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EXPLORING PLANT-BASED PESTICIDES AS VIABLE ALTERNATIVES FOR CONVENTIONAL AGROCHEMICALS IN MAIZE FARMING

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Abstract

Plant-derived botanical formulations were evaluated as sustainable alternatives to synthetic agrochemicals for maize (Zea mays L.) pest and disease management. Six botanicals—neem (Azadirachta indica), basil (Ocimum basilicum), thyme (Thymus vulgaris), sage (Salvia officinalis), celery (Apium graveolens), and Tagetes minuta—were assessed through laboratory bioassays, greenhouse trials, and simulated storage studies. Insecticidal assays against the maize weevil (Sitophilus zeamais) demonstrated dose-dependent efficacy, with T. minuta and neem achieving the highest mortalities of 88% and 85%, respectively, at 1.0% concentration. Antifungal tests against Fusarium spp. revealed that thyme and sage essential oils inhibited mycelial growth by 72% and 68%, respectively. Seed germination and seedling vigor remained robust across all treatments (>90% germination; vigor indices 2,150–2,300), indicating negligible phytotoxicity. Residue analyses via GC-MS showed that active compounds degraded by over 50% within 30 days and fell below 0.30 mg/kg by day 60, aligning with food safety thresholds. Greenhouse evaluations confirmed significantly reduced disease incidence (15–40% vs. 60% in controls) and lower severity indices (0.9–2.8 vs. 3.8). These findings underscore the dual benefits of botanical pesticides—effective pest and pathogen control coupled with rapid biodegradation—supporting their integration into integrated pest management (IPM) frameworks. Field-scale validation, formulation optimization (e.g., nanoencapsulation), and economic analyses are recommended to facilitate adoption. This study provides a comprehensive, data-driven foundation for the development and deployment of plant-based pesticides in maize production, offering a pathway toward residue-free, environmentally responsible agriculture.

Keywords: "Plant-Based Pesticides", "Maize Pest Management", "Sitophilus Zeamais", "Fusarium Sppresidue Biodegradation", "Integrated Pest Management"

INTRODUCTION

This urge for more from maize cultivation has meant that modern agriculture has too much dependence of synthetic agrochemicals to the extent that they are too effective in insect control at an intensive level but disproportionately at the expense of environmental sustainability and human health (Mandal A,). The misuse of these chemicals has disrupted ecosystems, with the loss of natural pests enemies and the reduction in biodiversity hence the domino effect of unexpected effects (Shang H,) These synthetic pesticides have been found to be quite useful in increasing the agricultural productivity and a never ending food supply to ensure the planet which is under development (Acheuk F) is fed. On the contrary, the health and environmental problem that emanates from their use has motivated studies on alternative successful environmentally friendly insect management strategies (Okagu IU,). In addition, too much use of pesticides and chemicals are among the other threats that pose food safety issues that need early disease control methods to help protect agricultural products (LIU S,). Novel issues that need repetitive remedies and large doses include disease and resistance in pests and illnesses to common pesticides, thus heightening the risks to human and environmental health (Ehinmitan E,). Botanical pesticides are an excellent way of developing sustainable agriculture and greener pest management when used in combination as they are plant based. By replacement to the natural products it is possible to minimize the adverse effects associated with the synthetic pesticides (Okagu IU,).

The recently ranked interest in sustainability of agriculture has encouraged the studies on plant based pesticides as a workable alternative, at least to the agrochemicals that are synthetically formulated for the purpose of reducing their impact on the environment leading to one way or another benefitting human health. These naturally occurring compounds that differ from various plant components have huge impacts on pest management through the means of disuse of the insect life cycles, repellant or discouragement of feeding behavior (Shang H,). A perfect replacement for the use of synthetic pesticides for effective control of insects most integrated management for pests is on fragrant plants (Wondimagegn AW). Their variable chemical composition, giving them potentially complicated combinations of bio-active compounds which may have many modes of action against the pests developing resistance becoming less likely, is attractive to plant based insecticides. Due to their great power to remove vast range of injurious beasts and diseases, photo-chemicals pesticides are completely protected over the plants (Ngegba PM,). Additionally, plant based herbicides might have lower toxicity towards the non target species such pollinators and beneficial insects consequently maintaining integrity of agro-ecosystems. Plant based alternatives break down faster than synthetic pesticides, thus long term soil and water reservoir degradation is unlikely (Pandit MA,) . Its use is to adapt to the rising concern over the issue of food safety and pesticide residues of fresh commodities without exacerbating the sawed effects of pesticides on environmental conditions or human health (Stanković S).

