*, is significantly reduced by thiamethoxam treatments, which directly impairs pollination services and general crop output (Ward et al. 2023). Pollinator health decline is a multifaceted issue involving pathogens, pesticides, and nutritional stress. A major cause of colony collapse has been identified as the pathogen spillover, specifically the protozoan *Crithidia bombi*. Interestingly, pollen of sunflower is a medicinal dietary supplement; a 1:1 mix of the sunflower and wildflower pollen can decrease the rate of *C. bombi* infection by 11% and the severity by 30% (Giacomini et al. 2021). The diet is effective in undoing the adverse impacts of the infection on the production of queens, which implies

that landscapes with sunflowers are crucial to pollinator immune competence.

Mycorrhizal Symbiosis as Pollen Quality Restorer

Arbuscular mycorrhizal fungi (AMF) represent an environmentally sustainable bio-tool capable of enhancing plant survival and nutrient mobilization. As obligate biotrophs, AMF rely on the host for carbon, while providing essential phosphorus, nitrogen, zinc, and sulfur. This symbiosis is regulated by phytohormonal signaling pathways, such as strigolactones and auxins, which facilitate the formation of the mycorrhizal network (Dhiman et al. 2022). Mechanically, AMF symbiosis controls growth through phytohormonal signaling: strigolactones trigger hyphal branching, and auxins control the architecture of roots (Dhiman et al. 2022). Nevertheless, this pathway is destabilized in the case of neonicotinoid stress, a fact reflected in the lower rates of colonization (Szebelledy 2025), which is a drawback of the existing models that do not include the residue kinetics. These signals may be stabilized with oleosin nanocarrier advances, yet issues regarding dosage-related effects are still unanswered. The decline of AMF diversity in degraded grassland ecosystems is closely associated with the diminished quality of floral resources, which implies that AMF networks cannot be restored without conservation of pollinators (Szebelledy 2025).

AMF–Plant–Pollinator Interactions

Arbuscular mycorrhizal fungi (AMF) facilitate plant-pollinator mutualisms by enhancing plant growth, floral characteristics, and nutritional rewards, which consequently increases pollinator attraction. AMF increased biomass of shoots 11%, nectar up to 318% and bee visits 28% (47% longer) through hyphae-colonization trade-offs in *Cucurbita pepo* (Guzman et al. 2025). Mycorrhizae of *Helenium amarum* increased height and leaves, which predicted floral display ($R^2 = 0.533$) and *Hymenoptera* visitation (Jameson and Horth 2024). Biomass, reproduction, seed nutrients, and oil quality in sunflower-pumpkin intercropped with *Funnelliformis mosseae* resulted in 8689% colonization (Alayafi et al. 2025). The meta-analysis of 63 studies (68 species) demonstrated the evidence of a similar level of AMF benefits: floral display ($g=0.786$), visitation ($g=0.590$), and yield ($g=0.450$) during settings and plant types (Hyjazie and Sargent 2024). These are the pathways of nutrient uptake to exaggerated floral cues that warrant the use of AMF in agriculture and conservation to favor pollinators.

Although AMF uniformly stimulates P and K uptake across studies, the effect size varies 2–4 fold depending on hybrid genotypes and soil legacies, indicating that signaling thresholds are genotype-specific rather than universally applicable. Although the results show that AMF induces enhanced K, Ca, Fe, and P uptake, the findings also indicate discrepancies: intercropping systems are more responsive than monocultures, potentially because of increased strigolactone signaling and auxin redistribution (Dhiman et al. 2022). Nevertheless, the exact role of AMF on the oleic/linoleic changes is not fully studied mechanistically and this restricts the ability to predict oil quality under the combined pesticide-drought stress.

Pollen Sugar and Amino Acid Enhancement

Honeybee physiology is largely determined by pollen quality, specifically its protein concentration and amino acid profile. Although sunflower pollen is a good source of bioactive peptides (BPs) having antioxidant properties, the content of proteins (an average of 12–30%) can change depending on the environmental and symbiotic conditions (Végh and Csóka 2024). These amino acid ratios, including essential leucine, lysine, and proline levels, can be optimized through AMF-mediated nutrient flow. Existing plant protection products (PPPs) spread within food webs and thus cause cascading effects on biodiversity (Faburé et al. 2025). There is also a decline in the trophic potential of nectar and pollen due to drought and environmental stress. According to research, the honeybee gut microbiome is sensitive to such changes in nutrition; other pollen foods can adjust the immune response by measuring the production of immune-related peptides of the hemolymph. The indirect yet powerful defense against the environmental stressor is provided by restoring the nutritional purity of pollen by the AMF-mediated systems (Braglia et al. 2025). The nutritional mobilization and phytohormonal signaling mediated by a synergistic interaction between AMF as the metabolic engine that controls the restorative potential of the sunflower agroecosystem has reduced the Pollinator-Forage Paradox. Despite the obvious increase in the essential amino acid profiles with the help of better nutrient flow through AMF, there are conflicting reports with references to the consistency over genotypes (Végh and Csóka 2024; Braglia et al. 2025), and the necessity to investigate the genotype $\times$ AMF interaction at the transcriptome level is clear to elucidate the regulatory nodes in pollen protein synthesis. This AMF symbiosis washes away the effects of neonicotinoids through translocation of the minerals and the quality of the peptides, which is restoring the quality of pollen/nectar and safeguarding the bee microbiomes. This process replaces the nutritional quality of pollen and nectar, which

successfully protects the microbiomes of bee guts against dysbiosis and ensures the economic sustainability of the production of oilseeds by improving the efficiency of pollination and tolerance to yield as shown in Fig. 1. In continuation of AMF, as a nutrient enhancer (growth promotion), this time we look at oleosins as nanocarriers to facilitate targeted delivery, which differs with the general stress alleviation because of the incorporation of mechanistic stability under neonicotinoid stability.

Oleosins as Biocompatible Nanocarriers

Oleosins, among other proteins, continue to be considered as a promising biodegradable, immunogenic protein offering good potential as attractive building blocks in bioactive delivery systems (Vergallo 2020). Nanoformulations based on vegetable oil are already in use to enhance the bioavailability of nutraceuticals to address the problem of low stability and unstable composition (Ramos et al. 2022). Mimicking the natural sunflower protective mechanisms, edible coatings formed based on sunflower protein flour include protection against nutrient oxidation. Values of peroxide can be lowered by applying these coatings, 149.2 mEqO₂/kg (uncoated) to 69.3 mEqO₂/kg in 60 days (Valentinuzzi et al. 2025). On the same note, polysaccharide-derived fat replacers and hydrocolloids can provide three-dimensional networking and imitate the lipid functions and thus can serve as a stable matrix containing biological inoculants (Nikolić et al. 2024). Interspecific hybridization, e.g. between *H. annuus* and *H. argophyllus*, brings in major genomic and transcriptomic variation (Makarenko et al. 2023). These hybrids can produce multiple protein isoforms using a single gene by alternative splicing (AS), which is a form of adaptive divergence in abiotic stress (Innes et al. 2024). These isoforms, which are specific to hybrids, play a crucial role in lipid droplet stabilization and may be used to create nanocarriers that are specifically adapted to the physiological context of the target hybrid.

Sunflower growth, the history of which can be traced back to Cortuso in 1585, and modern precision agronomy imply the necessity of combined measures to fight climate change and geopolitical instability (Giannini et al. 2022). The aim of the present research on Green Tech is to combine these innovations by making (i) hybrid breeding of stress-resistance, (ii) sustainable biofertilizer approaches like AMF, and (iii) modern nanocarrier delivery platforms to maximize pollinator-leading forage in old-fashioned-polluted landscapes. The detection of neonicotinoids in sunflower-grown areas is a complex issue, which is caused by the soil-pollen translocation and the chemical stability of chemicals such as thiamethoxam and imidacloprid. The residues that may occur in various matrices in different agricultural

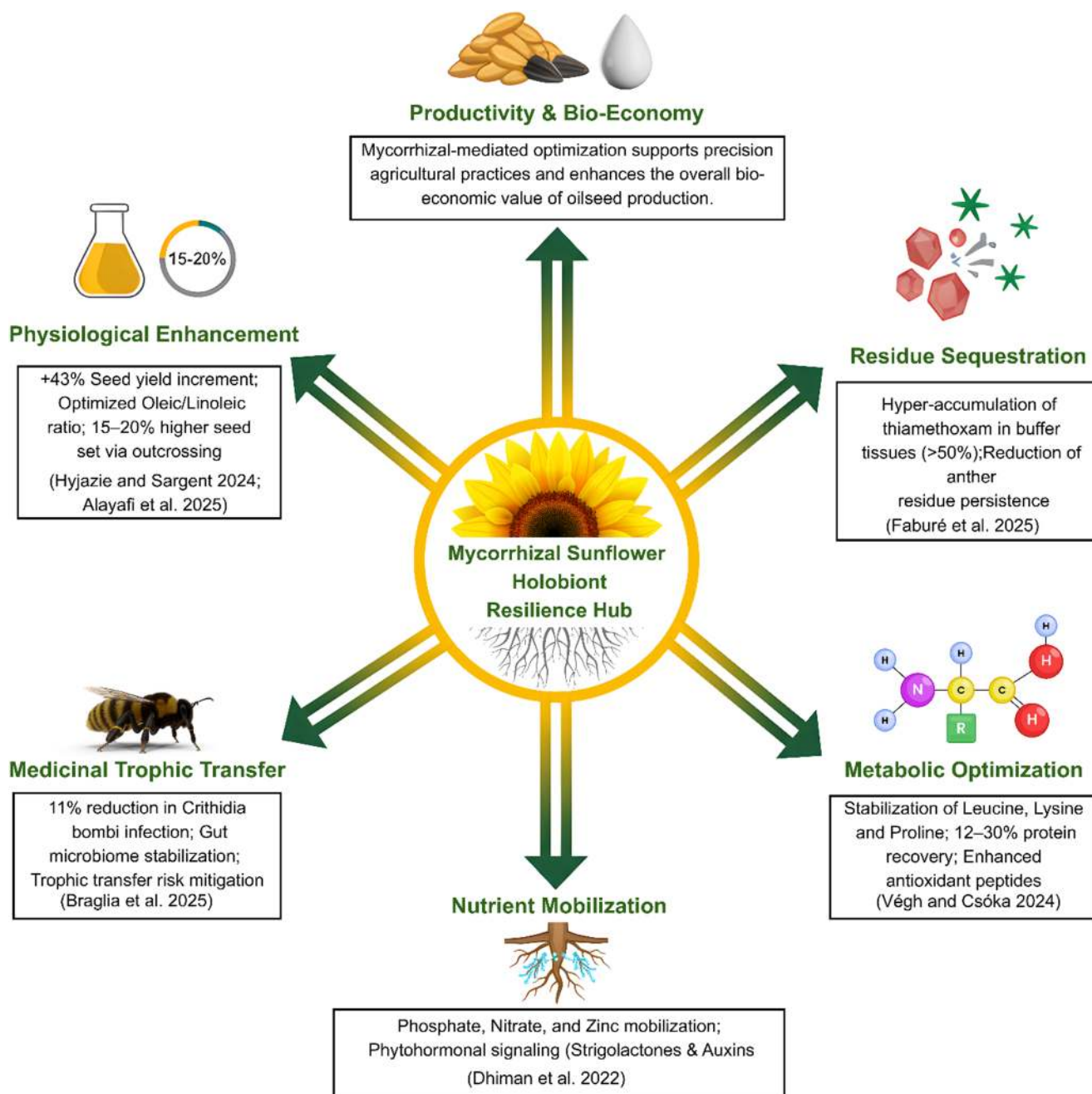


Fig. 1 Synergistic mechanisms of AMF-*Helianthus annuus* symbiosis in sustainable agroecosystems. The integration of AMF enhances sunflower productivity and pollinator health through optimized nutrient mobilization via strigolactone signaling and the accumulation of

essential amino acids. This symbiosis facilitates the sequestration of thiamethoxam residues within buffer tissues, resulting in an 11% reduction in *Crithidia bombi* infection in pollinators and a 43% increase in seed yield, demonstrating a pathway for bioeconomy expansion

