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Nature's Complexity for Crop Protection: Integrating Botanical Solutions into Biodiverse Agricultural Landscapes

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Abstract: In this concept paper, we examine multidimensional effects of botanical, plant-based pesticides through a farmer-centric lens. We first analyse the existing literature regarding the environmental and crop-protection benefits of botanicals and then explore challenges associated with their adoption. Additionally, we analyse the context-dependent impacts of botanicals on beneficial non-target organisms, such as parasitoids. Throughout, we emphasize our understanding of the direct implications for smallholder farmers. We show that most methodologies used in developing botanicals are not participatory but rather top-down and driven by interests and decisions of researchers. Furthermore, existing literature remains highly technical, focusing mainly on biochemical properties and species-specific impacts while overlooking field relevance for resource-constrained producers. The outlook similarly prioritizes laboratory efficacy, biochemical optimization, and commercial-scale production, while neglecting socioeconomic and infrastructural limitations faced by rural communities. Finally, our evaluation indicates that existing research into botanicals tends to be reductionist, often focusing on single compound or pest species, and thereby does not consider the influence of agrobiodiversity on the potential applications and effectiveness of botanicals, limiting their development and use in practice. To bridge this critical gap, we propose farmer-inclusive research pathways and a multi-dimensional matrix to ensure that future botanical innovations are practically and economically viable.

Keywords: Agrobiodiversity · Botanical pesticide · Non-target organisms · Participatory research · Smallholder farmers

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1. Introduction

1.1 *Crisis Related to Reliance of Agriculture on a Handful of Synthetic Pesticides*

Reliance on synthetic pesticides in agriculture tends to go along with the use of high-productivity monocultures[1] that are optimized for performance under certain management conditions and form extremely low-diversity environments. The diversity, or lack thereof, of plants in agricultural landscapes is a fundamental determinant of insect habitat quality and of sustainable crop management.[2–5] This is because of the contribution of plant diversity to ecosystem resilience, including through balancing diseases and pest loads.[6–8] Indeed, a recent study found that all plant diversification practices in agriculture are largely effective in pest control.[9] Despite these benefits, there is a continuous increase in the use of synthetic pesticides, which negatively affect the diversity and abundance of the beneficial insect species[10,11]

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– such as pollinators and natural enemies of pests[11–13] – that are required for crop health and natural pest suppression, exacerbating the impacts of monoculture. It is estimated that since the 1990s, pesticide usage has increased by 50%[14] and currently approximately 3.7 Tg (Tg = teragrams 10^{12} g) of pesticides are used annually in global crop production.[15] Another major concern is pesticide resistance; it is estimated that worldwide over 600 pest species have developed resistance to one or more synthetic pesticides.[16] By harming beneficial species and by being ineffective against specific pests, these pesticides can trigger a self-reinforcing feedback loop that necessitates even higher pesticide applications to manage agroecosystems, ultimately resulting in high economic costs for farmers.[17] These costs arise not only due to the need to purchase pesticides, but also due to detrimental impacts of long-term (increasing) pesticide exposure on the health of farm workers.[18] Many synthetic pesticides are further persistent, with the potential to bioaccumulate through food chains; residues accumulating in soil, water, and food can pose serious health risks to humans[16] and other organisms. To break this cycle, a shift in paradigm is required. One proposed sustainable alternative to synthetic pesticides is plant-based pesticides called botanicals.

1.2 *The Botanical Advantage: Why Complexity Matters*

Botanicals can make an important contribution to sustainable crop protection, offering unique advantages rooted in their evolutionary history. Botanicals contain mixtures of plants secondary metabolites such as phenols, terpenes, and alkaloids[16,19] that have evolved through interactions between plants and insects and are part of a plants' own defensive strategies. Originating from diverse plant families, botanicals are applied either as essential oils, extracts, or a combination of both. The specific plant parts harvested to make botanicals can range from roots, leaves, barks, and stems to seeds, fruits, flowers and rhizomes.[20] Historically, pyrethrum extracted from the dried flowers of *Tanacetum cinerariifolium* (Astaracear) and azadiractin extracted from neem (*Azadirachta indica,* Meliaceae) have been the two of the most widely used commercial botanicals worldwide.[21] However, in the past decades, research and commercial efforts have been shifting towards botanicals made from essential oils (EOs).[22] This shift is based on multiple perceived advantages of EOs, including the integration of volatile bioactive substances suitable for fumigation and other effects that do not rely on direct contact to a surface;[23,24] technologies to extract EOs without the need for toxic solvents *e.g. via* steam distillation;[25] and the fact that EOs are more aromatic and pleasant for humans than plant extracts.[26]