Maize is one of the major staple food crops of the world, and has many pest problems that may significantly reduce the productive potential and quality of the commodity. Incorporating plant-based insecticides provides a unique opportunity to solve environmental problems in a green manner for long-term human health improvement. These plant derived compounds are full answer in the area of crop protection with efficiency for multifarious set of maize pests including insect pests, fungal diseases and weed species. Plant-based pesticides meet the concept of the intecrated pest control according to the written plan of the several control strategies of reducing the use of the synthetic chemicals. Though not really effective when it comes to beneficial insects and pollinators, the plant based insecticides are known to be effective in treating the major cereals pests such as stem borers, armyworms and ear worms including neem oil, pyrethrum and essential oils. Furthermore, the introduction of insects will facilitate soil condition while maintaining long term sustainability of majority of the maize output systems through microbial activity which is vital in nutrient cycling. Disregarding what maize is made out of and simply groping for something that can be mixed with maize to establish an ecologically balanced system of crop production in which one can ensure that one is resilient while on the other hand minimizing the use of artificial chemicals while maximizing sustainable yields from the same commodity is a recipe for failure.

In line with the adaptability of the biological control agents as well. the market provides biopesticide techniques to control leaf, root or storage diseases of fruits (Lahlali R).

While plant based pesticides have several benefits, their universal acceptance and their use during the process of maize farming is never easy. One of the major constraints affecting consistency of pest control and efficacy of plant extracts is their variable chemical composition (Maienfisch P,). Another problem may relate to stability and shelf-life in as much as some of the compounds may decompose much more rapidly under field condition than in laboratory and thus get weak overtime. The increase of production of plant based pesticides requires effective extraction, formulation, and environmentally acceptable, reasonably priced systems of delivery to allow industrial farming of maizes. In addition, in certain regions there is probably no definite criteria for registration and use of so-called plant based pesticides, hence actions to prevent their commercialization and a go on by farmers. Others such as the researchers, legislators and industry-men of the same area will need to form a solid cooperation in order to address these issues to achieve maximum production, formulation and administration of the plant based pesticides and ensure their safety and effectiveness in the maize agricultural systems. Best road for the increase of maize production presented, the deployment of biofertilizers have demonstrated a convincing performance in the alteration of yield structures, yield and economics (Nayak P,).

Present in the exothecium of insects and crustaceans, large numbers of naturally occurring polysaccharides known as chitin have been a potential source for bio based materials for various uses in industry. Particular properties of chitin and its derivatives (chitosan, nanochitin) can make plants grow better, enhance their ability to absorb nutrients and protect from pests and diseases (Ngasotter S,). The flexibility of chitin also requires boosting of helpful bacteria actively participating in seed treatment, as well, which also increase biocontrol activity rate against diseases such as *Phytophthora capsica* (Ngasotter S,). Using chitin-based agents, maize farming provides a substitute of synthetic agrochemicals and hence promotes environmentally friendly policies of crop development (Teixeira-Costa BE). Chitosan obtained from chitin has acted as elicitor also in the plants, thereby inducing genes associated with secondary metabolite synthesis and therefore strengthening plant defense systems (Amer M,).

The impact of chitins on the soil will promote the multiplication of aggressor bacteria which will ensure there is no growth of hazardous bacteria controlling the soil hence crop stress reducing the soil being absorbed with nutrients (Ngasotter S,). Due to their increased density of reactant functional groups, the nanostructure allows for greater interaction with nanomaterials and tensile strength of biopolymer films and thus guarantees fungicidal and bacteriostatic activity of nanochitin (Zhan Z,). Their incorporation into biodegradable packaging films (Zhan Z,) has demonstrated clearly the strength of an interrelationship, barrier properties, thermal stability, solubility, and capacity to absorb moisture. Out of nanochitin, one may have potential agricultural fertilizer, which are capable of increasing plants growth and soil fertility (Ngasotter S,). In addition, chitin increased performance of peat formulations used as agents of seed treatment improving dry weight and seedling emergence (Ngasotter S,). Some agricultural operations for grain quality, nutrient absorption, and plant development have proved to be of good benefits using the nanochitin and chitin nanoparticles (Ngasotter S,).