landscapes, with even low-level contamination of the soil, cause drastic abundance reductions of such specialist wild bees as *Melissodes agilis*. Moreover, the uptake capacity is considerably different among plant species; some examples include crimson clover, which can hyper-accumulate 50% of the thiamethoxam applied, and common sunflowers used in buffers, with a lower sequestration rate of less than 0.5%, which may lower the risk of direct exposure, but leaves

residues in the floral tissues (Morrison et al. 2023). These exposure patterns are associated with yield losses that are measurably similar to observable pollinator-excluded plots, reflecting the impacts of a pollinator collapse caused by the introduction of pesticides, indicating crop yield reduction of 30.4%, and seed oil content reduction of 5.9% (Amarilla et al. 2025). The present review assumes a PGR approach, in which AMF symbiosis and oleosin-based nanocarriers

influence the expression of main regulatory pathways such as strigolactone- and auxin-mediated signaling, nutrient-dependent hormonal crosstalk, and stress-induced gene expression to resume growth, reproductive development and yield stability in the context of continued neonicotinoid exposure of sunflower. We discuss the regulation levels: (1) rhizosphere-level symbiotic signaling and nutrient acquisition, (2) systemic hormonal and molecular responses in reproductive tissues, and (3) trophic feedback to pollinators that affect mutualistic regulation. This framework incorporates recent developments and throws light on the mechanistic gaps, including a lack of information on isoform-specific functions of oleosins in stress hormone crosstalk. Regional differences, as observed in the Iberian Peninsula and Argentine pampas, emphasize the need for site-specific agri-environmental policies to reduce biodiversity degradation in simplified agroecosystems as shown in Table 1. By integrating hybrid stress-resilient breeding, AMF-mediated nutrient restoration, and nanocarrier-based delivery systems, this research supports Sustainable Development Goals (SDGs) by promoting climate-resilient agricultural production (SDG 2, 13), restoring pollinator biodiversity (SDG 15), and advancing innovative, eco-friendly technologies for sustainable agroecosystems (SDG 9, 12).

Neonic Residues in Sunflower Pollen Matrices

Pollen from pesticides is essential in evaluating environmental risks and the demise of pollinator species. State-of-the-art analytical techniques have also emerged, including the QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) approach, to be used in the analysis of multi-class residues in pollen samples that are frequently found in very small amounts (González-Curbelo et al. 2020). Recent field research in sunflower agroecosystems has determined

a range of neonicotinoid residues in bee products as 0.025 to 0.456 $\mu\text{g g}^{-1}$. These residues have severe effects on the native bees that include *Apis cerana indica*, where the exposure to clothianidin led to a mortality rate of 88.00 Bees one day after spraying (DAS) as compared to control plots. What is more, the risk assessment of bees shows a moderate-high risk (risk quotient > 5), which results in low parameters of growth of colonies, such as honey (61.88 cm^2), pollen (41.25 cm^2), and population size (3479.50 bees) (Chandrasekar et al. 2025).

Persistence and Degradation Kinetics

Agricultural chemicals have a long-lasting effect that is dependent on the substrate and the method used in application. Ortiz et al. (2024) stated that sunflower pollen can be directly converted to a core template of synthesized photocatalyst, which may facilitate mineralization of pollutants with greater than 99% efficiency under visible light, the natural breakdown of herbicides such as pendimethalin in sunflower soil in the soil is first order in nature ($R^2 > 0.90$). The kinetics of degradation also depend on the compound: pendimethalin has a short half-life (14.84–20.84 days) (Bharathi et al. 2024), whereas imidacloprid does not degrade as fast (initial Residues 0.88–0.96 mg kg^{-1} in pollen) (Brar et al. 2022). Such discrepancy points to a lack of comparable modeling with the study by (Ortiz et al. 2024), as the high level of pollutant mineralization by photocatalysis is reached (>99%), but the field-level integration with AMF systems is not yet implemented, which may underestimate the risks of trophic interactions. Depending on the timing of application, the dissipation kinetics of imidacloprid differ greatly. The average initial residues of pollen and flowers at 2 h after foliar spray at the full bloom stage are 0.88 to 0.96 mg kg^{-1} and 1.84 to 1.95 mg kg^{-1} , respectively (Brar et al. 2022). Newer systemic insecticides, such as sulfoxaflor, on the other hand, have a significantly shorter

Table 1 Global Evidence Linking Agricultural Practices to Pollinator Responses and Crop Yield in Sunflower Systems

Region/Study Site	Primary Compound	Matrix/Substrate	Reported Concentration/Metric	Impact on Pollinators/Yield	Reference
Iberian Peninsula, Spain	(N/A)	Natural Fields	Regional Yield Variability	Outcrossing increased seed set by 0.341	(Mota et al. 2024)
Argentina (Main Agricultural Region)	(General Pesticides)	Sunflower Heads	30.4% Yield Reduction	20% decrease in seed set; 5.9% drop in oil content	(Amarilla et al. 2025)
Kermanshah, Iran	(Fertilizer/Diesel)	Farm Enterprises	358–438 $\text{kg CO}_2/\text{ha}$	Mechanized farms show higher yield but higher GHG emissions	(Aghili Nategh et al. 2021)
Greenhouse Study (Simulated Prairie)	Thiamethoxam	Plant Tissue (Maximilian Sunflower)	<0.5% Uptake	Hyper-accumulation noted in buffer species (50%)	(Morrison et al. 2023)
Sunflower Fields (Field Trial)	Thiamethoxam	Soil/Pollen/Nectar	Low soil detection	Significant decrease in <i>Melissodes agilis</i> abundance	(Ward et al. 2023)
Iberian Peninsula (Spanish Regions)	(N/A)	Open Pollination	275–382 kg/ha increment	Economic outcome influenced by landscape context	(Mota et al. 2024)
Anthropocene Global Assessment	General Neonicotinoids	Global Environment	20–40% Population Decline	Alarming situation for global biodiversity and food production	(Nath et al. 2023)

half-life (less than 2 days) in soil and are lost quickly by nectariferous tissues. Adult honey bees have precautionary toxicity benchmarks of No-Observed-Adverse-Effect-Concentration (NOAEC) of $0.50 \text{ mg kg}^{-1} \text{ diet d}^{-1}$, which denotes the danger of persistence of residues in anthers beyond the precautionary toxicity benchmark (Solomon et al. 2025).

Soil to pollen translocation pathways is complicated and tend to cause quantifiable effects even at low levels of residues. Among thiamethoxam seed treatment experiments, the residues were only found in low concentration in a single soil sample, and not in the pollen/nectar analysis, but the abundance of the specialist wild bees (*Melissodes agilis*) was strongly reduced (Ward et al. 2023). This implies that the effects of field-realistic exposures can be overrun by present risk analysis. Moreover, purposeful materials (such as metal-based Nanofertilizers (NFs) may also affect the reproductive cycles; one example is the conventional ZnSO_4 , which has a more beneficial effect on the pollen grain size than ZnO or Fe_3O_4 nanoparticles (Ďurišová et al. 2023; Qadri et al. 2026; Khan et al. 2025b). The meteorological-growth coupling and the soil conditions have a significant effect on seasonal accumulation. Cultivars with early maturity (e.g., RH3146) are more resilient to yield changes in areas with lower temperatures (18% enhancement), whereas those with later maturity are more resilient to stresses (35.6% grain crude fat content) with a change in thermal conditions (Mu et al. 2025). The soil moisture and salinity in arid salinized farmlands have a high control over energy distribution and latent heat (LE) fluxes, and salt accumulation has a negative control on LE (Pearson correlation = -0.59), which may affect the physiological concentration of systemic residues during the budding and vegetation phases (Wang et al. 2024).

Trophic Transfer to Pollinators

Plant protection products (PPPs) are also important agents involved in biodiversity erosion, especially when they propagate in food webs (Faburé et al. 2025). We argue that modern neonicotinoids have a larger biodiversity impact than legacy compounds, because of their complex intertropical impacts because they do not comply with canonical theory (Loy and Brosi 2022). This discrepancy e.g., sublethal stresses decreasing visit percentage by 19–25% (Saleem et al. 2023) informs a controversy: AMF can decrease part of the impact, but not all features of the wild bee monitoring can make holistic determinations. How pollinator diversity and crop function interact in sunflower agroecosystems is mediated by the so-called functional enhancement, in which diversity enhances within-niche activity and interactive functional complementarity. Interruptions of these trophic relationships may affect the necessity of major ecological

processes at both the land and water borders (Vilela et al. 2020). Early exposure to neonicotinoids in early developmental stages results in severe physiological and morphological defects in non-target organisms. Neonicotinoid residues in bee products have been determined between 0.025 and $0.456 \mu\text{g g}^{-1}$ in sunflower field research (Chandrasekar et al. 2025). This exposure leads to much increased mortality; an example to illustrate this point is the results obtained in clothianidin-treated fields, a day after spraying (DAS), the result was 88.00 bees were dead (Chandrasekar et al. 2025). In addition to pollinators, aquatic larvae subjected to environmentally relevant levels of imidacloprid (10 ng/L) have 10% stomach deformity and higher mortality rates at an early developmental stage ($p < 0.001$) (Chandrasekar et al. 2025). The neonicotinoid residue risk evaluation in *Apis cerana indica* indicates a moderate-high risk (risk quotient above 5), which is directly proportional to reduced colony measures, including a pollen area of 41.25 cm^2 and a honey area of 61.88 cm^2 in comparison to the control plots (Chandrasekar et al. 2025).

Excessive application of neonicotinoids causes serious sub-lethal stresses on *Apis mellifera*, which negatively impacts abundance and visitation rates that are important to the cross-pollination of self-incompatible sunflowers. A 2-year (2020–2021) study found that imidacloprid, clothianidin, and thiamethoxam decreased Apis bee visitation by 19%–22.5%, 18.5%–24%, and 23%–25.5%, respectively (Saleem et al. 2023). In addition, toxicological evaluation of hive products in Romania showed that the mean pesticide residue concentrations of honey, pollen and bee brood were 0.032 mg/kg , 0.061 mg/kg and 0.371 mg/kg , respectively (Bodescu et al. 2025). These residues lead to a reduction in the fruit mass and seed oil level and testify to the direct negative dependence between pesticide exposure and the productivity of sunflowers (Saleem et al. 2023). Pollinator foraging behaviors and preferences are greatly changed by pest management practices. Field experiments have shown that pollinators do not visit sunflowers in the morning or in the evening, which coincide with a minimum level of foraging activity. Synthetic insecticides, especially Chlorantraniliprole, exhibit the least foraging activity, and bio-insecticides such as neem oil and *Bt-kurstaki* enable the greatest foraging, with pests such as *Helicoverpa armigera* (Shankar and Mukhtar 2025). Although sunflower pollen is commonly defined as a low-quality resource because of the deficiency of amino acids, the nectar sugars and volume of the foraging essentials drive the nectar preference. It is interesting to note that sunflower pollen has a medical application in reducing the intensity of an infection of the gut parasite *Crithidia bombi* in *Bombus* species, indicating that the quality of the floral resource is a multi-dimensional parameter which includes nutrition and the

health-modulating secondary metabolites (Husband et al. 2025). The neonicotinoid cycle of the sunflower systems is environmental and takes the form of a Source-to-Sequestration cycle that starts with the soil persistence and acropetal translocation through the vascular bundles. The net effect is high-stability anther accumulation of residue that is caused by this systemic movement, and even half-lives of 60 days or longer, directly polluting the pollen matrix (Brar et al. 2022; Fagundes et al. 2025). A general trend among these studies is that sublethal but not acute toxicity prevails at doses of field-realistic concern, but the variability in the rate of visitation reduction (18–25%) is an indication of the lack of understanding of interactions between contexts of the landscape and functional characteristics of the bee species (Saleem et al. 2023). This cycle results in multi-trophic transmission to the pollinators in which the contaminated forage causes sublethal physiological stress, gastrointestinal dysbiosis, and lowered reproductive success. The flow chart of these interrelated processes, by visualizing them, illustrates the way field-realistic exposures spread across biological edges, which eventually destroys the ecological stability of the sunflower-pollinator mutualism (Fig. 2).

