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Article

Advances in the Mechanisms and Control Strategies of Continuous Cropping Obstacles in Medicinal Plants

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Abstract: Continuous cropping obstacles constrain the yield, medicinal quality, and sustainability of medicinal plant production. These obstacles arise from coupled changes in soil physicochemical properties, accumulation of bioactive metabolites with allelopathic potential, and rhizosphere microbial imbalance that increases disease pressure. This review summarizes typical symptoms and the progression of continuous cropping obstacles in medicinal-plant systems, with emphasis on allelopathy and microbe-associated processes that regulate metabolite persistence and pathogen enrichment. We further compare current mitigation options, including agroecological management, soil amendments, and microbiome-based interventions. Key priorities for future research are to establish causal links and effect sizes under field conditions, identify functional taxa and pathways that mediate metabolite turnover and disease suppression, and integrate multi-omics measurements with a small set of interpretable indicators to support early warning and targeted management for soil recovery and sustainable cultivation.

Keywords: rhizosphere microecosystem; root exudates; soil nutrients; continuous cropping obstacles; medicinal plants

1. Introduction

Medicinal plants constitute a key raw material base for the traditional Chinese medicine sector, and both yield and medicinal quality are closely tied to the sustainable supply of herbal resources. In recent decades, medicinal-plant cultivation in China has expanded substantially, while suitable production zones for many quality-sensitive species remain geographically constrained [1]. This mismatch between land availability and production demand has increased cropping intensity and encouraged repeated planting of the same species in the same fields, making continuous cropping obstacles increasingly prominent in practice [2]. The problem is particularly evident for medicinal crops harvested for roots or rhizomes, including *Panax ginseng*, *Salvia miltiorrhiza*, *Panax notoginseng*, and *Glycyrrhiza uralensis*, which are often cultivated for multiple years at fixed sites to maintain stable traits and active constituents [3]. However, prolonged continuous monocropping is frequently associated with degradation of soil physicochemical properties, elevated soilborne disease pressure, and declines in yield and medicinal quality traits, thereby constraining sustainable production [4]. As a result, continuous cropping obstacles have become a major bottleneck for standardized, environmentally responsible, and sustainable cultivation of medicinal-plant resources.

Earlier work often attributed continuous cropping obstacles to single drivers, such as nutrient depletion or soilborne diseases. Increasing evidence, however, supports a systems perspective in which these obstacles reflect cumulative shifts within the plant-soil-microbiome system [5]. Under continuous monocropping, root exudates and residue inputs can accumulate in soil and reshape the rhizosphere environment. Concurrent changes in soil structure, pH, and nutrient balance can further influence metabolite persistence and microbial assembly, collectively favoring pathogen buildup and functional instability [6]. In response, a range of mitigation strategies has been explored across medicinal-plant systems, including crop diversification practices such as rotation and intercropping, soil amendments, microbiome-based regulation, and plant-based approaches. Yet performance remains variable across species, soils, and management contexts, and mechanistic understanding is still incomplete, particularly with respect to causal pathways and feedback directions. This review synthesizes current advances in the mechanisms underlying continuous cropping obstacles in medicinal plants and summarizes recent progress in mitigation strategies, with the aim of supporting mechanism-informed management and more sustainable cultivation.

2. Mechanisms of Continuous Cropping Obstacles in Medicinal Plants

Continuous cropping obstacles in medicinal plants are best understood as cumulative, system-level shifts within the plant-soil-microbiome system rather than the outcome of any single factor [5]. Under continuous monocropping, plants commonly show reduced seedling emergence, impaired root growth, and declines in key secondary metabolites, whereas soils often exhibit changes in structure, nutrient stoichiometry, and soilborne disease pressure (Figure 1). Accordingly, this section synthesizes evidence across three interconnected domains: degradation of soil physicochemical properties; allelopathic effects, including autotoxicity, associated with root-exuded and residue-derived metabolites; and rhizosphere dysbiosis with pathogen enrichment. These domains are mechanistically coupled; for instance, soil structure and pH influence the transport, sorption, and persistence of allelochemicals, and the microbiome mediates both compound turnover and disease suppression. Because much of the current literature remains correlational, we distinguish well-supported mechanisms from associations that still require manipulative validation.