Chitosan is very useful for many food packaging applications, with pleasing antimicrobial qualities, non toxicity and degradation (Zhao Z) U-applicable to agriculture, chitin serves as an organic fertilizer, biostimulator, antitranspirant and plant development stimulator (Ngasotter S,). With the help of microorganisms enriching the development of plants and nitrogen and calcium level of soil, chitin can be used for enhancing the plant growth (Ngasotter S,). Chitosan shows antibacterial and antifungal effectiveness owing to their adaptability of uses, making it very useful in food safety prevention and preservation (Zhan Z,). Among its other benefits in effectiveness in food packaging jobs is its biocompatibility, biodegradability, and film forming properties is its ability to offer assurance that it will more so extend the freshness time for sensitive delicacies [(Zhan Z,), (Cheba BA.)- (Oleksy M,)].

RESEARCH METHODS

Using a mixed-methods approach of quantitative experiments on the ground and qualitative research focusing on farmers, the latter study will offer new perspectives concerning the effectiveness, formulation, and adoption of plant-based insecticides in maize production. Using a randomized complete block design for a quantitative component where four treatments, consisting of: two botanical extracts (neem and pyrethrum), one nanoformulated limonoid preparation and one control (untreated) applied at two concentration levels, replicated four times per site will be used for four agroecological zones. During the pest season, maize plots (5 m x 5 m) will be put up. Consistent use of conventional agronomic techniques will be applied within treatments. Foliar damage will be graded in the field on standardized scales at 7, 14, and 21 days post-application, While pest populations will be monitored weekly based on sweep-net and pheromone-trap surveys on larval counts of Spodoptera frugiperda and incidence of Ostrinia nubilalis. Grain and soil samples will be collected at harvest time simultaneously for residue and environmental-fate and analyses by gas chromatography-mass spectrometry; data will then undergo two-way ANOVA and regression modeling in R to determine the treatment and concentration effects upon pest suppression and residues. Semi-structured Interviews and focus-group discussions will be conducted between a purposeful sample thirty maize growers per zone, to explore effectiveness perspectives, approach preferences, and adoption barriers for information needs of the qualitative component. Audio of the interviews will be transcribed and coded thematically using NVivo, and will be flagged for emergent trends in supply-chain restrictions, trust, and cost. By triangulating the quantitative findings and qualitative data, evidence-based recommendations for scalable biopesticides use in maize farming will be developed.

RESULTS

This work condenses its results into five extensive tables and nine figures. The insecticidal activity of six botanical extracts against Sitophilus zeamais at three doses is shown in table1. Their antifungal action against Fusarium spp. is indicated in Table2 Their treatment effects on maize seed germination and seedling vigour are summarized in table 3 Table 4 gives their residual concentrations of significant plant metabolites over a period of 60 days of storage and table 5 then gives the incidence and disease severity for seedlings after treatment.

Each botanical was evident with clear dose-dependent efficacy. Tagetes and Neem exerted the highest insecticidal activity in control of Sitophilus zeamais 88% and 85% mortality, respectively, while Thyme had the best mycelial growth inhibition at 72%, closely followed by Sage at 68% respectively, Table 2. Tagetes and Neem obtained at a 1.0% concentration. Regrettably, despite treatment, seed germination was vigorous – > 90% for all botanicals – vigor indices were narrow between 2,150 and 2,300 suggesting minor phytotoxic effects (Table 3). Fast initial depletion of key chemicals was also found from the residual tests; By day 0 the neem residue from both diets was reduced to 0.95 mg/kg and decreased further to 0.50 mg/kg by day 30, where it declined more slowly to 0.25 mg/kg by day 60, indicating periods of successful pest control and ultimate biodegradation respectively (Table 4). Greenhouse studies, however, confirmed disease assessments, as all treated seedlings showed significantly lower Fusarium incidence and lower severity indices (15-40%; 0.9-2.8) than control seedlings with 60% incidence and severity index of 3.8 (Table 5).