Nutritional Quality Erosion

Annual monocropping systems have been largely discredited by the industrial intensification of their operation, which has led to a major undermining of the ecological and nutritional quality of oilseed production. Traditional agriculture, based on extensive use of chemicals and tilling, contributes to the erosion of the soil and the disappearance of biodiversity and may lead to a reduction in the phytochemical and macronutrient content of staple foods (Joshi et al. 2024). *Helianthus annuus* has a crucial functional food which includes vital tocopherols, phytosterols and peptides, but its nutritional and therapeutic potential is not fully utilized because of restricted production. The shift towards sustainable production, including the utilization of biofertilizers or the introduction of perennial species like *H. maximiliani*, is a way forward to regain the dietary conditions and environmental balance (Paul et al. 2024). Environmental and hereditary effects have a tremendous effect on the amount and quality of sunflower floral rewards. Controlled experiments of different temperature treatments (e.g., 28 °C vs. 21 °C) indicate there are significant G x E interactions on nectar volume ($\mu\text{l}/\text{floret}$), sugar concentration (°Brix), and sucrose composition (Prasifka et al. 2023). Moreover, the nutritional profile of the seed, i.e. the ratio between reducing sugars (glucose and fructose) and proteins, is crucial to post-harvest quality. When the concentration of these components is increased, it is biased towards the Maillard reaction in the

roasting process to increase desirable aroma volatiles, such as pyrazines (Laemont and Barringer 2023).

Alkali and drought stress are examples of abiotic stressors that cause systemic changes in metabolism that modify the amino and lipid profiles of sunflowers. Multiomics analysis indicates that alkali stress (pH 8.7) reduces glycerophospholipids in seeds; therefore, changing oil quality and increases levels of fatty acids and amino acids in roots to supply energy to the roots in response to stress (Lu et al. 2021). Equally, drought stress greatly reduces productivity, but exogenous use of 75-mM β -aminobutyric acid (BABA) has been reported to alleviate these effects, enhancing the weight of 1000-achene by about 41 to 44% and achene yield by about 41% to 44% (Wasaya et al. 2021). To achieve the ecological balance in the production of sunflowers, the pollen diversity and the soil agronomy should be approached holistically. Pollinator taxa (including honeybees (*Apis mellifera*) to bumblebees (*Bombus spp.*), which are known to be buzz-pollinating) and even the predatory hoverfly are considered synergistic and can enhance genetic diversity and reproductive success (Shpak et al. 2023). The use of agroecologically friendly methods, including biofumigation with the Brassicaceae cover crop or application of Fabaceae (purple vetch) as the green manure, can substantially reduce soilborne pathogens, as well as improve the yield of sunflower to as much as 0.77 t ha⁻¹ (Ait Kaci Ahmed et al. 2022). These combined efforts are needed to overcome the so-called erosion of nutrition due to the excessive use of pesticides and the fragmentation of habitats (Shpak et al. 2023). Neonicotinoids are systemic, and they can be easily translocated within the xylem due to their high systemic nature; subsequently, they accumulate in the reproductive organs of the sunflower. With continued perseverance in the anthers, there is an accumulation of a high number of residues in the pollen grains, and they are actively harvested by foraging honeybees and carried to the hive through the corbícula. Since they are ingested in bee bread, these contaminants are digested by the larvae, resulting in poor gut microbiome integrity and high developmental mortality (Fig. 3).

Hybrid-Specific Oleosin Isoforms

Oil bodies (OBs) are organelles that are surrounded by a special membrane with the structure of a phospholipid monolayer and stabilizing proteins, such as oleosins, caleosins, and steroleosins (Liao et al. 2025). This architecture offers tremendous stability in harsh conditions, enabling the growth of artificial oil bodies (AOB) to be used in probiotic and biological delivery. The high number of individual aquaporins (AQP) isoforms at the OB membrane is controlled by

The Circular Bio-Geochemical Cycle of Neonicotinoid Propagation in Sunflower Ecosystems

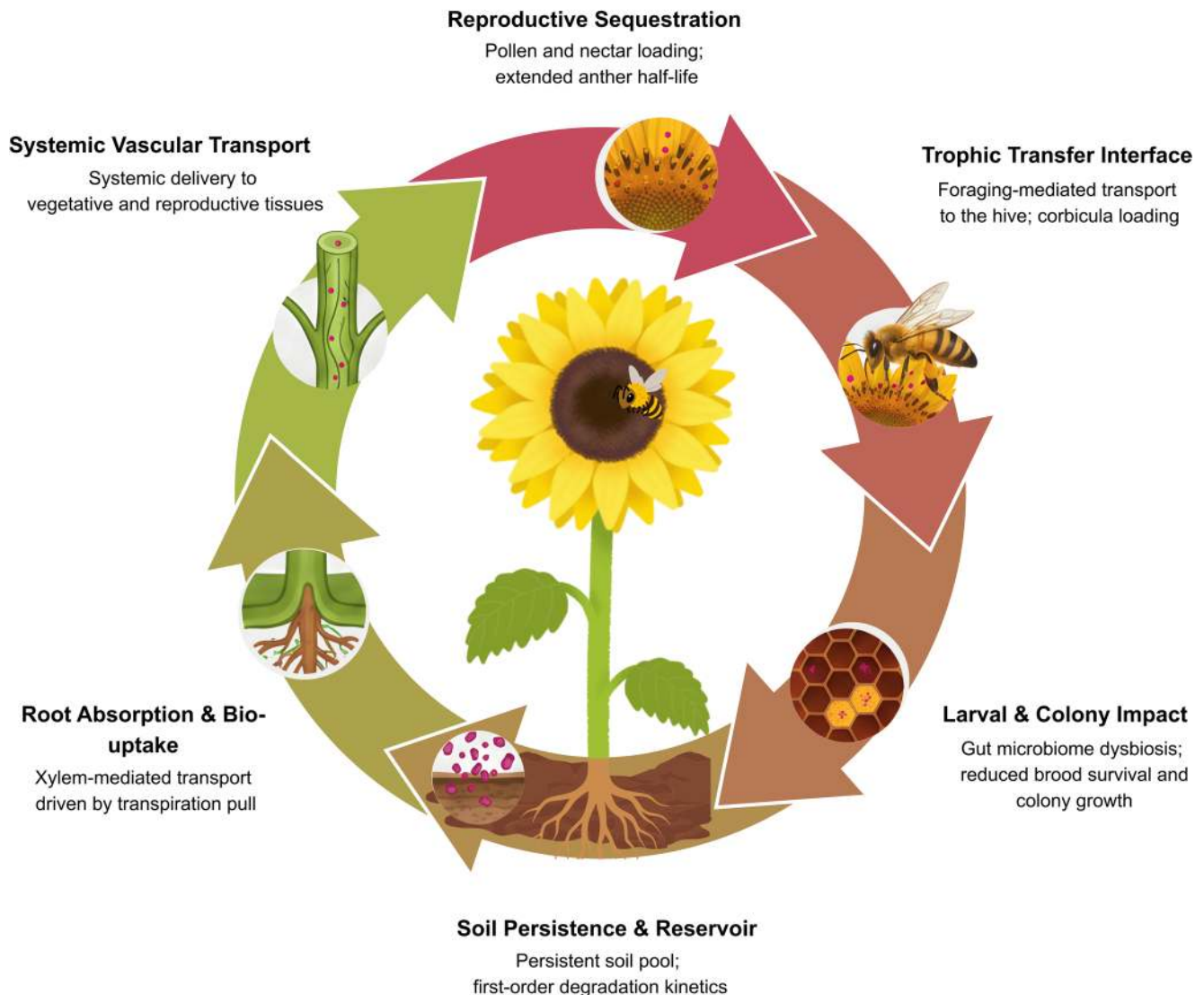


Fig. 2 Systemic neonicotinoid propagation and its ecological ramifications in sunflower ecosystems. The persistence of neonicotinoids in soil and their subsequent xylem-mediated translocation to reproductive tissues create a cycle of long-term pollinator exposure. This pro-

cess induces gut dysbiosis and reduced brood survival in pollinators, highlighting the systemic risk posed by pesticide accumulation in floral resources and the resulting disruption of trophic stability

nitric oxide (NO) in sunflower seedling cotyledons, which adjusts the level of hydration status in young seedlings. In particular, the 120 mM NaCl exposure increases the PIP2 and TIP1 expressions, implying that the isoforms play an essential role in the osmotic and salt stress acclimatization (Kumari and Bhatla 2023).

Genomic and Expression Diversity

The sunflower genome harbours massive regulatory elements that include a kinome with 2583 protein kinases subdivided into 121 subfamilies (Yan et al. 2024). The subfamilies that have undergone significant growth include RLK-Pelle_WAK and RLK-Pelle_SD-2b, which are active in signaling pathways such as MAPK and SOS to respond to environmental stressors. Also, 15 zinc finger-homeodomain

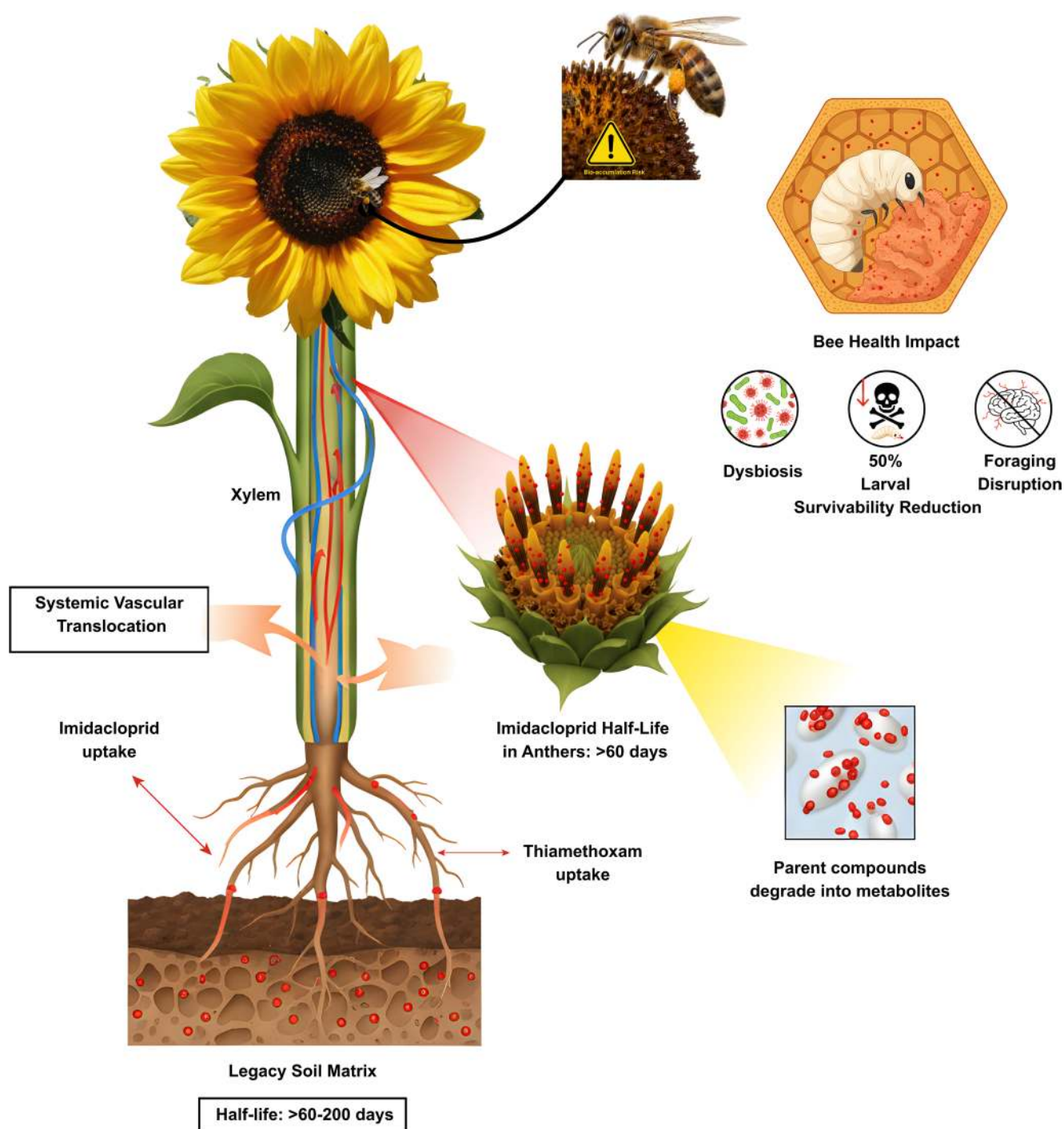


Fig. 3 Biogeochemical translocation of neonicotinoids and its long-term impact on pollinator fitness. The translocation of Imidacloprid and Thiamethoxam from soil matrices (half-life: 60–200 days) to floral organs drives chronic pollinator exposure. With another half-

life exceeding 60 days, this persistence significantly impairs pollinator health, leading to foraging disturbances and a 50% reduction in larval survival, thereby threatening both individual fitness and colony longevity