Several factors make botanicals excellent candidates as sustainable alternatives to synthetics: a lower likelihood of pests developing resistance due to their chemical complexity and thus multiple modes of action; rapid biodegradability as natural products; limited known negative impacts on non-target organisms in many cases; and the potential to be produced locally and even by farmers themselves. While it should be noted that many synthetic pesticides are engineered to be relatively less toxic to humans – for example, neonicotinoids are less toxic to humans than is the natural product that inspired them, nicotine[27] – this can be offset by their lower biodegradability and thus greater potential for bioaccumulation. However, when designing botanicals, it is essential to keep in mind that there are many plant natural products that are highly toxic to humans, and that these and their natural sources must be avoided or handled appropriately.

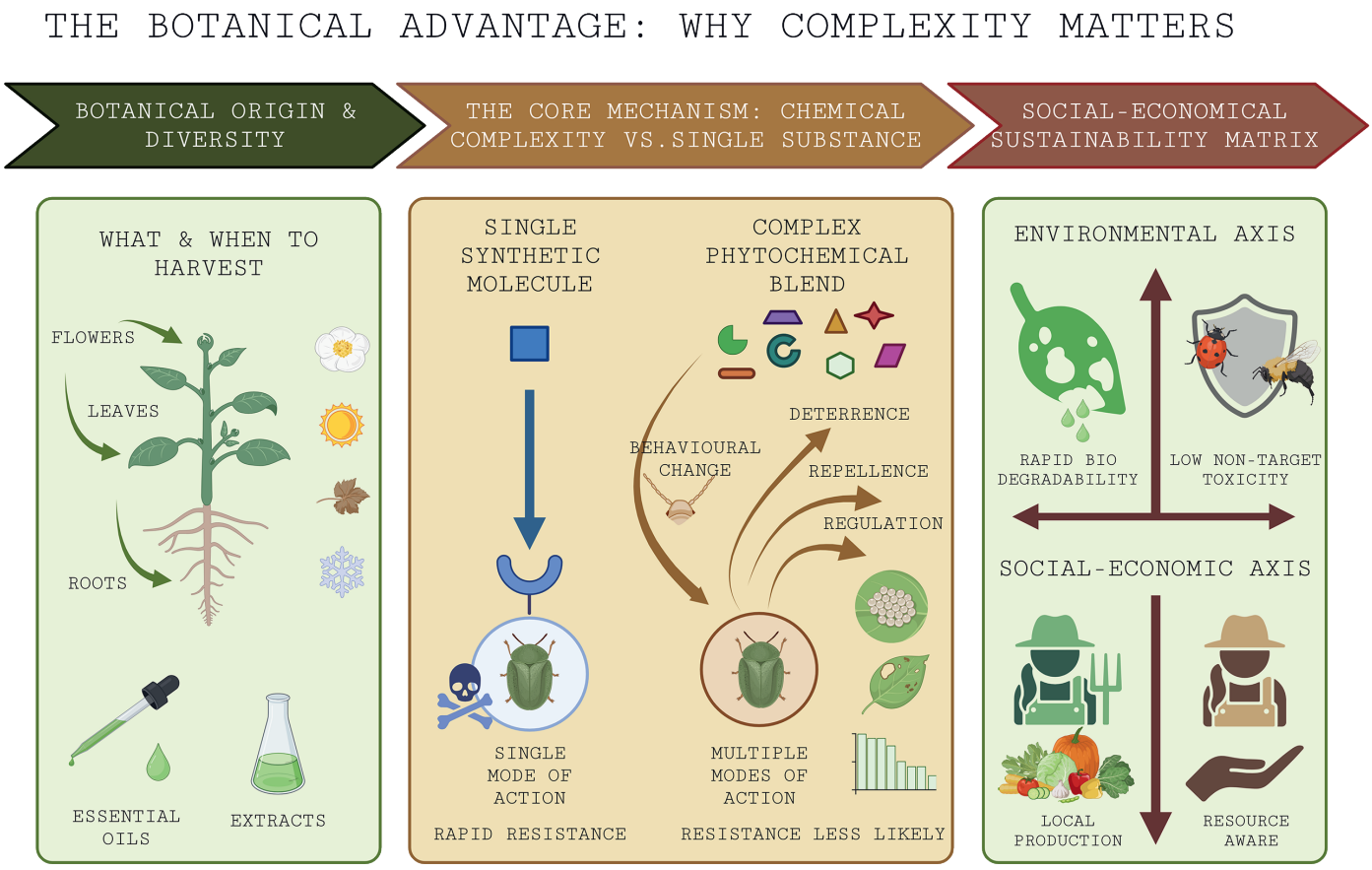

Fig. 1. Schematic representation depicting botanical options and advantages along the environmental and socio-economic axes. The axes and quadrants are purely schematic and conceptual; they represent qualitative gradients and relative contrasts rather than quantitative scales or measured values. Created in BioRender by D. Lucas-Barbosa, (2026) https://BioRender.com/1mbr0i5.

As botanicals are composed of complex phytochemical blends, they utilise multiple modes of action against pests[20] (Fig. 1), each one of which may be driven by a specific component substance as well as by the synergies of multiple substances.[28,29] These modes of action can include repellence or deterrence of feeding and oviposition, toxicity that slows development, lethal activity, and interfering with other physiological activities. Repellence can work by disrupting pest sensory perception through olfactory and gustatory mechanisms, interfering with host plant location and therefore decreasing colonization of treated areas.[30] This repellent effect can lead to a reduction in pests directly by pushing them away from plants, or indirectly by decreasing oviposition rates.[30,31] Behavioural changes in response to botanicals are triggered by compounds belonging to classes such as alkaloids, quassinoids, phenolics, and saponins.[32] These work peripherally on specific deterrent receptors in insects, directly suppressing a pest's urge to feed.[32] In addition to altering pest feeding habits, botanical compounds can influence pest development through several different biological mechanisms. These include interfering with hormonal pathways to halt growth and moulting, disrupting metamorphosis, larval toxicity, interfering with hormonal processes, and inhibiting digestive enzymes.