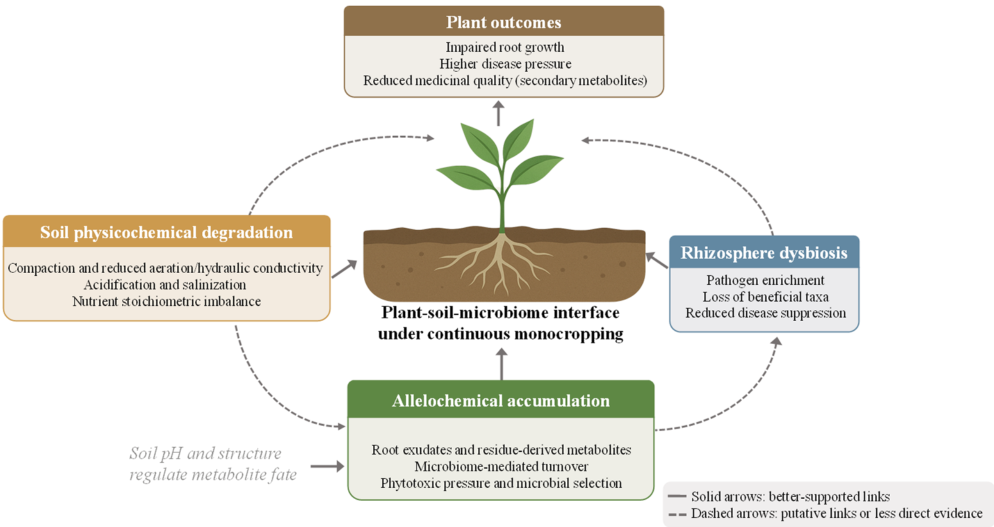

Figure 1. Mechanistic framework for continuous cropping obstacles in medicinal plants.

2.1. Degradation of Soil Physicochemical Properties

2.1.1. Soil Physical Properties

Continuous monocropping is frequently associated with deterioration of soil physical properties, manifested by reduced aggregate stability, increased bulk density, declines in effective porosity, especially macropores, and compromised soil aeration and hydraulic conductivity [7]. These changes are often attributed to long-term shifts in near-surface inputs and the turnover of organic matter, including root exudates and residue inputs, together with altered microbial activity that modifies the formation and persistence of soil aggregates [8]. In *Panax ginseng* production systems, longer continuous cropping duration has been reported to coincide with a higher fine particle fraction and a higher proportion of poorly functional pores. These changes can restrict gas exchange and water movement and have been linked to inhibited root elongation and deterioration of medicinal quality [9]. Similarly, soil compaction can create rhizosphere hypoxia. Under low oxygen conditions and during reoxygenation, roots may experience oxidative stress and membrane damage, which can increase susceptibility to root disorders in continuously cropped soils [10]. Beyond direct mechanical impedance to roots, structural degradation can also exacerbate vertical heterogeneity of soil moisture, with surface waterlogging alongside drier subsoil, thereby constraining root respiration and reshaping microbial microhabitats [11]. Collectively, these physical constraints not only limit root growth and function but also influence the transport and persistence of root-derived compounds and microorganisms, thereby interacting with allelochemical accumulation and rhizosphere dysbiosis [12].

2.1.2. Soil Chemical Properties

Continuous monocropping of medicinal plants is often associated with soil acidification, soluble-salt accumulation, and shifts in rhizosphere ion equilibria. Soil acidification is commonly linked to high ammonium nitrogen inputs and subsequent nitrification, net removal of base cations by harvest, and rhizodeposition of organic acids and other acidic metabolites, which together increase rhizosphere proton loading [13]. As soil pH declines, buffering capacity can be exhausted, and Al may become more bioavailable, which is frequently linked to oxidative damage in roots, including lipid peroxidation, and compromised membrane integrity [14]. Soil acidification has been reported across multiple medicinal-plant monocropping systems, although the magnitude and drivers vary with soil type and management. In *Salvia miltiorrhiza*, soils with longer monocropping histories show a clear downward trend in pH [15]. In *Panax notoginseng*, continuous cropping is linked to soil acidification and altered nitrogen transformation, including ammonium accumulation consistent with suppressed nitrification [16]. Moreover, pH shifts can change the speciation and sorption behavior of phenolic allelochemicals, affecting their mobility, persistence, and bioavailability. This provides a plausible linkage between acidification and allelopathic pressure, but evidence based on field-relevant concentrations is still needed [17].