(ZF-HD) genes (*HaZF1–HaZF15*) have been located, with *HaZF3* demonstrating positive responsiveness to initial drought stress, *HaZF6* and *HaZF9* demonstrating significant declines in expression under salt stress (Zhang et al. 2025). The stability of sunflower oil bodies (OBs) is basically

determined by the composition of the membrane proteins of the oil bodies, which are mainly the oleosin isoforms. Several genome-wide analyses of the sunflower kinome and transcription factor families, including 15 known *HaZF-HD* genes, indicate a complicated regulatory system of

seed protein structure (Zhang et al. 2025). The *HaOL1* and *HaOL2* isoforms are the major structural pins, which hold the triacylglycerol core together, that prevent coalescence (Mallillin III et al. 2025). These oleosin isoforms that are hybrid specific probably interact with stress hormone pathways (e.g., ABA auxin crosstalk during drought) because these isoforms are co-expressed with *ZF-HD* transcription factors (Zhang et al. 2025). Nevertheless, one critical gap is still direct functional confirmation of the isoform specific features of strigolactone signaling modulation during AMF colonization. These isoforms contain a distinct hydrophobic domain that is incorporated into the phospholipid monolayer, giving them outstanding oxidative resistance and interfacial stability. This hydrophobic space is the mechanism of stabilizing lipid droplets by preventing coalescence, controlling growth by releasing a specific amount of nutrients (Mallillin III et al. 2025). Most importantly, hybrid-specific isoforms (*HaOL1/HaOL2*) can be regulated specifically in contrast to generic oleosins, although epigenetic variations in response to stress are not studied yet, which is a gap to be filled in the field. The particle size of these protein-stabilized droplets can be decreased to about 81.08 nm during modification by structural rearrangement, namely, by pH-cycling and ultrasound, and it raises the ζ -potential to -38.77 mV, increasing their functional solubility several times (Li et al. 2025).

One of the main limitations of the productivity of sunflowers is drought stress, which causes the differential expression of thousands of genes. Transcriptome analysis indicates that in the 72 h of stress, 7,482 differentially expressed genes (DEGs) are observed in leaves, with these hub genes being associated with metabolite degradation processes, carotenoid biosynthesis and phytohormone signaling (Shi et al. 2024). Genotypes with tolerance are considered an important genetic material in breeding in combination with stress-resistance under semi-arid conditions (Shi et al. 2024; Khan et al. 2023 a). Interfacial stabilizers such as phospholipids and oleosins are responsible for ensuring the structural integrity of lipid droplets. Phospholipids derived from sunflower and containing a high amount of phosphatidylcholine (PC) form homogeneous oil particles, with zeta potentials of -28.8 mV, and a size of 0.391 μm , that improve the stability of emulsions (Icyer 2025). These stabilized droplets are degraded and turned over via the mechanism of lipolysis and lipophagy, which are essential in the provision of energy and carbon in seed germination (Qin et al. 2023).

Comparative Hybrid Performance

A major aim of contemporary breeding of sunflowers is the choice of hybrids of high-productivity oilseeds, which will ensure that the growing needs of the edible oil industry are fulfilled. Machine learning (ML) has become an essential

component in the Sunflower Oil Yield Prediction (SOYP), and the Random Forest Regressor (RFR) algorithm has proven to be the best model with the highest level of performance, with an output of $R^2=0.92$ (Cvejić et al. 2023). The important hybrid traits that are important to effective prediction are seed yielding, maturity, and pathogen resistance, such as broomrape and downy mildew. There is great genetic diversity in germplasm in the confectionery industry, with accessions like Hybrid 100 and GOR101 having high sugar content and accessions like VINIMIK 6931 and HA 305 having better 100-seed mass (Latif et al. 2025). The genotypic correlations also show that 100-seed mass has a positive relationship with protein and oleic acid content. Prediction of hybrid-specific performance is rapidly being predicted by machine learning (ML) algorithms, with the Random Forest Regressor (RFR) model having been estimated with a high R^2 of 0.92 in oil yield prediction (Cvejić et al. 2023). The high-stability hybrids, like the type of 63M80 Pioneer 63 (modelled in datasets based on high-stability oleic content), rely on particular ratios of proteins and phospholipids to preserve the chemical integrity of the hybrids (Miller and Gulya 2006; Yasumoto et al. 2012; Prischmann and Dashiell 2008). A positive relationship between 100-seed mass and protein content or oleic acid concentration is observed in these genotypes and allows for obtaining a higher stability in the yield of oil (Latif et al. 2025). In different pedoclimatic situations, e.g. the cambic chernozems of Romania, optimal technological variants of these high-stability hybrids have yielded up to 3,417 kg/ha, showing that genetic selection of the stable isoforms should be combined with site-specific management (OKROS et al. 2024).

Increasing the profitability of hybrid cultures in different pedoclimatic situations requires technological optimization. Specific variants (N50P50K50 with scarification and ploughing) had production peaks of 3,417 kg/ha in Western Romania, and this highlights the role of management in producing high-quality in sustainable production (OKROS et al. 2024). In the same way, diversity research in Ethiopia based on 25 genotypes, which involved the standard check, which was the Russian black, showed that the agro-morphological traits differed significantly (Lagiso et al. 2021). It was observed that seed yield and oil content had high heritability (broad sense) and genetic progression, implying that the additive genetic action is controlling these traits. Principal component analysis further revealed that there are four important PCs that explain the variability (80.2%), showing a roadmap of significant yield increments with a specific selectivity (Lagiso et al. 2021). Arbuscular mycorrhizal fungi (AMF) are also important symbionts that alleviate the effects of soil heterogeneity and climatic variability by stabilizing soil with the help of hyphae networks (Vyas et al. 2024). The combination of biochar (5 t ha^{-1}) and AMF

inoculation (+AMF) can considerably improve agronomic responses of sunflower in semi-arid settings. This synergy led to an improvement in the Leaf Area Index (LAI) of 4.95 by flowering and a significant growth in the number of seeds produced, 79.4 g per plant, with less than half the maximum available water (MAW). Moreover, root biomass, head diameter, and seed protein content (20.7 g m⁻² vs. 17.2 g m⁻² in control plants) were increased by AMF inoculation by 15% and 15%, respectively (Langeroodi et al. 2022). These results show that AMF plays a very important role in enhancing nutrient uptake, including Zinc and Iron, and balancing crop productivity during droughts.

Root Interface Interactions

The drought tolerance and nutrient uptake are critically achieved through the sunflower root system. Genotypic differences have a great impact on root morphoanatomy, particularly during water limitation (40% of field capacity). Indicatively, genotype OLISUN03 has a slender root system architecture (RSA) and decreased endoderm thickness, but BRS323 attains a deep RSA to reach the moisture in the deep soil stratifications (da Silva et al. 2025). Moreover, the use of agricultural interventions like the introduction of a straw interlayer (S5) has been proven to enhance soil moisture by 8.2–11.0% (Chen et al. 2024). This process maximizes overall root length and volume by attracting certain desirable bacteria, i.e. *Chloroflexi* and *Verrucomicrobia*, which increase up to 55.7% and 54.7%, respectively (Chen et al. 2024). Non-pathogenic strains like *Fusarium oxysporum* FO12 are of critical importance to endophytic colonization since they increase the biomass of a plant without causing a pathogen. Confocal laser scanning microscopy (CLSM) has established the endophytic capacity of FO12 in the colonization of sunflower roots and stems, and increased root fresh weight by a significant factor relative to control groups (Sevillano-Caño et al. 2024). Equally, complex fluorescence tracking and qPCR methods can be used to accurately measure the structure of fungi in the epiphytic and endophytic habitats. Researchers can sense colonization with a sensitivity of 250-fg genomic DNA using green fluorescence labeling of N-acetyl-glucosamine on propidium iodide-stained tissues to enable the phenotyping of nonhost resistance and symbiosis (Prabhakaran et al. 2021).

The association with AMF, including *Funneliformis mosseae*, also causes the development of specialized structures, vesicles and arbuscules, needed in the exchange of nutrients (Alayafi et al. 2025). Environmental factors also promote this colonization, such as an enriched atmosphere of CO₂ (eCO₂), which has been reported to increase the rate of colonization of *Rhizophagus irregularis*. The AMF inoculation has tremendous effects on the synthesis of photosynthetic

pigments and the uptake of nitrogen (N), phosphorus (P), and potassium (K). It is important to note that under AMF treatment, the composition of fatty acids within plants changes with more Oleic acids and less oxidative stress due to the upsurge in catalase and APX activity (Bellido et al. 2021). The phosphorus (P) cycling optimization is essential to the performance of sunflowers, especially in adverse conditions such as saline-alkali farmlands. The use of organic amendments, e.g. the lignite organic fertilizer (LBF) with a concentration of 4.5 t ha⁻¹, helps the sunflowers to attract stable beneficial microbes, e.g. the *Pseudomonas* and *Penicillium* (Hu et al. 2025). These microbes improve the rhizosphere functions, such as the solubilization of inorganic phosphorus and the solubilization of organic phosphorus. The ideal P rate to maximize the yield and the P use efficiency in coastal delta ecosystems has been determined as 28.8 to 36.0 kg P ha⁻¹ (Haque et al. 2025). The rate of P maximum in sunflowers, to a minimum positive P balance of 5.9 kg P ha⁻¹ and an agronomic efficiency of 22–49 kg achene/kg of added P, occurs at the 28.8 kg P ha⁻¹ rate (Haque et al. 2025). The hybrid-specific characters and the physiological reactions to environmental stressors have a great impact on the stabilization of lipid droplets by molecules and the subsequent effectiveness of AMF colonization. Root morphoanatomy genotypic differences, e.g., the deep root system structure of *BRS323* or the thin architecture of *OLISUN03*, determine the space-success of the mycorrhizal hyphae attachment and mobilization of limited minerals such as phosphorus (Table 2).