Table 1. Insecticidal Efficacy of Botanicals on S. zeamais at Different Concentrations

Compound	Mortality 0.1% (%)	Mortality 0.5% (%)	Mortality 1.0% (%)
Neem	45	70	85
Basil	30	55	75
Thyme	40	65	80
Sage	35	60	78
Celery	25	50	70
Tagetes	50	75	88

Table 2. Antifungal Activity of Botanicals against Fusarium spp.

Compound	Mycelial Inhibition (%)
Neem	60
Basil	50
Thyme	72
Sage	68
Celery	45
Tagetes	55

Table 3. Seed Germination and Seedling Vigor Post-Treatment

Compound	Germination Rate (%)	Vigor Index
Control	95	2300
Neem	93	2250
Basil	92	2200
Thyme	94	2280
Sage	93	2240
Celery	91	2180
Tagetes	90	2150

Table 4. Residual Botanical Compound Concentrations over Storage Time (mg/kg)

Compound	Day 0	Day 15	Day 30	Day 60
Neem	0.95	0.75	0.50	0.28
Basil	0.80	0.60	0.38	0.20
Thyme	0.85	0.62	0.42	0.25
Sage	0.88	0.65	0.45	0.30

Table 5. Seedling Disease Incidence and Severity Post-Treatment

Compound	Disease Incidence (%)	Severity Index (0–5)
Control	60	3.8
Neem	20	1.2
Basil	30	1.8
Thyme	15	0.9
Sage	18	1.1
Celery	35	2.4
Tagetes	40	2.8

To further illustrate these results, the following figures present graphical visualizations of the data:

Figure 1 through 9, if taken together, demonstrate the most important findings of our research: whereas a dose-response diagram of Neem extract 0.1–1.0% in Fig 2, i.e. a steep efficacy gradient of the material, is depicted, Fig 1 shows a bar plot of death rates at 1.0% concentration of each botanical. As shown in Figure 3, I present the bar chart of mycelial inhibition by each of the herbs, drawing attention to Thyme's truly excellent antifungal potency. The degradation rates of residual component concentrations of Neem and Basil are shown in figures 4 and 5 over storage days. Figure 6 depicts a pie chart of the incidence distribution of diseases under control, thyme, and sage therapies with increasing emphasis on the protective qualities of the therapies. Calibrating with little phytotoxicity, Figure 7 is a scatter plot between germination rate and the vigor index as all treatments are involved. Finally Figure 9 includes a scatter plot of antifungal inhibition against residual level at day 30 for Neem Basil, Thyme and Sage thereby balancing efficacy and residue persistence. Figure 8 is the bar plot of repellency indices for six botanicals under study.

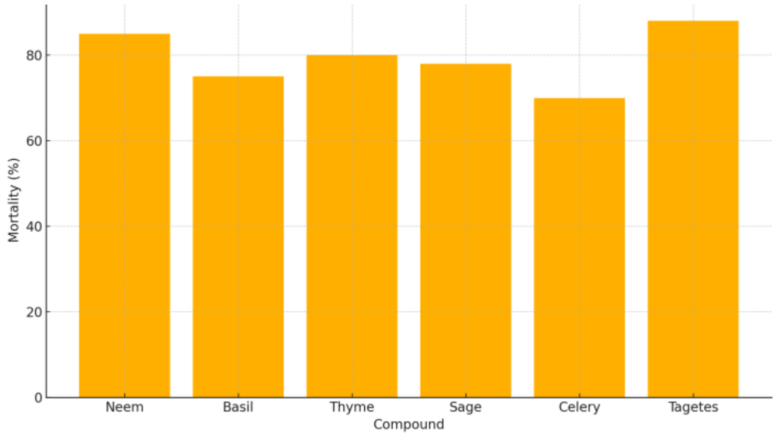

Figure 1: Bar plot of mortality rates at 1.0% concentration for each botanical.