Soluble-salt accumulation is another facet of soil chemical degradation, especially under high fertilization and irrigation inputs with limited leaching [18]. Salinization elevates soil electrical conductivity and increases osmotic stress by lowering soil water potential, restricting root water uptake and contributing to physiological drought. Concomitant shifts in cation composition can further perturb nutrient uptake. Such ionic stress can also reshape rhizosphere microbial activity and enzyme processes, reinforcing chemical and biological feedbacks that are unfavorable for plant performance. Collectively, degradation of soil chemical properties can interact with disrupted nutrient cycling (Section 2.1.3) and rhizosphere dysbiosis (Section 2.3), thereby amplifying continuous cropping obstacles in medicinal-plant systems.

2.1.3. Soil Nutrient Imbalance

In continuously monocropped medicinal-plant systems, the availability and balance of soil nutrients often shift over time. Because species differ in nutrient demand and fertilization regimes are often adjusted in response to yield decline, long-term monocropping can deplete some nutrients while allowing others to accumulate, resulting in an imbalanced nutrient supply. In *Salvia miltiorrhiza*, declines in available phosphorus and potassium and a shift in inorganic nitrogen pools, with higher ammonium relative to nitrate, have been reported under continuous cropping. These patterns are consistent with reduced nitrification activity, although confirmation at field scale is still needed [19]. Similarly, in continuously cropped *Codonopsis* soils, depletion of exchangeable base cations, including Ca and Mg, and broader shifts in nutrient balance have been observed, suggesting progressive cation depletion with repeated planting [20]. These nutrient imbalances can constrain root nutrient acquisition and restructure the rhizosphere microbiome by changing resource limitation and soil carbon, nitrogen, and phosphorus stoichiometry [21].

2.2. Allelopathy in Medicinal Plants

2.2.1. Major Types and Characteristics of Allelochemicals

Allelopathy, which often overlaps with autotoxicity, is frequently implicated as an important contributor to continuous cropping obstacles in medicinal plants. It refers to the production and release of bioactive secondary metabolites from root exudates and residue inputs, including litter decomposition products, which can directly inhibit conspecific or neighboring plants and indirectly reshape rhizosphere microbial interactions [22]. In medicinal-plant monocropping systems, allelochemicals derive primarily from root exudates, residue inputs, and litter decomposition products, and commonly include phenolic acids, terpenoids, flavonoids, and quinones [5]. Among these, phenolic acids such as vanillic acid, p-hydroxybenzoic acid, ferulic acid, and cinnamic acid are repeatedly reported across continuous monocropping systems and have been quantified in rhizosphere soils, although concentration ranges are highly context-dependent and vary with species, soil type, depth, and season [23]. In *Panax* species, multiple phenolic acids have been detected in continuously cropped soils, and p-hydroxybenzoic acid and ferulic acid have been linked to inhibited root growth and to shifts toward disease-associated fungal taxa in some systems [24]. In the rhizosphere of *Salvia miltiorrhiza*, phenolic acids have been identified in rhizosphere soils and are discussed as candidate autotoxins, while bioassays suggest inhibitory effects on germination and root elongation [25]. In addition, volatile organic compounds, particularly terpenoids, may exert allelopathic effects by moving through air-filled pores at the soil and air interface, thereby suppressing nearby plants or modulating the activity of specific soilborne pathogens [26]. The accumulation and activity of allelochemicals are strongly conditioned by soil physicochemical context because pH, temperature, moisture, redox status, and sorption and transport processes jointly regulate their release, transformation, and degradation rates [27]. Under long-term continuous monocropping, reduced microbial diversity or loss of allelochemical-degrading taxa can lower degradation capacity, increasing the residence time of allelochemicals in the rhizosphere and potentially amplifying phytotoxic pressure and rhizosphere dysbiosis [23].