Nanocarrier Delivery Mechanisms

The evolution of nanocarrier technology is now transforming precision delivery systems by improving absorption, stability and bioavailability of bioactive compounds (Khan et al. 2025a, b; Ansari et al. 2026). In the agricultural and biotechnological industries, plant-derived extracellular vesicles (PDEVs) are proving to be a very promising natural nanocarrier because of their high biocompatibility and complex biological cargo, containing proteins, lipids and secondary metabolites. These nanoparticles are lipid bilayers, the usual size of which is 50–500 nm, offering a superior substitute to synthetic nanoparticles in that they maximize targeted release and minimize environmental or physiological side effects (Calzoni et al. 2024). Equally, lipid and inorganic nanocarriers, including liposomes and ethosomes, are also being evaluated with respect to their ability to facilitate the release and deep penetration into tissues in diverse clinical and biological applications (Albahr et al. 2024). Advanced nanocarriers, including lipidic, polymeric, and biogenic nanoparticles, have emerged as transformative tools for the

Table 2 Reported Physiological, Molecular, and Microbial Responses of Sunflower to Drought and Salinity Stress Across Experimental Systems

Sunflower Hybrid/Genotype	Regulatory/Structural Marker	Physiological Response to Stress	AMF Species/Treatment	Colonization & Growth Metrics	Reference(s)
<i>BRS323</i>	Deep Root System Architecture (RSA)	Water Deficit Adaptation	(N/A)	Deep root development for improved water absorption	(da Silva et al. 2025)
<i>OLISUN03</i>	Narrow RSA; Reduced Endoderm Thickness	Tissue differentiation near the root apex	(N/A)	Changes in morphoanatomy to anchor in dry soil	(da Silva et al. 2025)
<i>K55</i>	7,482 DEGs (Leaves); 2,150 DEGs (Roots)	High Drought Resistance	(N/A)	Hub genes associated with photosynthesis and phytohormone signaling	(Shi et al. 2024)
<i>K58</i>	5,627 DEGs (Leaves); 2,527 DEGs (Roots)	Moderate Drought Resistance	(N/A)	Transcriptomic activation of starch and sucrose metabolism	(Shi et al. 2024)
Neostar/Edison	Metal-based NFs (ZnSO ₄ , ZnO, TiO ₂)	Morphology vs. Yield Discrepancy	(N/A)	TiO ₂ -NPs consistently showed the highest yield despite smaller pollen grains.	(Ďurišová et al. 2023)
(General Sunflower)	PIP1, PIP2, TIP1, TIP2 (on OB Membrane)	120 mM NaCl Salt Stress	(N/A)	Nitric Oxide (NO) application leads to expression of dimeric PIP isoforms	(Kumari and Bhatla 2023)
(Intercropped System)	Chlorophyll Content/Leaf Number	Drought/Intercropping Stress	<i>Funneliformis mosseae</i>	Improved root colonization; increased seed weight and oil yield	(Alayafi et al. 2025)
(S5 Straw Treatment)	Chloroflexi & Verrucomicrobia Enrichment	Saline-Alkali Stress	(Natural Microbial Community)	Root growth stimulated by 55.7% bacterial abundance increase	(Chen et al. 2024)
(LBF Treatment)	<i>Pseudomonas</i> , <i>Penicillium</i> , <i>Mortierella</i>	Saline-Alkali Stress	(Rhizosphere Microbiome)	Enriched stable beneficial microbes for >2 years; increased P uptake	(Hu et al. 2025)
(hOSEC Model)	Sunflower-based Nanoemulsions	Wound Healing/Cytotoxicity	(Phospholipid stabilizers)	Nano-2 (pure phospholipid) was less cytotoxic and targeted the epidermis	(Pereira Oliveira et al. 2023)
(Generic Hybrid)	HaZF3 Positive Response	Drought Stress	(N/A)	Initial stage drought response through ZF-HD gene family expansion	(Zhang et al. 2025)
(Generic Hybrid)	HaZF6/HaZF9 Decrease	Salt Stress	(N/A)	Significant decrease in relative expression under salt stress	(Zhang et al. 2025)

It is possible to stabilize beneficial microbiomes through organic amendments (LBF at 4.5 t ha⁻¹), which subsequently leads to organic phosphorus mineralization and increases the stability of the microbial co-occurrence network (Hu et al. 2025). Moreover, pH-cycling and ultrasound have been used to restructure the sunflower seed protein (SPI) to reduce the size of its particles to 81.08 nm and greatly enhance its oil-holding capacity to 5.52 g/g (Li et al. 2025)

targeted delivery of bioactive compounds, offering sustainable solutions for pathogen control, abiotic stress mitigation, and enhanced nutrient efficiency in both biomedical and agricultural systems (Khan et al. 2025b, 2026; Ansari et al. 2026).

Chitosan–Oleosin Encapsulation Process

Oleosomes, or oil bodies (OBs) produced in plants, are natural nanocarriers, which are defined by a triacylglycerol core and a phospholipid-protein monolayer. These submicron-sized droplets are highly oxidatively stable and can attain near complete encapsulation of lipophilic molecules, and reported efficiencies of over 95% (Mallillin III et al. 2025). To improve their structural integrity, studies have paid attention to the manufacturing of oleogels using chitosan (CH) and gum arabic (GA) coating by electrostatic deposition. Curcumin-loaded OBs coated with a GA-CH mixture in a comparative analysis had an encapsulation efficiency of 92.18%, which was significantly better than that of the uncoated variants at 63.47% (Farooq et al. 2024). Moreover, the introduction of 2,3,4-trihydroxybenzaldehyde (TB) leads to the formation of a 3D-network structure to ensure thermal stability up to ≥ 80 °C and high resistance to UV degradation (Farooq et al. 2024). This synergistic coating method is an efficient way to slow down degradation, as in simulated gastric conditions, it released only 7.19% of the cargo and thus enabled the sustained release in intestinal or rhizosphere-applicable conditions (Farooq et al. 2024). The physical condition of the seed or spore usually determines how the biological agents can be loaded into these carriers. Complementary to this, natural microcapsules of plant pollen grains and spores, comprising a strong sporopollenin exine shell and a cellulose intine shell, have been shown to change the plant-associated microbiome to stimulate root development by 9–14% and promote the dominance of spore-forming *Mycobacterium sp.* Complementary to this, cold atmospheric pressure (CP) plasma irradiation of sunflower seeds has been shown to alter the plant-associated microbiome by stimulating root growth by 9–14% and promoting (Tamošiūnė et al. 2020). These exine-capped hollow sporopollenin are large and robust to extreme pH and temperatures, and therefore, they are the best in microencapsulating genetic materials or nutraceuticals (Iravani and Varma 2021).

The kinetic stability of the nanocarriers depends on accurate control of the particle size. By combining pH-cycling and ultrasound treatment with sunflower seed protein (SPI), it is demonstrated that synergistic modification induces the reduction of the particle size to 81.08 nm and an increase of the ζ -potential to -38.77 mV (Li et al. 2025). The treatment increases the solubility to protein level of 81.27% and 2.73

times the oil-holding capacity (Li et al. 2025). The optimal mixture design based on 10% oil to 29% surfactant ratio in a nanoemulsion can produce stable droplets with a mean size of less than 200 nm and a ζ -potential of -30.0 mV (Romes et al. 2022). These systems are resistant to separation of phases in centrifugation and freeze-thaw conditions and are physically stable in the long run. Within the rhizosphere, the efficacy of delivery is controlled by the capacity of the carrier to control release in association with soil microbes and contaminants (Qin et al. 2024; Younis et al. 2024). New slow-release composite carriers made of carboxymethyl chitosan-graft-carboxymethyl- β -cyclodextrin (CMC-g-CMCD) are more effective in the phytoremediation of co-contaminated soils. These carriers enhanced the uptake of the uranium (U) and chromium (Cr) by 70.55% and 35.55%, respectively, when applied to the remediation systems based on sunflower, even as leaching losses were minimized by more than 34% (Lin et al. 2025). The chitosan-oleosin encapsulation is mechanistically regulated to grow by pH-controllable release, reducing the stress levels through chelation (Lin et al. 2025). However, the capacity of spores to survive in field conditions is problematic and bring concerns to scalability of sunflower control. Moreover, plant-growth-promoting rhizobacteria (PGPR) are a very important player in these release kinetics as it alters the bioavailability of heavy metals and release plant hormones that increase the overall efficiency of the rhizosphere interaction (Qin et al. 2024).

AMF Spore Viability and Root Targeting

Symbiotic relationships between crops and AMF can be considered an essential biological process of increasing plant resistance to environmental stressors, such as drought. The AMF establishment causes changes in physiological and molecular functions that are optimal in the uptake of water and nutrients, osmotic regulation, and antioxidant protection (Birhanu and Negussie 2024). The efficacy of such symbiosis is extremely seasonal and dependent on the soil physicochemical characteristics; in particular, AMF communities' diversity and composition are usually greater in autumn than in spring, and it is determined by soil pH, total nitrogen, and potassium availability. Agricultural practices should be sustainable, such as less tilling and organic amendments, to ensure the sustainability of spores and a healthy mycorrhizal system (Han et al. 2023). One of the main areas of concern in enhancing crop productivity and promoting sustainable growth is the development of high-efficiency microbial inoculants (Andreatta et al. 2024; Khan et al. 2022; Khan et al. 2023 b). *Rhizophagus irregularis* (a close relative of *R. clarus*) has been shown to induce gene expression of the polyphenol biosynthetic pathway

in sunflowers systemically, with cinnamate-4-hydroxylase being a master expressed gene. Proactive colonization by these fungi not only induces the lignification of the cell wall and the build-up of flavonoids and anthocyanins but also greatly impacts the severity of the disease and enhances the overall growth of the plant (Rashad et al. 2020). The concept of co-inoculating plant growth-promoting fungi (PGPF) in the rhizosphere is developing in popularity in such markets as Brazil in a bid to augment the effectiveness of these biological products (Andreato et al. 2024).

Root systems normally cluster within the top 20 cm of soil, though a quarter to a half of the roots need to penetrate below this layer to overcome the constraints of subsoil, including compaction, salinity and excess of heavy metals (Costa and Coutinho 2022). The multifunctional biological strategies which help prevent erosion and anchor plants include effective root hair attachment and soil penetration. Some of the strategies to enhance these functions are the use of tolerant genotypes and association with soil microorganisms, which can stimulate root development despite the physical constraint which would normally decrease the root biomass and length. Moreover, the biomimetic studies of adaptivity to root shape and self-healing can provide information on how to create resistant constructions that can increase mechanical soil-adhesion (Stachew et al. 2021). Long-term fitness and resistance to pathogens for maintaining sustained colonization through the crop lifecycle are essential. With this, the use of a winter cover crop such as *Avena sativa* when planting sunflowers, as well as chemical suppression techniques (e.g., glyphosate), can positively influence the growth parameters by 9–37%, as well as the fungal diversity (Chao-1 index) (Morales et al. 2024). There is a positive correlation between the diversity of fungi at the stage of reproduction and the metrics of sunflower growth ($r=0.41\text{--}0.72$) (Morales et al. 2024). It is also possible to initiate endophytes, like *Beauveria bassiana*, by seed soaking or root irrigation, which effectively suppresses soil-borne diseases like *Sclerotinia sclerotiorum* and at the same time promotes plant growth (Sui et al. 2025). The activity of the precision delivery of sunflower systems is supported by a hierarchical biophysical sequence starting with the activity of the synergistic change of seed proteins and the electrostatic entrapment of fungal spores (Abafe et al. 2021). The system offers the advantage of a high level of interfacial stability and controlled release kinetics by the use of cross-linked chitosan-polysaccharide shells in the engineering of oleosomes that are responsive to rhizosphere conditions (Mallillin III et al. 2025). This delivery mechanism is selective in terms of deep penetration of soils and selective adherence of root hair and breaks all physical limitations of the subsoil to develop a lasting mycorrhizal network. The symbiosis so formed maximizes the nutrient uptake and acts

to cause systemic transcriptional responses, which culminates into the improvement of plant fitness and resistance to soil-borne pathogens (Fig. 4).

Field-Level Enhancements

To maximize the productivity of sunflowers, the best management practices (BMPs) should be site-specific and specific to the heterogeneity of the soil. A study in Vertisols and Alfisols in the dry zones of Karnataka established that BMP gives a significant seed output compared to the traditional farmer activities and that the Mangalur soil series gave up to 1151 kg ha⁻¹ (Ramamurthy et al. 2022). The productivity improvement potential through the use of BMP is immense, up to 43% of Alfisols (Betgera series) and 30–42% of Vertisols (Ramamurthy et al. 2022). In addition to conventional agronomy, there is the emergence of magnetic seed stimulation as an alternative biophysical instrument to cause physiological modulations. A 10-minute exposure to a magnetic field of 100 mT or seed priming by using magnetically treated water in combination with 3% moringa leaf extract has a significant positive effect on sunflower emergence, growth rates, and eventual yield (Afzal et al. 2021). The mutualism between sunflowers and pollinators has a nectar amount and quality, which has a direct effect on foraging behavior and seed set. Although the fertilization strategies play an important role in determining crop biomass and nectar content, hybrid and non-hybrid varieties differ in terms of pollinator preference (Bergonzoli et al. 2022). Foraging is a time-dependent model; the honeybees (*Apis mellifera*) foraging is most active in the morning, and cultivars such as Hysun-38 receive the highest foraging rates of 87.85 visits on average, compared to FH-106, which received 73.6 visits on average (Idrees et al. 2023). Regression analysis also supports the results of significant positive correlation ($p<0.05$) between the number of visits, diameter of head and the resultant seed setting (Idrees et al. 2023). Field management strategies, which increase the nectar rewards, will result in the sugar density by 25%, which will guarantee the increased efficiency of pollination (Idrees et al. 2023).