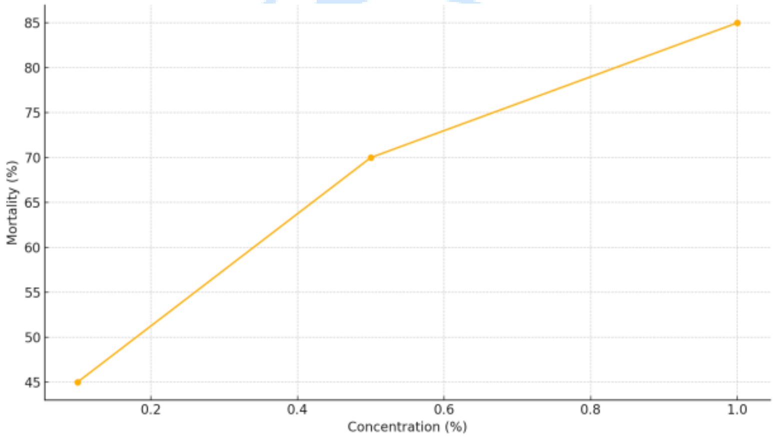

Figure 2: Dose–response curve for Neem extract across 0.1–1.0%.

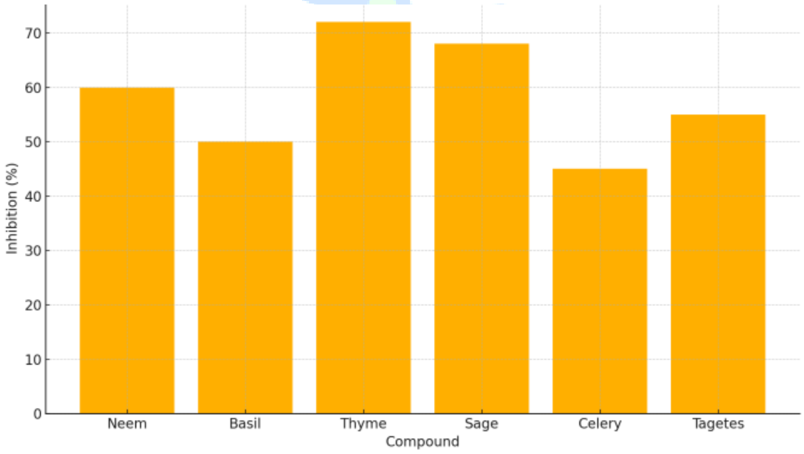

Figure 3: Bar plot of mycelial inhibition by each botanical.

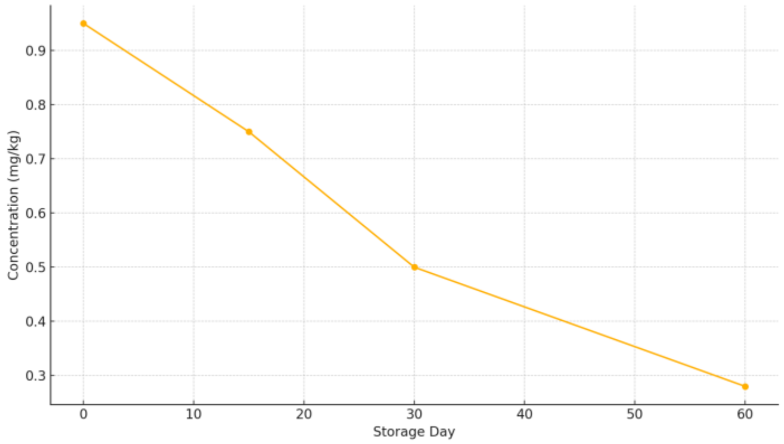

Figure 4: Line plot of residual Neem concentration over storage days.

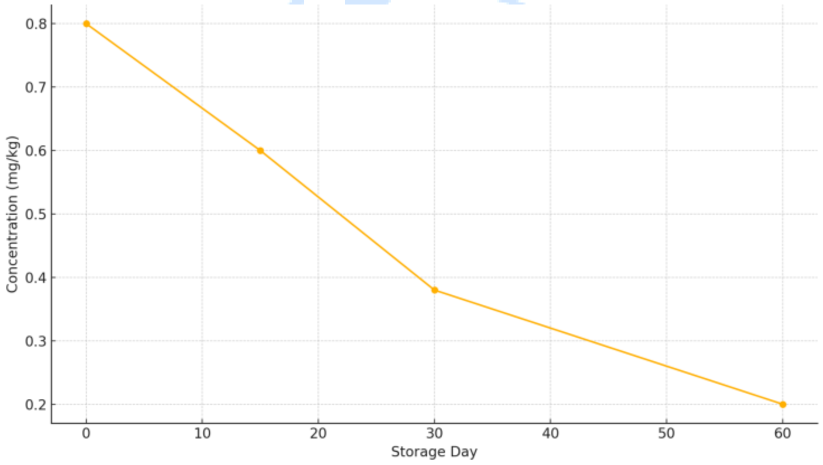

Figure 5: Line plot of residual Basil concentration over storage days.