2.2.2. Mechanisms of Allelochemical Effects

Allelochemicals can influence plant performance and rhizosphere microbiome stability through both direct phytotoxicity and indirect microbiome mediated pathways. Phenolic acids and related compounds can compromise membrane integrity and cellular redox homeostasis, leading to reactive oxygen species accumulation and lipid peroxidation, with consequent inhibition of root elongation [28,29]. Depending on compound identity and dose, these stresses may also be accompanied by altered cell-cycle activity in root meristems [30]. In *Panax* systems, phenolic acids are frequently discussed as candidate allelochemicals linked to growth suppression and pathogen enrichment under continuous monocropping, but mechanistic claims should be linked to primary studies and interpreted in relation to field-relevant concentrations [1]. Allelochemicals can also perturb phytohormone signaling, including auxin and ethylene pathways, by altering biosynthesis, transport, and signaling-gene expression, thereby reshaping root development and stress responses [30]. Beyond direct plant effects, phenolic acids can differentially favor pathogen-associated taxa and attenuate beneficial populations, contributing to rhizosphere dysbiosis in consecutive monocropping systems [31]. At the system level, reduced microbial degradation capacity can prolong allelochemical residence time in soil, thereby promoting accumulation and reinforcing phytotoxic pressure as well as pathogen-enabling microhabitats [17]. At the same time, allelochemicals are not uniformly negative. Dose dependence and environmental context may produce hormetic effects or priming-like responses in some systems, but whether such benefits occur under field-relevant concentrations in medicinal-plant monocropping remains insufficiently resolved [32]. Notably, the disease-suppressive potential of allelochemical-degrading microbes underscores degradation capacity as a mechanistically meaningful lever in some pathosystems.

2.3. Imbalance of the Soil Microecosystem

2.3.1. Shifts in Soil Microbial Communities

Across medicinal-plant systems, long-term continuous monocropping is consistently accompanied by shifts in rhizosphere microbial community composition and functional potential, with recurrent signatures of pathogen enrichment, depletion of beneficial or disease-suppressive taxa, and reduced community/network stability [33]. In *Panax ginseng*, amplicon-based surveys across cultivation ages report increased relative abundance of soilborne pathogenic fungi, particularly *Ilyonectria* spp. and *Fusarium* spp., together with broad community turnover [34]. In *Panax notoginseng*, continuous cropping is associated with reduced fungal diversity and enrichment of taxa positively associated with plant mortality, including *Fusarium* spp. (e.g., *Fusarium* oxysporum) [35]. Multi-year comparisons in *Salvia miltiorrhiza* likewise report declines in beneficial bacteria (e.g., *Bacillus*) and higher *Fusarium* abundance in some continuous-cropping years, coinciding with measurable changes in root quality in certain studies [15]. Importantly, intervention evidence supports a microbial component: soil fumigation or disinfestation can redirect microbial recovery trajectories and improve plant performance in *P. notoginseng* systems [24]. Beyond taxonomic shifts, decreases in beneficial functional groups, such as plant growth-promoting rhizobacteria, antagonistic Actinobacteria, and symbionts including arbuscular mycorrhizal fungi (AMF), are frequently reported and may weaken nutrient mobilization and biological disease suppression. Observations in *Glycyrrhiza uralensis* and *Scutellaria baicalensis* are informative, but key quantitative claims are best anchored in peer-reviewed field studies [36]. Collectively, the literature supports rhizosphere dysbiosis and elevated soilborne disease pressure as common features of continuous monocropping. At present, however, pathogen enrichment is difficult to classify as strictly causal or purely consequential: early shifts in soil conditions and exudate chemistry may favor pathogenic taxa, whereas pathogen attack and host stress can further reshape exudation and suppressive functions, reinforcing dysbiosis. Resolving directionality and feedback strength will require time-resolved field designs coupled with manipulative tests (e.g., inoculum addition or suppression, soil sterilization followed by reinoculation, and synthetic-community reconstruction).