[16,33] The potential for combined and reinforced modes of action makes pest resistance significantly less likely compared with single-molecule pesticides – generally the case for synthetics – as pests would need to overcome several mechanisms simultaneously.[34,35]

Botanicals are generally susceptible to photodegradation, abiotic oxidation, or loss through volatilization when applied in the field.[22] For example, natural pyrethrins undergo photodegradation in the presence of sunlight and oxygen from 100% to about 1% in only five hours,[36] and the half-life of azadirachtin, isolated from neem, is between one and two days in crops and soil, respectively.[20] Although such susceptibility to degradation can be seen as a drawback, it is also the reason why botanical residues do not persist for long, and there is little risk of their accumulation in water bodies and soils. This results in relatively low long-term environmental toxicity,[37] especially in comparison with synthetic pesticides, which are generally more stable and have been shown to persist in the environment for decades.[38,39]

Finally, a key socioeconomic advantage of botanicals is that they can be produced locally by farmers using native species and relatively simple protocols that allow botanical extraction and preparation on-farm.[40–42] This is critical for subsistence farmers in lower-income countries that may not have access to, or be able to afford synthetic pesticides.[42] We note that on-farm preparation raises important safety considerations and argue that these are important targets for research and development of botanicals. Pest control using traditional knowledge of botanicals is still widespread amongst subsistence farmers and smallholders, especially in the global south. For example, up to 100% of farmers in some areas of Zimbabwe and Uganda report using botanicals, derived from native plant species.[43,44] Hence, botanicals not only reduce the market dependence of farmers but also support them in retaining control over their own resources. Strategies for conservation and preventing over-exploitation of valuable botanical species should therefore also be included into botanical research and development programs. Finally, despite the potential of botanicals to provide sustainable pest control solutions for smallholders, challenges remain in maintaining their efficacy, in their widespread adoption and commercialisation.