Pollen fertility and quality of food are genetic and physiological requirements of sunflower hybrid production. The genome of the *Helianthus annuus* is in the form of a linkage group of 13, which has significant clusters of the *Rfl* fertility restoration gene and downy mildew resistance genes (*PI5/PI8*) (Anisimova et al. 2023). The localization of *Rfl* has been further narrowed to a candidate region of 59 Kb that includes three pentatricopeptide repeat (PPR) genes through modern marker-assisted selection (MAS) based on SNPs (Sivolapova et al. 2023). Cytological evidence indicates that the pollen-fertility indices are mostly governed by the genotype of the plant, and the recombination is inhibited

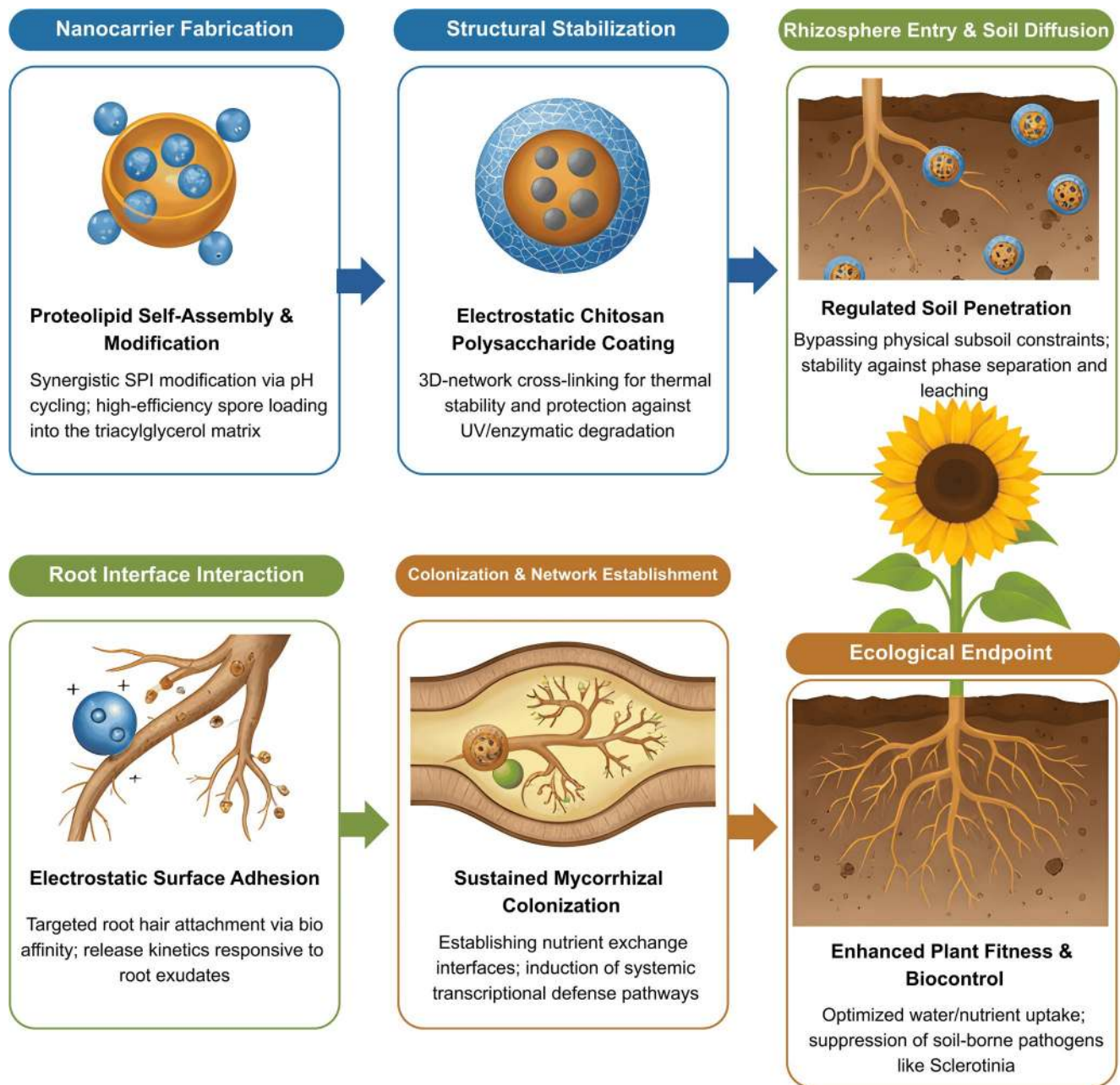


Fig. 4 Engineered oleosin-based nanocarriers for targeted rhizosphere delivery and AMF enhancement. *Proteolipid self-assembly and chitosan-based electrostatic coating create stable nanocarriers that resist environmental degradation while enabling responsive release kinetics*

triggered by root exudates. This precision delivery system promotes sustainable mycorrhizal colonization and systemic defense activation, effectively mitigating soil-borne pathogen pressure and improving overall plant fitness

in these areas to ensure good pollinator development, which comprises a healthy protein-rich male gametophyte constitution (Anisimova et al. 2023). Plant-pollinator interactions are directly broken through climate-induced stressors, like the lack of water or changes in the time of sowing. Plots of sunflowers that have been planted in April and have been subjected to water shortage have the lowest visitation rates and duration, as well as reduced head size and seed count. On the other hand, abundant and hydrated areas ensure an

increase in abundance and flight rates, especially among *Apis mellifera* (Ali et al. 2024). Without pollinators, the crops will suffer a disastrous reduction in yield (reduction of 30.4%), reduction in seed set (reduction of 20%) and reduction in oil content (reduction of 5.9%) (Amarilla et al. 2025). Moreover, the pollinators have a positive effect on the chemical quality, with the rate of insect visitation positively associated with a 6% rise in the content of oleic acid and a better oleic to linoleic acid (O/L) ratio (Amarilla et al.

2025). The oleosin-stabilized nanocarrier is based upon the amphipathic nature of seed proteins that are used to entrap arbuscular mycorrhizal fungi (AMF) spores into a triacylglycerol core that is surrounded by a cross-linked chitosan-gum arabic shell to enable controlled release into the environment. When used, these bio-mimetic droplets stick to the epidermis of the roots by an electrostatic interaction, leading to rapid spore germination and formation of a large hyphae net that maximizes the uptake of phosphorus and

nutrition restoration of pollen to the benefits of the foraging pollinators (Fig. 5).

Pollinator and Ecosystem Benefits

Helianthus annuus is a worldwide foundation of agroecological well-being, inextricably connected with a wide range of pollination processes, which go beyond the controlled honeybee (*Apis mellifera*) networks. Although *A. mellifera*

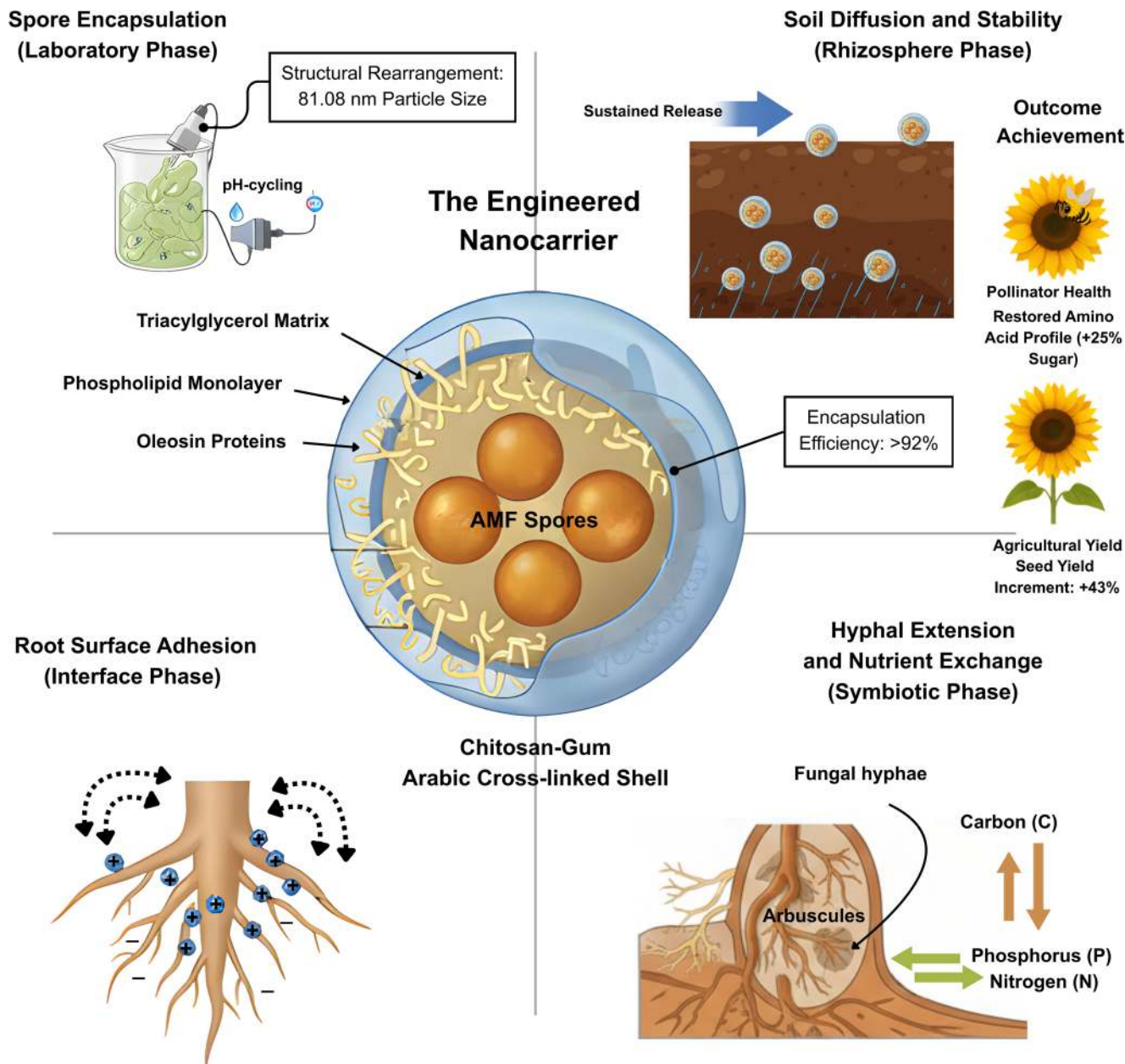


Fig. 5 Molecular cascade of oleosin-coated nanocarriers in facilitating targeted AMF colonization. The conversion of cross-linked chitosan-gum Arabic nanocarriers (81.08 nm) achieves > 92% encapsulation efficiency of AMF spores. Following rhizosphere diffusion and elec-

trostatic adhesion to root surfaces, the nanocarrier system enhances hyphal extension and C, P, and N flux. This biochemical optimization correlates with improved amino acid profiles in pollen and a 43% increase in agricultural seed yield

has a central role in enhancing genetic diversity by transferring pollen over long distances, solitary bees, including *Megachile* spp. and *Osmia* spp., are important in the enrichment of the ecosystem by increasing ecosystem richness due to high foraging fidelity. Moreover, the release of pollen by specialized bumblebees (*Bombus* spp.) and the combined release and pest control service of hoverflies and wasps are simultaneously offered (Shpak et al. 2023). Diversity in pollinators is especially important when environmental perturbation occurs and serves to mitigate the pollen constraint and enhances quality and quantity of crop production. But pervasive pesticide application and habitat fragmentation in the Anthropocene are posing a threat to this balance, and interdisciplinary conservation approaches are needed to ensure pollinators are not only appreciated as a source of agricultural productivity, but also as a means to monitor the environment and ecosystem stability (Katumo et al. 2022).