2.3.2. Interactions between Allelochemicals and Microbes

Allelochemicals can influence medicinal plants directly and can also modulate rhizosphere community composition and activity, creating bidirectional feedbacks within the coupled plant–soil–microbiome system [33]. Specific microbial taxa can assimilate, transform, or mineralize allelopathic compounds, whereas sustained inputs and accumulation of these compounds can impose selective pressure that reshapes community structure and functional potential. Crucially, both magnitude and direction of responses are often concentration- and soil-matrix dependent. At low, field-relevant concentrations, some compounds may have weak or context-dependent effects on microbial activity, whereas higher concentrations, prolonged exposure, or reduced soil pH buffering and sorptive retention can increase bioavailability and select for disease-associated taxa, consistent with the dose dependence discussed in Section 2.2.2. In *Panax notoginseng*, multiple studies report phenolic acids in rhizosphere soils and show that phenolic-acid perturbations can restructure the microbiome and favor taxa associated with disease outcomes [23]. Related work further indicates that reduced autotoxin-degradation capacity can accompany disease development, highlighting microbial turnover of phytotoxic metabolites as a mechanistically meaningful leverage point [37]. More broadly, continuous monocropping across medicinal-plant systems is frequently associated with reduced abundance of antagonistic taxa and higher prevalence of potential pathogens; exudate chemistry is a plausible driver, but field-based causality remains incompletely resolved. Progress toward causal inference will benefit from manipulative validation under field-relevant exposure regimes, ideally using concentration gradients in authentic field soils, paired with sterilization–reinoculation or synthetic-community approaches and metabolite fate tracking (including isotope tracing where feasible) [38].

2.4. Interconnected Feedback Loops Driving Continuous Cropping Obstacles

The three domains summarized above are coupled through feedbacks within the plant–soil–microbiome system rather than acting independently. Soil physical and chemical constraints regulate the transport, retention, and persistence of root-exuded and residue-derived metabolites, thereby shaping the spatial and temporal pattern of allelopathic exposure [12,17,27]. These metabolites can act as selective filters on rhizosphere communities; in turn, rhizosphere dysbiosis may weaken disease suppression and reduce the microbiome capacity to transform or degrade allelochemicals, increasing residence time and reinforcing phytotoxic and disease pressure [23,33,37]. Plant stress can further shift exudate profiles and residue inputs, feeding back to soil conditions and microbiome assembly. Because much of the current evidence remains correlative, these feedbacks should be tested using manipulative designs conducted under field-relevant exposure ranges and evaluated with comparable field endpoints.

3. Mitigation Strategies for Continuous Cropping Obstacles in Medicinal Plants

Mitigating continuous cropping obstacles in medicinal plants should be guided by an integrated plant, soil, and microbiome perspective, with the practical goal of restoring rhizosphere functions such as nutrient cycling, pathogen suppression, and community resilience [33]. Because continuous cropping stress is multifactorial and can become self-reinforcing, single measures rarely deliver stable long-term benefits. More durable outcomes typically come from combining complementary strategies that target soil physicochemical constraints, allelochemical pressure, and microbiome dysbiosis. Commonly used mitigation strategies are compared using four applied criteria (Table 1): efficacy in reducing soilborne pathogens, time scale of impact, practicality for small-scale vs large-scale production, and environmental risks or trade-offs, while the typical evidence base for each strategy is also indicated. Current mitigation options can be grouped into agroecological management, biological regulation, chemical and physical remediation, and plant-based strategies. These measures should be integrated and optimized according to crop species, cropping history, and local soil conditions to improve soil health and reduce the risk of continuous cropping obstacles.

3.1. Agroecological Measures

Agroecological measures are often the most foundational and cost-effective approach, because they aim to address upstream drivers of rhizosphere dysfunction through cropping-system design rather than short-term suppression alone [5]. Crop rotation can interrupt continuity between hosts and pathogens and diversify carbon inputs, which is frequently associated with reduced soilborne disease pressure and partial recovery of microbial diversity and function. In *Panax notoginseng*, longer rotation intervals have been reported to reduce replant failure and disease incidence, consistent with rotation-driven shifts in soil microbial communities [39]. In American ginseng (*Panax quinquefolius*), a time-dependent recovery pattern has also been reported after long rotation cycles, indicating that the interval between consecutive plantings is an important determinant of restoration [40].

Intercropping can provide complementary benefits by increasing plant diversity and reshaping rhizosphere niches. Intercropping between *Panax ginseng* and *Arisaema amurense* improved soil nutrient status and was associated with shifts in microbial community composition relative to monocropping, alongside improved ginseng quality [41]. However, statements that intercropping reduces allelochemical pressure should be made cautiously unless field measurements directly quantify allelochemical dynamics and link them to biological outcomes. Fallowing and mulching have been reported to promote recovery by improving soil structure and moderating moisture and temperature regimes, which can stimulate microbial activity and support the turnover of phytotoxic compounds; nevertheless, effect sizes vary across sites and practices. Soil disinfestation methods such as solarization, steam treatment, biofumigation, and fumigation can rapidly suppress soilborne pathogens, but nonselective treatments may also reduce beneficial taxa, and effects may be transient unless followed by practices that rebuild microbial function [42]. Overall, agroecological measures are generally scalable and durable, but benefits often accumulate over medium-to-long time scales and depend on local feasibility (Table 1).