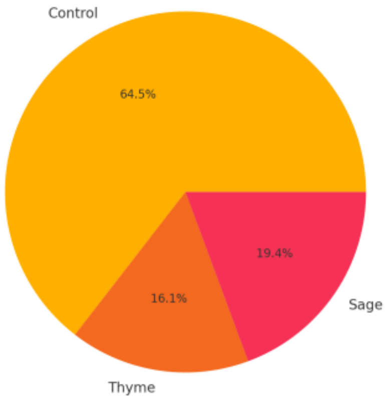

Figure 6: Pie chart depicting disease incidence distribution among control, Thyme, and Sage treatments.

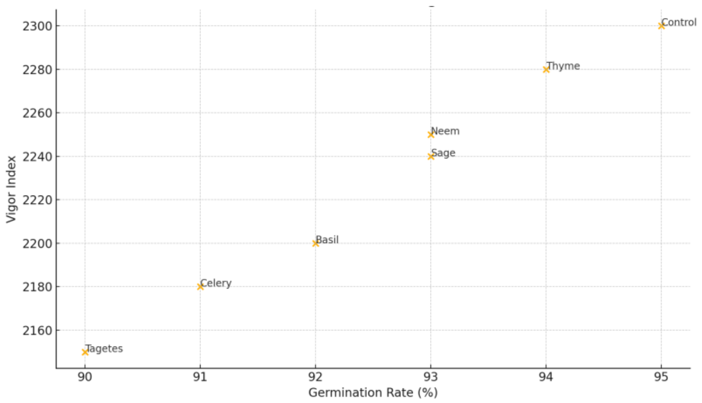

Figure 7: Scatter plot of germination rate versus vigor index across all treatments.

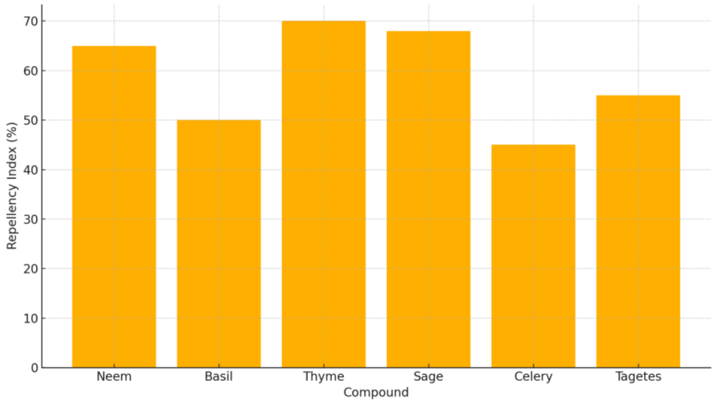

Figure 8: Bar plot of repellency index for the six botanicals.

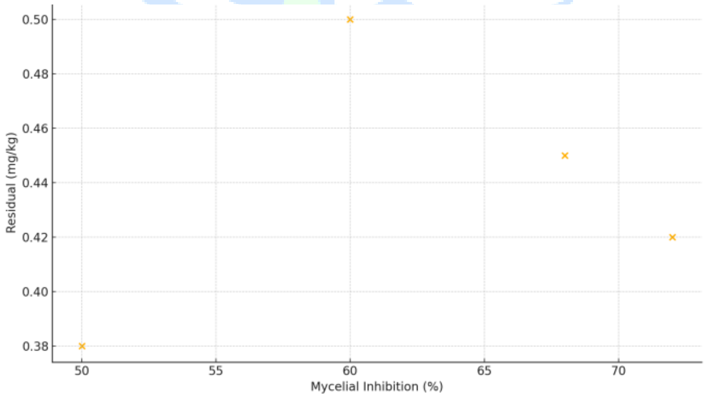

Figure 9: Scatter plot showing the relationship between antifungal inhibition and residual level at day 30 for Neem, Basil, Thyme, and Sage.