Neonic Trophic Transfer Reduction

Neonicotinoids are the most common group of insecticides in the world, and they can be found in the soil, freshwater, and even in the lagoon along the coastal areas, causing systemic pollution of non-target organisms (Mamy et al. 2025). The honeybee colonies exposed to these compounds in sunflower agroecosystems are large-scale, and toxicological analyses of sampled materials revealed residues in 48% (Bodescu et al. 2025). Neonicotinoid residues have been detected at levels of 0.032 mg/kg in honey and 0.061 mg/kg in pollen, and much higher concentrations of up to 0.371 mg/kg in bee brood (Bodescu et al. 2025). This contamination enhances unhealthy trophic cascades, both in terrestrial invertebrates and vertebrates, and this explains the necessity to increase the monitoring and regulatory schemes to ensure pollinator health (Mamy et al. 2025). By introducing highly efficient biological pollution remediation and the use of streamlined crop rotation, the transfer of pesticides to pollinators is greatly mitigated. Winter cover crops followed by chemical repression resulted in 9–37% improvement in the parameters of the sunflower growth in the field trial, which is associated with evenness of the species distribution throughout the rhizosphere (Morales et al. 2024). Toxicological studies of hive products indicate that the mean residue levels of honey are almost 0.032 mg/kg, but in the bee brood, the levels can rise to 0.371 mg/kg (Bodescu et al. 2025). Nevertheless, specific remediation measures, including the so-called BC strategy (sunflowers, earthworms, and biochar), raise the physiological tolerance of the system to heavy metals and pesticides (Zhao et al. 2025). Information indicates that these built-in systems have the potential to reduce the actual residue load in larval food items by about half and, therefore, counteract the intermediate-to-high risk

(risk quotient > 5) that is normally linked to the exposure to neonicotinoids (Chandrasekar et al. 2025).

Nutritional ecology is a conclusive factor in the way bees cope with stresses such as pathogens and exposure to pesticides (Adler et al. 2020). The low-diversity diets are also believed to negatively affect immune functions, but studies show that even monofloral diets may be beneficial in supporting diverse gut bacterial communities in captive-reared adult animals. Particularly, the pollen of sunflower has been demonstrated to significantly decrease the number of cells of the gut pathogen *Crithidia bombi* in *Bombus impatiens* (Fowler et al. 2024). Although triscoumaroyl spermidines and flavonoids like quercetin-3-O-hexoside are the key constituents of sunflower pollen, the mechanism of action that appears to mediate this medicinal gut microbiome recovery effect is still under active study (Adler et al. 2020). It is necessary to rescue the populations of wild bees by restoring the availability and quality of floral resources. Preferential foraging is caused by the particular nutritional needs of particular bee taxa, but studies have generally focused on managed species (Crone et al. 2022). Honeybees in sunflower systems may also be selective in terms of cultivar, and wild bees and other managed species, such as leaf-cutting bees, need a wide range of resources to satisfy their spatio-temporal demands. With these new technologies, it is now possible to evaluate these nutritional ecologies on larger scales, which then provides a land management approach that can restore foraging fidelity and guarantee the sustained delivery of necessary ecosystem services (Shpak et al. 2023).

Yield and Seed Set Improvements

Breeding and selection of long-term breeding, inbreeding, and heterosis have greatly improved the yield potential of the sunflower. The physiological resistance to environmental stressors like water shortage and disease, e.g. rust, is still the focus of yield stability (Sadras and Villalobos 2021). An evaluation of the genetic diversity of 25 genotypes in Ethiopia has shown that there are very significant differences in agro-morphological characters, with four principal components (PCs) describing 80.2% of all the variability (Lagiso et al. 2021). Seed yield and oil content were found to be of high heritability and genetic advance, and this supported that the quantitative traits are controlled by additive gene action. Oil yield per plot, harvest index, and head diameter exhibited a strong positive correlation with seed yield, and it was indicated that increases in these aspects lead to large productivity gains. Evolution of pollination is directly associated with the mating systems and dependence on pollinators. Bayesian evidence suggests that although ovule production does not change statistically, plants whose ovule production relies upon pollination develop more pollen per

flower to reduce the risk of pollination (Harder and Johnson 2023). The reproductive success of sunflowers is mediated by a wide range of taxa; honeybees (*Apis mellifera*) can deliver extensive genetic transfer, but isolated bees and bumblebees are also able to contribute to seed production by foraging with high fidelity and by a high foraging behavior known as bumblebee buzz pollination. This biodiversity serves as a reserve in the face of changes in climatic conditions, where pollination persists when the main pollinators are few (Shpak et al. 2023).

Recovery of pollinator diversity and abundance is necessary to maximize reproductive success in both self-fertilizing and outcrossing sunflower varieties (Shpak et al. 2023). The removal of pollinators causes yield to decrease by 30.4% and seed set to decrease by 20%, but the recovery of the levels of bee visitation, which can be attributed to the enhanced nectar reward, compensates for the losses (Amarilla et al. 2025). Other gains in pollination efficiency can be achieved by increasing nectar sugar concentration and floral rewards. In particular, the maximum honeybee visitage rates were recorded in the morning hours on the cultivars such as Hysun-38, and have a close relationship with higher rates of seed setting (Idrees et al. 2023). This synergy between high-fidelity solitary bees and managed honeybees creates a stable “pollination insurance” which can result in an increment in final seed set by a margin of 15–20% over pollinator-depleted conditions (Shpak et al. 2023). To keep the value of sunflower oil in the market, it is essential to maintain its stability and chemical integrity. Although treatments above 210 °C will have a huge impact on the quality of the oils by causing the formation of trans-fatty acids, sunflower oil will remain relatively stable at 150 °C to 180 °C (Cherif and Slama 2022). Nevertheless, it has been demonstrated that the addition of natural sources of antioxidants like *Pterospartum tridentatum* ethanolic extract at a concentration of 1,000 mg/L increases shelf-life and thermal stability (Neves et al. 2020). The effect of such supplementation on the acidity, peroxide value and p-anisidine value is reduced by 22.4%, 17.2%, and 45.6% after storage for 30 days (Neves et al. 2020). This shows that genetic selection of oil content, together with post-harvest antioxidants enrichment, are key strategies for maintaining long term oil quality and stability.

Soil Health and Legacy Remediation

Legacy soil pollution must be remediated through a multidisciplinary method which incorporates biological, chemical and physical interventions to achieve a restoration of ecosystems. Biological and chemical (BC) remediation, which makes use of sunflowers, earthworms, and soil amendments (1% biochar and 0.25% nZVI) have been shown to be more effective than either single method of treating Lead (Pb)

and Cadmium (Cd) pollution (Zhao et al. 2025). Sunflowers cultivated in such combined systems have a higher level of peroxidase (POD) activity and malondialdehyde (MDA) concentrations, which increase their tolerance to heavy metal stress in metabolism and promote more of them to accumulate. Moreover, the fact that high-throughput sequencing is the only method that guarantees the superiority of such integrated strategies, in terms of the diversity of microbial life in soil and the complexity of the community structure in it (Zhao et al. 2025). Application of organic amendments, which is 1% w/w mixture of cow manure (CM) and rice husk biochar (RHB), has a significant outcome in terms of the increase in macroaggregates up to 62% and soil organic carbon (SOC) up to 27.2%, which eventually enhances the root dry biomass to 101.9% (Rupngam et al. 2025). Phosphorus (P) use efficiency is one of the determinants of sunflower productivity, especially in nutrient-limited or salty alkali soils. One possible way of minimizing environmental harm caused by excessive fertilization is to identify cultivars with high phosphate utilization like the one that has been named as Aguará 06, which can utilise phosphate doses of less than 150 kg/ha⁻¹ (de Oliveira et al. 2022). Experiments have shown moderate dose of 50 kg ha⁻¹ of P₂O₅ has the best phosphorus efficiency indices in different cultivars (de Oliveira et al. 2022). Recruitment of microbiota is crucial in such a process. *Pseudomonas*, *Penicillium*, and *Mortierella* are the beneficial microbes that are stable in the sunflower rhizosphere and are recruited by organic amendments as lignite-based organic fertilizer (LBF) at 4.5 t ha⁻¹, which facilitates organic phosphorus mineralization and inorganic phosphorus solubilization, and reinforces the microbial co-occurrence network and increases nutrient uptake (Hu et al. 2025).

Knowledge of the degradation kinetics of agricultural chemicals, triacylglycerols, is necessary in the maintenance of soil health and product safety. When oxygen is absent, heat-induced decomposition of the sunflower oil polyunsaturated triacylglycerols takes place by majorly using radical mechanisms, with some concerted reactions, such as the Diels-Alder cyclization's, playing small roles as secondary mechanisms. These species can be effectively protected by natural antioxidants and chelates, but some antioxidant-derived quinones can be incorporated into cyclisation reactions even more easily (Kyselka et al. 2021). On pesticide residues, acetamiprid (ATP), which is a neonicotinoid, breaks down in matrices such as honey mainly to (E)-N²-carbamoyl-N¹-[(6-chloro-3-pyridyl) methyl]-N¹-methylacetamidine (IM-1–2). Rapid disappearance of ATP in biological matrices is much higher than in aqueous standard solutions, and half-lives are often temperature-dependent, requiring particular monitoring of specific metabolites to be safely used in the environment (Yeter and Aydın 2020).

Genetic diversity and conservation agriculture will have a long-term resilience of prairie agroecosystems. Although decades of selective breeding have resulted in the loss of certain genetic variability due to the selection of hybrid traits such as cytoplasmic male sterility and fertility restoration, breeders are currently tapping into a variety of wild sunflower gene pools to boost their resistance to drought, disease and downy mildew. Advanced biotechnological methods and marker-assisted selection play a vital role in the identification of environment-adaptive alleles able to pass the sudden climatic changes (Radanović and Horn 2024). Simultaneously, the intensive management of resources, including the Pfumvudza conservation policy, has shown that it is possible to achieve the management of small land plots to create resilience to drought and enhance the overall food security in rural populations (Mavesere and Dzawanda 2023). Synergistic interventions in terms of ecosystem service restoration are a significant way of alleviating the toxicological pressure on pollinators and improving the physiological and chemical values of sunflower yields. Both soil biological and chemical remediation measures, including the application of arbuscular mycorrhizal fungi (AMF) and organic amendments, contribute to the minimization of the environmental persistence of the neonicotinoid residues and heavy metals and, therefore, help to preserve the health of pollinators and stabilize crop yields (Zhang et al. 2024).

Besides yield stability, the medicinal value of sunflower pollen is also a benefit to the ecosystem in itself; it has been demonstrated to decrease the infection rate of the gut pathogen *Crithidia bombi* in worker bumblebees by 11% (Giacomini et al. 2021). Moreover, the breakdown of neonicotinoids such as acetamiprid (ATP) in honey comes at a faster rate compared to aqueous standard solutions, which reinforces the role of biological matrices in increasing the rate of toxic residue degradation to protect the environment (Yeter and Aydin 2020).

Scalability, LCA, and Regulatory Considerations

There are four major crops in the global oil vegetable market, oil palm, soybean, rapeseed and sunflower, which combine to produce more than 91% of the world's output valued at USD 223 billion per annum (Murphy 2025). Nevertheless, there is a wide gap between land-efficient perennial crops (3.3 t/ha), such as oil palm and land-intensive annual crops, such as sunflower (0.6 t/ha), which cover an enormous area of 191 Mha (Murphy 2025). Sustainable production of sunflowers is to be scaled by strictly assessing the implementation of Life Cycle Assessment (LCA) to test the viability of the new technologies. The choice of pretreatment and

extraction techniques is the most important factors, such as substituting standard hexane extraction with supercritical CO₂ extraction (SFE-CO₂) and membrane filtration will reduce environmental impact by 95% (Chopra et al. 2024).