3.2. Biological Regulation

Across medicinal-plant continuous monocropping systems, biological regulation generally relies on microbial inoculants, AMF-based symbioses, and organic amendments, with the shared goal of rebuilding a more functional, resilient, and disease-suppressive rhizosphere [33]. At the inoculant level, biocontrol fungi and bacteria can reduce soilborne disease pressure and shift rhizosphere communities in ways that support plant performance. *Trichoderma* addition has been tested in continuously cropped *Salvia miltiorrhiza* soils and was associated with improved plant growth and altered soil microbial profiles [19]. In *Panax notoginseng*, *Bacillus*-based inoculants have been reported to suppress *Fusarium* associated root rot and to reshape rhizosphere community structure and functional potential [43]. Evidence also supports multi-strain or functionally complementary inoculation under continuous cropping stress. In *Pinellia ternata*, combined application of *Streptomyces* and *Bacillus* improved soil health indicators and mitigated continuous-cropping obstacles, consistent with a microbiome-mediated mitigation pathway [44]. AMF-based approaches can complement microbial inoculants by improving nutrient acquisition and buffering stress. In American ginseng grown under a continuous-cropping regime, AMF biofertilizer increased plant growth and modified soil microbial properties. In addition, AMF has been shown to enhance disease resistance in *Salvia miltiorrhiza* against *Fusarium* wilt under controlled infection conditions, supporting a plausible disease-suppression pathway through host defense and root physiology [45].

Organic amendments such as compost, manure-based inputs, and biochar are often used to provide labile carbon, improve soil structure and buffering, and create conditions that favor beneficial microbial recovery. In continuously cropped or replanted ginseng systems, cow dung, biochar, and compost have been linked to shifts in rhizosphere microbiota and reduced disease pressure [46]. Moreover, because continuous monocropping can be associated with loss of autotoxin-degrading functions in the resident microbiome, a key practical target is not only reducing soilborne pathogen pressure but also restoring degradation capacity and functional resilience [37]. Endophyte-oriented strategies are also emerging. In ginseng, applying PGPR has been reported to reorganize root endophytic community structure while improving root-rot control, suggesting that integrating rhizosphere inoculation with endophyte recruitment and community assembly is a potential approach in medicinal plants [47]. For stronger causal inference and more stable field translation, synthetic community designs provide an actionable direction. A microbiome study in *Astragalus mongholicus* demonstrates that a simplified synthetic community can rescue plants from root rot via induced systemic resistance, offering a methodological template for medicinal-plant systems [48]. Biological regulation can act within one to a few seasons, but field robustness is frequently constrained by establishment consistency, formulation quality control, and soil-context dependence (Table 1).

3.3. Chemical and Physical Remediation

Chemical and physical remediation focuses on correcting soil constraints that accumulate under continuous monocropping over multiple years, including acidification, mobilization of Al and Mn, and the persistence of bioactive compounds derived from roots or residues, thereby reducing continuous-cropping stress. Liming and calcium-based phosphate amendments can raise soil pH and improve buffering capacity, which may reduce the bioavailability of phytotoxic ions and create a more favorable chemical environment for beneficial microbial recovery [49]. Biochar is another widely used amendment. Its porous structure and sorption capacity can decrease the freely available pool of phenolic allelochemicals while improving aggregation and water-holding capacity;

accordingly, biochar application has been reported to shift rhizosphere microbial communities and alleviate replant or continuous cropping obstacles in several medicinal plants [50–52]. In contrast, leaching should be considered primarily as a transport process rather than a broadly applicable management practice. Vertical leaching can redistribute allelochemicals and alter their bioavailability, but deliberate flushing is highly dependent on soil texture and can increase nutrient losses [53]. Physical interventions such as deep tillage and thermal disinfestation, including steam treatment and microwave treatment in niche high-value production, can disrupt pathogen habitats without conventional pesticides. However, high costs, energy demands, and non-target effects on beneficial microbes often limit scalability; therefore, these approaches are best positioned as auxiliary tools that are integrated with agroecological and biological strategies to support rhizosphere recovery over the longer term [1]. Disinfestation methods provide rapid pathogen suppression, whereas pH correction and sorbent-based amendments typically show slower but more persistent benefits; therefore, rapid interventions usually require follow-up rebuilding to reduce rebound risk (Table 1).