1.3 *The Challenge of Complexity*

The very traits that make botanicals sustainable often result in a lower effectiveness in reducing pest damage or abundance when compared to synthetic pesticides. As mentioned above, due to the short persistence of botanicals in the environment and their rapid rate of biodegradation,[22] they may not provide long-term protection against persistent agricultural pests. To maintain pest control, farmers would thus need to apply botanicals more frequently,[42] which could increase both labour time and input costs. Furthermore, as the mechanisms through which botanicals work against pests are often slower than acute toxicity, such as growth inhibition or feeding deterrence,[20,31] they may not show immediate effect. Due to this delayed response, pests may continue to inhabit and damage crops for several days before botanicals take effect. If there is a sudden and severe pest outbreak, this critical lag time can translate directly into substantial yield and economic losses. Consequently, farmers may be reluctant to adopt botanicals, especially when they have access to and can afford synthetic pesticides.[37]

Unlike synthetic formulations with fixed and standardized active ingredients, botanicals are subject to significant natural variation. The concentration of bioactive compounds in plants fluctuates based on seasonal shifts and the specific developmental stage of the plant at the time of harvest.[45] Furthermore, phytochemical profiles can vary widely across different plant genotypes, meaning that a botanical extract's effectiveness may be significantly reduced if it is sourced from a population at a time when specific active compounds are naturally low.[46] Additionally, many botanical pesticides also have undesirable properties, such as strong odours that might or might not correlate with human toxicity, and poor water solubility, which make the preparation of formulations more challenging. These factors make botanicals difficult to handle, apply, and store, hampering adoption by farmers to date.[16] These are areas in which research in natural product chemistry and chemical ecology have many potential solutions to offer.

Another reason why botanicals may have a low rate of adoption by farmers is the disparity between laboratory precision and field reality. Current high-efficiency extraction methods often require costly infrastructure, such as nitrogen liquefaction and modern laboratory facilities, which are inaccessible to smallholder farmers.[22] Smallholders frequently lack the capital for such infrastructure and often rely on easily accessible but less efficient solvents like water or cow urine, which frequently results in formulations with low concentrations of the necessary active compounds and thus reduces potential efficacy.

There are further ecological and regulatory aspects that pose a barrier to scaling up the production of botanical pesticides. Producing enough botanical extract to meet global agricultural demand would require intensive, large-scale cultivation of specific plant species, which may lead to overexploitation of vulnerable wild plants. In addition to these supply chain bottlenecks, the path to commercialization is restricted by regulatory frameworks. Many regulatory agencies rely on registration protocols originally designed for single-molecule synthetic chemicals, making the approval of complex, multi-compound botanical mixtures exceedingly costly and time-consuming.[22] Together, these supply constraints and rigid regulatory barriers limit the widespread market availability of botanicals. Finally, an important argument against the widespread use of botanicals is that there is limited information on their impacts on non-target organisms and on human health.

2. Deep Dive: Addressing the Non-Target Organism Gap

The impact of botanicals on beneficial species represents a critical and often understudied dimension of their activity. A recent review suggests that only 2% of studies involving botanicals have explored their impacts on non-target organisms (NTOs).[47] Existing research has focused on only a few specific organisms – primarily pollinators like the honeybee (*Apis mellifera*) and selected parasitoids – and on a narrow range of compounds,[48,49] with studies frequently highlighting negative impacts. However, a

closer look at the data reveals that the magnitude and direction of these impacts are highly species-dependent, varying significantly with plant source, exposure pathway, and application method. For instance, a meta-analysis conducted on the effects of different botanical pesticides (including extracts from *Azadirachta indica*, *Calceolaria andina*, and *Cymbopogon schoenanthus*) on hymenopteran parasitoids found that while these compounds can increase mortality and reduce parasitism or adult emergence, under laboratory conditions, their negative impacts can vary significantly depending on the parasitoid family and the botanical source.[50]

EOs demonstrate similarly nuanced effects. One study demonstrated that EO solutions sprayed directly on parasitized eggs can hinder adult parasitoid emergence, likely because specific volatile compounds diffuse through the host egg chorion and disrupt the nervous system of the developing embryo.[50,51] Conversely, EOs from plants like *Hyptis marrubioides* and *Ocimum basilicum* were found to be toxic to the pest *Spodoptera frugiperda* when applied topically, yet remained entirely harmless to the parasitoid *Trichogramma pretiosum*.[51] Pollinator responses to EOs are also species-specific.[49] For example, *Apis mellifera* foragers exposed to ginger, mint, oregano, and thyme EOs displayed lower tolerance levels than *Trigona hyalinata* foragers.[52] Similarly, certain essential oils, such as those derived from *Corymbia citriodora*, proved toxic to stingless bees like *Tetragonisca angustula*, whereas oils from *Persea venosa* and *Lippia sidoides* were harmless.[47]