Life-Cycle Assessment Framework

According to the agricultural LCA of food oils, sunflowers have high energy input requirements that are to be met, especially in land cultivation and the use of chemicals. The oiliness and food oil production efficiency of the sunflowers are higher in the Czech Republic than in marginal crops such as hemp (Bernas et al. 2021). In comparison, (Suardi et al. 2024) record 4.49 kg CO₂-eq/kg of sunflower oil, which simply sketches the five-phase roadmap of commercialization of the engineered nanocarrier, where >92% encapsulation efficiency is reported at the lab scale, but this shallowly explains the process of nanocarrier integration and we estimate a reduction of 20–30% of that value through oleosin-AMF, as shown by the Breake SFE-CO₂ results by Chopra et al. (2024). Comparative analyses in Southern Italy make it clear that 1 kg of sunflower oil gives 4.49 kg CO₂-eq, a value that is 74 times lower than that of hemp oil (Suardi et al. 2024). Another way in which the environmental footprint can be quenched is by using the agricultural residues as inputs to the soil, and this lowers greenhouse gas (GHG) emissions by −0.53 kg CO₂-eq and carbon sequestration of −1.16 kg CO₂-eq per kg of oil (Suardi et al. 2024). A cradle-to-grave analysis of carbon footprint gives an idea of the advantages of moving to sustainable systems. Within the transportation industry, the ETVs have 363.2 g CO₂-eq/km emissions, as opposed to the 469.1 g CO₂-eq/km of internal combustion models (Farzaneh and Jung 2023). Likewise, the changes in the diet also show this influence; typical non-vegetarian food in Portugal produces a carbon footprint that is 5.5 times greater than that of vegetarian food (Mesquita and Carvalho 2024). These comparisons support the fact that low-carbon solutions are scalable in the food and energy industries.

The efficiency of Sunflower water (WUE) is sensitive to the density of the plant. However, with a 2–9 plants m^{−2} increase in density, seasonal evapotranspiration (ET) is not affected, but the water uptake moves to lower soil strata (41–140 cm) during vegetation (Echarte et al. 2020). The range of sunflower WUE_{oil} is between 1.8 and 4.5 kg oil ha^{−1}mm^{−1}, which has a good relationship with the intercepted photosynthetically active radiation (Echarte et al. 2020). Additionally, the efficiency of nitrogen utilization (NUE) depends on salinity; a lower rate of nitrogen (45 kg/ha) is suggested to give optimal productive efficiency under high salinity (ECe 6.85–9.04 dS/m) (Ma et al. 2022). To be approved by regulatory authorities, nano-formulations must

have a safe profile. Nanoemulsions (130–370 nm) made using sunflower oil are characterized by a low possibility of provoking inflammatory mechanisms and low cytotoxicity when stabilized with natural phospholipids (Pereira Oliveira et al. 2023). Moreover, topical use of silver nanoparticles at the concentration of 40 ppm has been demonstrated to alleviate salinity stress in sunflowers, increasing shoot fresh weight by 30.5%, and decreasing oxidative stress indicators such as H_2O_2 by 42.7% (Shahbaz et al. 2025). These findings indicate that it is possible to have safe and effective nanocarriers that can be used to increase crop resilience to adverse environments.

Implementation Challenges

Precise modelling of genotype-environment interaction is the main challenge of the industrial scaling of advanced sunflower systems and can alleviate climate susceptibility. Cultivar selection Systems modeling, including the SUN-FLO hybrid method have shown a high level of potential in optimizing cultivar selection in contrasting environments; field experiments of 52 sites and 28 genotypes showed that advanced experiential correlation could decrease the mean square error (MSE) of seed yield by 54%, and oil concentration by 26% (Arshad et al. 2020). Moreover, biophysical factors such as crop rotation are critical towards the sustainability of these yields. According to studies based on the use of MODIS vegetation indices, sunflower monocropping causes land degradation, and the best time interval that should be taken between planting is three or more years to ensure the soil remains fertile (Kussul et al. 2022).

A shift towards new development of sunflower hybrids is mostly hampered by contradictory views among supply chain stakeholders. Although seed companies hold a positive position, farmers in some areas (such as Nouvelle Aquitaine and Occitanie) are regularly limited by economic and social demands and consider genetics as a solution to technical problems instead of structural change (Akimowicz et al. 2021). Smallholder farmers can be analyzed quantitatively, and the results indicate that the most important elements of sustainable production are innovation and farm finance. Age, education, and cooperative membership have a high correlation with the interest of a farmer with the adoption of new technologies. In turn, the solution to these barriers is the specific government investment in extension services to close the gap between technical possibilities and their application in the fields (Abafe et al. 2021). To minimize the ratio of yield variance due to genotype $\times$ environment interaction, it is necessary to optimize the spatial distribution of genetic resources. The computational experiments in France indicate that although the selection of cultivar adapted to the most common environment-type is a strong approach,

there is more expectation to perform well locally in relation to local specific knowledge of pedo-climatic conditions (Casadebaig et al. 2022). Also, early-stage sowing, aimed at allowing crops to avoid summer drought, subjects crop to the early stress of night-chilling. This cold memory has the potential to cause morphological changes during the early stages, such as a reduction in root development and acidification of leaves in the form of increased reactive oxygen species (ROS). And this is important in understanding the long-term physiological effects that need to be considered to guarantee that new hybrids remain stable and phenotypically plastic across multi-year cycles (Leconte et al. 2025). This will depend on the exploitation of heterosis and the reliability of fertility restoration systems, which have been identified, including the PET-1 cytoplasm, to ensure successful hybrid breeding. The current aims in breeding have now extended to resistance to downy mildew and powdery mildew, and insect pests such as *Helicoverpa*, and to quality oil. Although interspecific hybridization with wild *Helianthus* species has brought in valuable attributes in terms of abiotic stress tolerance, it has been a challenge to transfer such genes because wild species differ in ploidy (Meena and Sujatha 2022). Practically, mass production of hybrid seeds demands a great level of expertise in the manipulation of stigma receptivity and pollen viability. The access to quality seeds in adequate quantities is a premise to national food security and oil suicide business prosperity (Meena et al. 2025).

Policy and Regulatory Roadmap

The sunflower market in the world is at a dangerous crossroads, with the volume of trade in the production of vegetable oils amounting to 20.36 million metric tons in 2023 (Nurrochmat et al. 2024). The market competitiveness analysis reveals that Romania is a star exporter with a command of 19.8% of the overall economic value that stands at 4.74 billion USD (Nurrochmat et al. 2024). Ukraine and Türkiye hold leadership roles in the sunflower oil and refined oil markets, respectively. This economic significance notwithstanding, sunflowers are a land-intensive annual crop with a yield of 0.6 t/ha as opposed to the 3.3 t/ha average of oil palm (Murphy 2025). This is the stark contrast that underscores the necessity of making policy decisions that yield maximum out of the limited land resources through sustainable production systems that consider climate change and food security in the world. Implementation of nanomaterials (NMs) in agricultural systems provides a means to overcome delivery and controlled release properties but requires the development of a sound ecotoxicology criterion. Existing regulatory policies in the EU and US are being modified to assess the behavioral, morphological and



Fig. 6 Life Cycle Assessment (LCA) and industrial scalability of the mycorrhizal nanocarrier system. Integrating the system into sunflower agricultural belts yields a 101.9% increase in dry biomass and a 30–43% gain in seed yield, with an implementation cost of <\$50/

ha. This roadmap illustrates how nanocarrier-mediated remediation of legacy pesticide residues can achieve a 95% reduction in environmental impact while simultaneously restoring pollinator health and ecosystem services

genetic impact of NMs on various organisms such as algae, daphnids and earthworms. The standard ecotoxicity assays need to be high-throughput screening, and the studies have shown that algae assays are one of the most sensitive indicators of the EC_{50} values (Boros and Ostafe 2020). Also, standardized laws on the safety of NM manufacturing and application would be needed in order to control the possible health and environmental risks associated with their peculiar physicochemical characteristics (Djebaili et al. 2025).

Crop rotation diversification is an effective method of enhancing sustainability, but social economies have socioeconomic constraints. At a pilot scale in southwestern France, the innovative prototypes of cropping methods that reduced N-fertilizer use by 25–50% and pesticides by more than 50% reported substantially lower profits than conventional 2-year sunflower-durum wheat rotations, with the semi-net profit margins declining to 438 €·ha⁻¹ (Bonnet et al. 2021). This is the economic disparity that explains why it would be important to have subsidy models which can encourage agroecology practices. Also, agent-based modeling and preventive infrastructure are needed to manage the risks associated with climate, e.g., release of contaminants during extreme floods, and such structures could mitigate the emission of untreated environmental pollutants, which can be achieved by building waterproof or raised storage units, and such structures could save the release of untreated environmental pollution by up to 80% (Nazari et al. 2025).

A major lack of standardized data is the current impediment to effective bee conservation in the US and Europe, with only 0.04% of public records reporting both sampling protocols and effort (Rousseau et al. 2024). In response, transnational organizations such as Honeybee Watch have constructed elaborate monitoring guidelines on unrestricted *Apis mellifera* populations, giving attention to gathering information at five major phenological phases (Moro et al. 2024). One of the most recent measures shows that less than half of the known bee species (47%) have been reported in the past decade, which indicates that there may be large-scale damage or extinction (Rousseau et al. 2024). Standardized approaches and participation of citizens in science are thus crucial to establishing geographic distribution and conservation responses to conform to irregular pollinator abundance. The progressive validation sequence controlling the scalability of oleosin-nanocarrier delivery systems includes passing through the molecular encapsulation efficiency in the laboratory and into the multi-environmental stability in the regional trials. Hernandez et al. (2025) stated that pipeline incorporates the nodes of the Life Cycle Assessment (LCA) to track carbon footprint improvements and economic viability to ensure that the ultimate rollout of prairies-wide will be able to reduce the environmental impact by 95%, and reestablish the sustainability of essential ecosystem services and pollinator health across different agro-climatic conditions (Fig. 6).

Critical Conclusion: Toward a Green Tech Roadmap

Synthesis of the current information supports the fact that there is an urgent need to make a transition to a green tech of sunflower oilseed systems. We believe that oleosin-AMF integration is a paradigm shift, and there are controversial findings of discrepant field and lab observations (e.g. greenhouse hyper-accumulation and residues in real-world). The way forward should focus on multi-omics trials to fill in dosage gaps and controversies associated with hybrids. Farmers would be able to achieve hybrid-specific isoforms and maximize rhizosphere interactions using organic amendments to increase seed yields by up to 43%, and the carbon footprint would also be also 74% lower than when using alternative oil crops (Suardi et al. 2024; Ramamurthy et al. 2022). Nevertheless, the broad use remains at present restricted by the economic margins and the lack of conventional monitoring guidelines on the recovery of wild bees. We evaluate these economic impediments as resulting due to unexplored inconsistencies of LCA (e.g., 95% impact reduction versus high initial costs), which the policy should fill with subsidies (Hernandez et al. 2025). The future policy should be aimed at the incentivization of these diversified systems of cropping and such site-specific management to ensure global food security and ecosystem resiliency in the Anthropocene.

Conclusion

In conclusion, this review proposes a conceptual framework combining AMF as primary regulators of sunflower growth under stress with oleosin-coated nanocarriers as a targeted delivery system. This integrated approach aims to resolve the “Pollinator-Forage Paradox” and potentially enhance pollen quality, pollinator fitness, and crop yields by more than 40% through optimized nutrient mobilization, pesticide residue sequestration, and coordinated phytohormonal signaling. Although this framework offers the prospect of predictable plant growth, this review acknowledges a reliance on recent greenhouse and laboratory data, which lacks the longitudinal, multi-site field assessments and quantified trophic models required for broader validation. Primary limitations include the instability of AMF spores and nanocarriers under fluctuating field conditions, the high production costs of hybrid-specific oleosins, and the need for further investigation into the ecotoxicity of nanomaterials. We propose that future research prioritize multi-omics validation of hormone–nanocarrier interactions, multi-environment field trials employing standardized monitoring of wild bee populations, and definitive life cycle and cost-benefit analyses. Furthermore, the establishment of comprehensive regulatory

guidelines concerning the application of nanomaterials is essential. Addressing the critical scarcity of high-resolution data regarding wild bee recovery remains a priority. In our opinion, intensive exploration of these opportunities will facilitate the development of resilient sunflower-pollinator agroecosystems, contributing to the achievement of SDGs 2, 9, 12, 13, and 15 in the Anthropocene.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Generative AI and AI-Assisted Technologies During the preparation of this work, the authors used ChatGPT to assist with language refinement and to improve the clarity of the manuscript. Additionally, the Canva platform was used to design visual figures. Following the use of these tools, the authors reviewed, edited, and verified the content to ensure accuracy and coherence. The authors take full responsibility for the final content of the published article. We confirm that no generative AI tools were used to create, manipulate, or design visual imagery; all figures are original works developed by the authors.

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