3.4. Plant-Based Regulation

Plant-based strategies aim to reduce intrinsic susceptibility to continuous cropping stress by improving host resistance to dominant soilborne diseases and by selecting traits that help maintain root function under degraded soil conditions [33]. Compared with agronomic or microbiome-based interventions, plant-based regulation is usually a medium to long term approach because cultivar development and field validation are time-consuming in many medicinal crops. Nevertheless, expanding genomic resources in *Panax* species and other medicinal plants is making resistance breeding more feasible, especially for root rot and wilt complexes [1]. In *Panax notoginseng*, genomic and transcriptomic analyses have identified candidate loci and pathways associated with root rot resistance, providing a practical starting point for marker development and resistance-oriented selection [54]. For *Panax ginseng*, cultivar and germplasm resources have been summarized with attention to disease resistance and continuous cropping suitability, supporting the view that continuous cropping tolerance can be treated as a target trait rather than an unavoidable constraint [55]. Marker-assisted breeding has also been used to develop a root rot resistant notoginseng cultivar based on SNP markers [56]. However, many plant-based claims still require stronger validation across multiple locations and over multiple years, and trade-offs between yield and active constituents should be reported more explicitly.

Beyond genetics, root traits are a plausible leverage point because continuous monocropping is often mediated through the root and rhizosphere interface. In *Astragalus mongholicus*, long-term continuous cropping has been linked to coordinated shifts in root-associated microbiota and root-exuded metabolites, consistent with the idea that exudate profiles can both reflect and shape belowground stress [38]. Under autotoxin stress in ginseng, changes in exudate composition have been associated with altered recruitment of beneficial bacteria, suggesting a practical path to select genotypes that more consistently support a functional rhizosphere [57]. Overall, plant-based regulation should be framed as a complement to agroecological and biological strategies. It can stabilize performance across sites, but credible translation requires validation at field scale and explicit links to medicinal quality endpoints. Plant-based strategies are slow to deploy but offer high scalability and persistence once resistant or tolerant cultivars are available and validated across environments (Table 1).

Table 1. Evidence-informed comparative evaluation of mitigation strategies for continuous cropping obstacles in medicinal plants.

Mitigation Strategy	Typical Evidence Base [a]	Efficacy in Reducing Soilborne Pathogens [b]	Time Scale of Impact [c]	Practicality (Small- and Large-Scale Production) [d]	Environmental Risks or Trade-Offs [e]
Crop rotation (adequate break length)	Field evidence available	Medium-High	Medium-Long	Medium; High	Opportunity costs of land and time; feasibility constraints in specialized production; incomplete control of broad-host pathogen complexes
Intercropping	Field evidence available	Low-Medium	Medium	Medium; Low-Medium	Higher management complexity; interspecific competition; context-dependent outcomes across sites and crop pairs
Cover crops, mulching, and fallow management	Field evidence available	Low-Medium	Medium	Medium; Medium	Residue-mediated pest/disease carryover; temporary N immobilization or excess moisture, depending on practice