3. A Missing Evidence Base for Impacts on Smallholders

Research to develop marketable botanicals has mainly relied on technical interventions. For example, to improve field efficacy or to mitigate toxicity on NTOs, the development of nano formulations is proposed. These are promising and should be encouraged but such interventions disregard socioeconomic and practical constraints of smallholder farmers, who lack the capital, infrastructure, and technical capacity to manufacture or purchase such products. Below, we further explore the disconnect between research on botanicals and smallholder contexts.

The EO bias: In recent years, multiple studies have assessed the impacts of botanicals on NTOs. These have focused on volatile EOs.[22] As EOs are increasingly desired for commercial registration and patenting (see section 1.2), they undergo strict regulatory screening against pollinators and natural enemies. Non-volatile Plant Secondary Metabolites (PSMs) such as the water- and alcohol-soluble alkaloids, saponins, and phenolics, which are the main form of smallholder household extracts, are rarely investigated. Exceptions are commercialized azadirachtin (from neem) and pyrethrum. This lack of research could potentially occur because crude, locally processed botanicals are assumed to be safe. Such a bias can lead to an underestimation of the ecological risks of localized botanical applications.

The reductionist bias: Most evidence on botanical efficacy or their impact on NTOs is derived from controlled laboratory studies. These are usually short-term, target a single arthropod species, and test the effect of a single plant compound. This does not reflect how botanicals are composed or applied. Studies in field settings are rare, and studies on the landscape effects of widespread botanical use are non-existent. Agroecosystems are dynamic: crops are attacked by a variety of pests, potentially attracting a diversity of beneficial species. Botanical pesticides are chemically complex, and their application could influence species dominance within insect communities, having unintended effects on crop yields. Evaluating the ecological impacts of botanical insecticides at a landscape scale is particularly critical for smallholder farmers, whose individual fields are usually located near other cultivated fields.

The research bias: It is well known that smallholders and subsistence farmers often use traditional pest control methods based on locally available plant species.[53] Despite this, the development of botanical formulations has been conducted in isolation by researchers, with farmers only involved at the final stage,[21] to be 'taught' application methods. Farmers' traditional knowledge-based practices rarely rely on a single active compound. Rather, they involve diverse plant mixtures, usually selected based on the contextual understanding of local plant-insect ecology. Hence, farmers' experience is critical for arriving at effective solutions.

The economic bias: The socio-economic impacts of botanicals are rarely explored, and it is assumed that home-made botanicals are 'zero-cost' in comparison to synthetic inputs. However, this assumption overlooks the labour costs and efforts required to harvest and process plants required to make botanicals, and to apply them. Specifically, such labour demands often disproportionately fall upon women and can worsen internal household inequalities.[54]

4. A Path Forward for Integrating Botanicals in Smallholder Systems

The ecological safety of botanicals is highly context dependent. The scientific and regulatory communities must shift away from assuming intrinsic safety and focus instead on evaluating specific application rates, timings, and formulations. Crucially, however, this framework must remain pragmatic and action-oriented: it should not introduce an insurmountable burden of proof that slows the adoption of bio-based alternatives or inadvertently fuels lobbying efforts by the synthetic pesticide industry to maintain market dominance. For smallholder farmers, replacing synthetic chemicals with botanicals will not be a simple one-to-one substitution, but rather a strategic integration into wider integrated pest management (IPM) programs. Here, we present a path forward for the integrated development of botanicals that aims to stimulate their integration in smallholder farming systems. We conclude the section by providing a multi-dimensional framework that can be used by researchers to evaluate botanical solutions.