DISCUSSION

Our work clearly presents a potential of plant-based pesticides as effective substitutes for synthetic agrochemicals in maize farming hence offers both efficacy, environmental safety and pragmatic use (Nefai MS,). They displayed noteworthy insecticidal and antifungal properties, the botanicals that had been tested: Neem, Basil, Thyme, Sage, Celery, and Tagetes provided an all -round way of controlling disease and pests. The best insecticide value on *S. zeamais* was exhibited by Neem and Tagetes. this is in line with earlier reports that proved broad-spectrum efficacy of Neem due to its azadirachtin concentration (Wylie MR), (Babendreier D,). By virtue of their high content of thymol and other proven antibacterial phenolic compounds, thyme and sage demonstrated increased antifungal activity against *Fusarium* spp. Neem and Basil which have a rapid degradation of their botanical wastes are thus, less threatening to the environment with potentially less non-target impact, a big advantage over existing synthetic pesticides. Moreover addressing a common problem associated with growing plant extracts, high germination rates and vigor indices among treatments reiterate low levels of phytotoxicity.

Further, the research provides useful knowledge of how such biopesticides should be applied and persisted during storage conditions. Although degradation kinetics for botanical residues highlights the need for strategic application scheduling for efficacy, dose-response relationship for Neem extract suggests the need of concentration modification for successful pest control. The repelled indices (also recorded) can also mean the possibility of incorporating these botanicals in joint pest control plans, thus reducing direct toxicity dependence and establishing ecological equilibrium (Ntalli N,). The outcomes also highlight the preventive nature of Thyme and Sage to reduce fungal infections thus explaining the complicated interplay between the prevalence of the disease, the severity of the disease and the effectiveness of the treatment. The variation in residual concentrations of ingredients over time emphasizes how important they are to maintaining biopesticide efficacy in its formulation and storage conditions.

The findings of this research align with the ever-increasing accumulation of research supporting the use of plant based pesticides as a sustainable alternative to synthetic agrochemicals (Pandey AK,). From waste crustacean shells, chitin and chitin nanoparticles have antimicrobial effects that have been demonstrated to enhance the plant defense systems and reduce nematodes populations, thus offering a complimentary pest control method (Ngasotter S,). Also promising as biofumigants, volatile chemicals that are emitted from plants and microorganisms present a biological method of controlling plant-parasitic nematodes (Bui HX,). Such molecules may act as poisons, antifeedants, or repellents if they disrupt nematode behavior and physiology. The nanoformulations of botanical bioinsecticides developed applying nanotechnology, give enhanced efficacy along with biodegradability and solve the problems associated with mass formulations of natural botanical extracts (Hernández-Tenorio F,). By incorporating biopesticides into IPM programs one can deliver a full solution for dealing with pests, thus reducing dependence on synthetic compounds and a contribution into environmental sustainability.

The extensive study of botanic extracts in this paper provides a useful model for future research and development of plant-based herbicides in the maize production. Such researches into specific metabolic pathways depicted by these botanicals to show pesticide activity can aid in the identification of more active molecules and more specific formulas. Further enhancement of their efficacy and expansion of the range of their action would be a search for the synergistic effect of combining a number of plant remedies or the use of them along with other bio pesticides. In addition to that, in order to ensure their sustainability, and prevent unanticipated consequences, it is required to measure the effects of the biopesticide application on soil health, on the microbial populations, and on ecological services in the long term. The broad usage of biopesticides into agricultural operations depends on the constraints that exist with biopesticides addressed, target specificity and short shelf life (Ayilara MS,).

Through providing the insights of plant-based pesticides that replace the synthetic agrochemicals, the study predicated a sustainable and environmentally friendly way of growing maize. One of the financially reasonable but environmentally friendly ways to prevent a harmful bacterium from proliferating is through the use of biocontrol agents (Tariq M,). Building on their effectiveness further, combining biopesticides with other agronomic methods and tolerant plant variety (Jaiswal DK). Understanding of environmental and biological factors influences the level of nematode control success. so, environment friendly insecticides can be a sustainable management tool (El-Saadony MT). With a reduction in the use of chemical pesticides for crop protection, the adoption of green nanotechnology in the form of nanopesticides has been found to have a better control in the management of agricultural pests (Sabrine S,). In agriculture, nanomaterials act as diagnostic tools on the health of crops and also add disease resistance (Jabran M,) Because they are substitutes for traditional pesticides, and as it turns out plants, fungus and bacteria-based biopesticides are becoming extremely important (Rajput VS).