Table 1. *Cont.*

Mitigation Strategy	Typical Evidence Base [a]	Efficacy in Reducing Soilborne Pathogens [b]	Time Scale of Impact [c]	Practicality (Small- and Large-Scale Production) [d]	Environmental Risks or Trade-Offs [e]
Biofumigation	Mixed evidence	Medium-High	Short-Medium	Medium; Low-Medium	Potential nonselective effects; efficacy depends on biomass, timing, and incorporation; repetition may be required
Solarization	Field evidence available	Medium-High	Short	Medium; Low	Plastic use and disposal; climate-dependent efficacy; rebound risk without follow-up soil rebuilding
Steam or thermal disinfestation	Mixed evidence	High	Short	Medium; Low	High energy demand and cost; nonselective impacts; benefits are often transient without post-treatment rebuilding
Chemical fumigation (where permitted)	Field evidence available	High	Short	Medium; Medium	Regulatory restrictions; non-target impacts; rebound risk; worker safety and environmental concerns
Microbial inoculants (single strain)	Mixed evidence	Medium	Short-Medium	High; Medium	Variable establishment; formulation and quality inconsistency; strong dependence on soil context and management
Microbial consortia or synthetic communities (SynCom)	Controlled evidence dominant	Medium-High	Medium	Medium; Medium	Community stability and compatibility constraints; manufacturing and QA complexity; regulatory compliance
Arbuscular mycorrhizal fungi (AMF) products	Mixed evidence	Low-Medium	Medium	Medium; Medium	Colonization is sensitive to soil P status and disturbance; pathogen suppression is often indirect and context-dependent
Compost- or manure-based amendments	Field evidence available	Medium	Medium–Long	Medium; Medium	Nutrient leaching or salinity if mismanaged; feedstock-dependent contaminants; variable product quality
Biochar amendment	Field evidence available	Medium	Medium-Long	Medium; Medium	Product heterogeneity; potential contaminants; rate- and soil-dependent responses
Liming and Ca-based amendments	Field evidence available	Low-Medium	Medium	High; High	Overliming and micronutrient imbalance; benefits may be transient if underlying drivers persist
Deep tillage or physical reconfiguration	Field evidence available	Low-Medium	Short-Medium	Medium; Low	Erosion and structure disruption; soil organic carbon loss; disturbance of beneficial networks
Soil replacement (high-value niche systems)	Field evidence (specialized or high-value contexts)	Medium-High	Short	Medium; Low	High cost; disposal constraints; limited scalability; re-contamination risk
Resistant or tolerant cultivars	Field evidence available	Medium-High	Long	High; High	Long breeding cycle; genotype-by-environment effects; yield-quality trade-offs; risk of resistance breakdown

a. Evidence-base labels are indicative: field evidence available; controlled evidence dominant; mixed evidence; field evidence (specialized or high-value contexts). b. Efficacy ratings are evidence-informed relative syntheses; field evidence prioritized where available. c. Short: within one season; Medium: 1–3 seasons; Long: multi-year. d. Practicality reflects operational feasibility (small-scale; large-scale) and is context-dependent. e. Trade-offs include ecological, agronomic, economic, and regulatory constraints relevant to field deployment. Abbreviations: AMF, arbuscular mycorrhizal fungi; SynCom, synthetic community; Ca, calcium; QA, quality assurance.

4. Future Perspectives

Continuous cropping obstacles in medicinal plants arise from coupled shifts in soil physicochemical properties, the input and persistence of bioactive metabolites, and the rhizosphere microbiome. Across systems, studies consistently document deterioration of key soil attributes, increased soilborne disease pressure, and weakened beneficial functions, supporting a plant–soil–microbiome feedback framework. Nevertheless, major gaps remain: initiating drivers and their temporal sequence are often unresolved, field-relevant dose response relationships for candidate allelochemicals are poorly constrained under realistic soil matrices where sorption and microbial turnover modify exposure, and microbiome evidence is still largely taxonomic rather than functional, limiting cross-site transferability.

Future work should move beyond descriptive correlations toward mechanism-based tests that isolate drivers and quantify their relative contributions under field conditions. Priority designs include multi-year field monitoring coupled with targeted perturbations; factorial manipulations of soil pH buffering capacity and sorptive retention (adsorption) capacity together with inoculum pressure; and gradient exposure experiments for candidate allelochemicals conducted in authentic field soils. Where feasible, stable isotope tracing would strengthen inference on metabolite fate and metabolite–microbe coupling. On the management side, more reliable gains are likely to come from integrated, mechanism-informed packages combining agroecological practices, amendments that enhance soil pH buffering and the sorptive retention of bioactive compounds, and microbiome-based interventions that support functional recovery. Such packages should be evaluated using standardized field endpoints (disease incidence and severity, emergence and stand density, yield, and medicinal quality traits) and should report core contextual variables such as cropping history, baseline soil properties, climate, and management details, with evaluation aligned to the applied criteria summarized in Table 1.

Author Contributions

M.W.: Writing—original draft, Investigation, Data curation, Conceptualization. Y.T.: Writing—review & editing, Methodology, Supervision, Resources, Funding acquisition, Conceptualization. S.D.: Investigation, Data curation. M.G.: Investigation, Data curation. X.L.: Investigation, Data curation. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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