4.1 Centring *Local Ecological Knowledge and Participatory Design*

To accelerate real-world adoption, chemical ecologists and agronomists must bridge the gap between scientific innovation and community experience by placing smallholder farmers and their local knowledge at the centre of botanical development. Farmer involvement is fundamental at all stages to gather insights into desirable properties and practical challenges that may occur during implementation.[55,56] Farmers' long experience and traditional knowledge of their regions and their natural resources is critical for arriving at effective solutions and, at the same time, realistic from a practical point of view **for ensuring adoption and sustainability** of these solutions.[57–60]

A critical yet underutilized foundation of this participatory approach lies in **formalizing and protecting traditional ecological knowledge (TEK)**. Ethnobotanical surveys indicate that smallholders worldwide hold a wealth of TEK on insecticidal plants and plant-based solutions for pest control.[42,43,61] In many cases, this knowledge is spread orally, not formally documented, and there is critical risk of it being lost.[62,63] While ethnobotany is increasingly valued, its integration in botanical development remains underutilised. Documenting TEK and placing this knowledge at the centre of botanical development would prevent this from being lost and may further lead to discovery of novel botanical formulations from underutilized plant species, for example using multi-omics strategies.[64]

4.2 *Grounding Safety, Feasibility, and Gender Realities in Farmer Contexts*

Alongside participatory co-design, developing viable botanicals requires a fundamental shift toward protocols that prioritize user safety, technological suitability, and farm-level economic constraints. Future research needs to move beyond identifying bioactive compounds to developing extraction and application methods that prioritize the safety of the user. Specifically, it is vital to **evaluate the risks of home-made botanicals**, which are usually made by smallholders using more than one plant species. Following this, protocols need to be developed for safe handling and processing of the botanical extracts and training provided to farmers for these safety measures. Most of the home-made botanicals to date are handled and prepared by smallholders by hand and without any personal protective equipment (PPE).

Ensuring safety must be paired with **low-cost, robust extraction and application protocols**, preventing effective botanical solutions from being locked behind expensive or inaccessible laboratory infrastructure. Current extraction methods (*e.g.* using liquid nitrogen) and solutions to enhance efficacy, to reduce effects on NTOs, and to reduce botanical degradation (*e.g.* nano formulations), require expensive infrastructure inaccessible to farmers. Simpler strategies to help maintain efficacy and reduce unwanted exposure, such as shade drying of plant material or proper ventilation, are more accessible for smallholders. Promising farmer-friendly extraction methods are being developed, such as the liquid-liquid extraction protocol developed by Lang *et al.*,[65] which has successfully been tested in hundreds of farmer fields in Africa,[66] but is only relevant for small (analytical) scales. Safety assessments of large application-scale protocols that are farmer-friendly are still lacking. Finally, to reduce impacts on NTOs, simple yet critical management steps can be integrated. For example, if a specific botanical impacts pollinators, application should be avoided during flowering stages when pollinators actively visit crops. If a specific NTO is only affected by topical application, applications should be targeted. By adopting such case-specific, field-level strategies, smallholders could leverage the crop-protection benefits of botanicals, while mitigating risks to agrobiodiversity.

Beyond technical feasibility and safety, adoption is ultimately dictated by household-level economics and labour dynamics, which are deeply gendered. Farmers' decision to use a particular pest-control strategy is strongly determined by factors such as profitability or reducing risks.[67] Synthetic pesticides are often considered 'quick' and 'easy' in their effect and less labour-intensive. For wider usage and adoption of botanicals, it is crucial to **conduct socio-economic assessments of their use cases and to provide this evidence to farmers**. Specifically, there is a need to quantify the farm-level profitability of botanical solutions (including input and labour costs) and test their viability against current pest control methods. It is estimated that 43% of the agricultural labour force globally comprises women,[68] and women continue to be burdened by household and care work.[54] It is thus critical to identify approaches that reduce individual labour, *e.g.* community input development centres. Hence, for a holistic understanding of socio-economic impacts, it is further important to collect gender-disaggregated data.[69]

4.3 *Enhancing Agrobiodiversity and Evaluating Multi-Trophic Field Dynamics*

Rather than treating botanicals merely as topical inputs, sustainable implementation hinges on integrating plant species directly into smallholder farming landscapes to enhance agrobiodiversity and support natural pest control. One of the main concerns regarding botanicals is that their large-scale usage can lead to overexploitation of plant species. Integrating plant species used to make botanicals in smallholder farming systems can be an approach to mitigate this concern. The 'cultivation potential' of a species determines how easily it can be integrated into the local landscape. Developing botanicals that utilize plant species with a high cultivation potential would empower smallholder farmers to generate their own crop protection while simultaneously promoting local plant diversity and avoiding overharvesting of wild populations. Here again, participatory approaches and farmer knowledge are critical to determine how to incorporate locally relevant plant species into existing farming systems. The incorporation methods could range from intercropping to agroforestry, to border crops and hedges, to home gardens.[70,71]

Diversified cropping systems further increase available habitat for pollinators and natural enemies of pests through several mechanisms.[72] First, with the presence of multiple plant species, there are multiple niches available for different insect species.[73] Second, an increase in plant species richness leads to an increase in insect diversity and plant food rewards, such as floral and extrafloral nectar.[74] Finally, a greater diversity of plants results in greater phytochemical diversity, including volatile organic compounds (VOCs)[46] – which directly suppresses pest colonization while enhancing biological control across trophic levels.[75] A diverse blend of VOCs has been shown to directly and indirectly reduce pest attack.[76] The direct reduction occurs, for example, by disrupting pest host location[77] and by inducing defences in neighbouring crops, making them less susceptible to herbivory.[78] When plants are attacked by pests, the release of herbivore-induced volatiles can still indirectly defend the plant by attracting natural enemies of herbivores,[79] and extrafloral nectar may also be induced by producing species in the attacked and in neighbouring plants, further attracting and supporting beneficial species.[80,81] Such mechanistic understanding of volatile compound has been used to develop crop mixtures that reduce pests,[82] however, the effect of such designs on beneficial insects is less often studied. It is critical to ensure that the selected phytochemical composition does not push natural enemies out of cropping systems. Realizing these ecological benefits in practice requires moving research beyond single-pest laboratory bioassays to evaluate complex multi-trophic interactions under variable field conditions.

To truly compete with synthetics, botanicals need to be tested under variable field conditions, and their impacts need to be modelled at a landscape scale. While laboratory studies are essential to establish standardized toxicity scores and mechanisms of action for pesticides, they do not, and are not meant to, incorporate ecological complexity of agricultural systems. Consequently, results from laboratory studies assessing the effects of botanical pesticides on isolated pests or NTOs often fail to translate to field conditions.[83] Smallholder farming systems are usually integrated in heterogeneous landscapes characterized by adjacent fields and hedgerows. Additionally, farmers have varied agronomic practices of soil fertility management.[84,85] In such complex agricultural systems, pests have access to alternative host plants, and beneficial insects may be affected by botanicals. Furthermore, pests are often influenced by localized soil and plant fertility management practices. For example, several studies indicate that the population of sucking pests specifically increases with an increase in the amount of nitrogen, phosphorus, and potassium (NPK).[86] Hence, future research must prioritize field studies that evaluate the impacts of botanical pesticides across trophic levels, include pests and beneficials, and consider farmer practices. Such field data could be used to estimate ecosystem-level and spillover effects on arthropod diversity, by development of predictive models that integrate climatic variables with agronomic variables such as NPK in fertilizers.

4.4 *Streamlining Regulatory Pathways and Evaluating Multi-Dimensional Sustainability*

Translating field-tested botanical innovations into widespread practice is frequently constrained by regulatory frameworks designed primarily for single-molecule synthetic pesticides. Furthermore, moving from the laboratory to the field is not only ecologically challenging but brings regulatory challenges as well. As discussed above, strict regulatory barriers or, alternatively, the total absence of a regulatory framework both hinder the widespread adoption of botanicals. For example, in Europe and in India, development of biopesticides falls under the same regulatory laws as those for synthetic pesticides.[47] These complex, high-cost regulatory frameworks disproportionately influence actors involved in less commercialized agriculture. Strict compliance requirements discourage smallholder farmers and local enterprises from developing and utilizing locally adapted, botanical formulations. Field environments are complex; hence, deriving pre-approval data for impacts on every NTO is an unrealistic prerequisite that cannot be fulfilled *via* laboratory studies alone. Regulatory bodies need to adopt an adaptive model and allow controlled field trials at established safety thresholds. Such an approach, together with continuous post-application monitoring, would yield more practical data while directly supporting innovation within resource-poor farming communities.

To reconcile these regulatory bottlenecks with practical on-farm needs, we propose a multi-dimensional sustainability matrix that allows researchers, extension agents, and regulators to systematically evaluate botanical solutions across socio-ecological metrics. The proposed multi-dimensional matrix can be used to evaluate the feasibility and long-term socio-ecological sustainability of a specific botanical solution. This entails (a) the mode of action of a specific botanical to establish its comparative value against synthetic standards, (b) the impacts on beneficial insects, (c) cultivation potential of the plant species, (d) overextraction risk, and (e) reported toxicity to humans. Toxicity to humans remains an indispensable safety metric. Evaluating the risks of potent botanicals – such as those containing cardiac glycosides or neurotoxins – is vital for co-developing safe handling protocols with farmers. By prioritizing species easily grown in agroforestry or mixed cropping systems, researchers can prevent ecological damage caused by over-reliance on wild harvesting. When these five dimensions are evaluated together, they form the sustainability matrix illustrated below (Table 1), ensuring a botanical formulation is field-effective, environmentally responsible, and safe for the practitioners who use it.

5. Conclusion

The transition toward a 'phytochemically diverse' agricultural future requires addressing the critical gaps between laboratory discovery and field reality. By integrating botanical-producing species into the livelihoods of smallholders, we can demonstrate that ecological resilience and economic independence are mutually reinforced. Moving forward, the success of botanical solutions will depend on our ability to embrace transdisciplinary approaches valuing the traditional knowledge of local and indigenous communities and their essential contribution. Ultimately, by replacing landscape simplification with ecological complexity, we can foster a resilient agricultural system that protects both our crops and the biodiversity upon which they depend. Our challenges should be to (a) improve the efficacy of botanicals while maintaining farmer autonomy and ease of use, (b) co-develop cropping systems that support beneficial insects and thereby botanical effectiveness, and (c) facilitate and build farmers' capacity in effective use and production of botanical pest-control strategies and in entrepreneurship, to improve their livelihoods. While acknowledging that botanical safety is

Table 1. Plant type and species with respect to effects on insect pests, cultivation potential, overextraction risk and reported toxicity to humans.

Plant Type	Species	Effect on Insect Pests	Effect on Beneficial Insects	Cultivation Potential	Over-extraction Risk	Reported Toxicity to Humans
Tree	Azadirachta indica (neem)[87,88]	Broad-spectrum: Antifeedant, growth regulator (Azadirachtin).	Low to Moderate: Generally safe for adults; can affect larval stages of predators if ingested.	High: Widely naturalized; drought tolerant.	Low: Well-established commercial plantations.	Low: Generally recognized as safe in moderate use.
Tree	Carica papaya (Papaya)[89,90]	Enzymatic: Papain/alkaloids affect larval gut and soft-bodied insects.	Unknown	High: Common fruit crop; easy to integrate.	Low: Usually a byproduct of fruit production.	Negligible: Widely consumed food; latex can irritate skin.
Tree	Millettia pinnata (Karanj)[91–93]	Toxic/Repellent: High oil content (Karanjin) disrupts feeding.	Moderate: Oil films can impact small parasitoids; repellent to some pollinators.	Medium: Hardy tree for degraded lands.	Medium: High demand for oil can lead to wild depletion.	Low-Medium: Oil/seeds are emetic; non-edible.
Forb/Shrub	Annona squamosa (Custard Apple)[94,95]	Contact Poison: Acetogenins cause rapid 'knockdown'.	High: Known to be toxic to some beneficial predators and pollinators on contact.	Medium: Can be intercropped or grown in orchards.	Medium: Wild collectionof seeds is common.	Medium: Seeds are toxic if ingested; eye irritant.
Forb/Shrub	Nerium indicum (Oleander)[96–98]	Potent Toxin: Cardiac glycosides act as strong repellents.	Unknown/High Risk: Likely toxic to any insect consuming nectar/pollen; needs study.	Low: Extremely common and resilient.	Low: Extremely common and resilient.	High: Extremely poisonous if ingested; requires gloves

context-dependent, we must shift from assuming intrinsic safety to evaluating specific application rates, timings, and formulations, and at the same time make sure that an evaluative framework remains pragmatic. Introducing an insurmountable burden of proof risks paralyzing the adoption of bio-based alternatives and inadvertently fuels synthetic pesticide industry lobbying to maintain market dominance.

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Author Contribution

A. S. and D. L. B contributed equally to the writing of the manuscript. M. C. S. contributed to the writing and revised the manuscript before submission. All authors have approved the final version of the manuscript. The authors declare no competing financial interests.

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