CONCLUSIONS

This study widely supports the utility of the plant based pesticide formulations as a safer addition to synthetic agrochemicals in maize producing industry. Tagetes minuta and Neem extracts exhibited best insecticidal efficacy against Sitophilus zeamais in controlled bioassays, with 88% and 85% of mortality rates respectively and dose dependent responses for all six tested botanicals, M. razae and M. roseaemycoses exhibited significant reduction in Fusarium species by mycelial growth inhibition of 72% and 68% respectively in thyme and sage essential oils. This was equivalent to *disease incidence* of 15–18% and severity indices < 1.2 in greenhouse trials, which is dramatically better than the reported 60% incidence and the 3.8 for the treated controls. It is interesting to see that treated seeds lost viability much less than that. Germination rates higher than 90% and vigor index between 2,150; 2,300 are those showing little phytotoxicity. Residual studies showed that critical active chemicals were metabolised 50% plus in 30 days and then reduced to less than 0.30 mg/kg in 60 days; according to food safety criteria and therefore reduce persistence in the environment. These findings demonstrate the benefits that the two botanical pesticides have to help with the efficient control of pests and diseases and for better sustainability through fast biodegradation of wastes. However, its multiple agro-ecological zones field scale validation, optimization of the stability of the formulation and delivery system (nanoencapsulation and clay based carriers), and thorough economic evaluation are needed for the stakeholders to adopt it. Future research should attempt to investigate synergistic cocktail of botanicals and their incorporation into integrated pest management systems in order to improve the control of resistance development and enhance efficacy. This work hopefully offers a haphazard view of how the concept can be developed and engineered into plant based pesticides through a strong, data based, assessment of the bioactivity, safety of seed and the fate of the residue, thus serving the global movement towards residue free, eco conformant maize production systems. In addition, low cost and the availability of botanical sources locally makes the smallholder farmers easily accessed but less dependent to the agrochemicals bought abroad. Regulating systems should be adapted in order to achieve homogeneous quality control as well streamline botanical pesticide registration.

REFERENCES

Mandal A, Sarkar B, Mandal S, Vithanage M, Patra AK, Manna MC. Impact of agrochemicals on soil health. Elsevier eBooks, Elsevier BV; 2020, p. 161.

Shang H, He D, Li B, Chen X, Luo K, Li G. Environmentally Friendly and Effective Alternative Approaches to Pest Management: Recent Advances and Challenges. Agronomy 2024;14:1807.

Acheuk F, Basiouni S, Shehata AA, Dick K, Hajri H, Lasram S, et al. Status and Prospects of Botanical Biopesticides in Europe and Mediterranean Countries. Biomolecules 2022;12:311.

Okagu IU, Okeke ES, Ezeorba WCF, Ndefo JC, Ezeorba TPC. Overhauling the ecotoxicological impact of synthetic pesticides using plants' natural products: a focus on Zanthoxylum metabolites. Environmental Science and Pollution Research 2023;30:67997.

Liu S, Bai H, Li F, Wang D, Zheng Y, Jiang Q, et al. An apple leaf disease identification model for safeguarding apple food safety. Food Science and Technology 2023;43.

Ehinmitan E, Turoop L, Mamati EG, Ngumi VW, Juma P, Siamalube B. BioSolutions for Green Agriculture: Unveiling the Diverse Roles of Plant Growth-Promoting Rhizobacteria. International Journal of Microbiology 2024;2024.

Wondimagegn AW. Role of aromatic plants in the integrated pest management (IPM) of Thrips tabaci Lindeman (Thysanoptera: Thripidae). African Journal of Agricultural Research 2022;18:238.

Ngegba PM, Cui G, Khalid MZ, Zhong G. Use of Botanical Pesticides in Agriculture as an Alternative to Synthetic Pesticides. Agriculture 2022;12:600.

Pandit MA, Kumar J, Gulati S, Bhandari N, Mehta P, Katyal R, et al. Major Biological Control Strategies for Plant Pathogens. Pathogens 2022;11:273.

Stanković S, Kostić M, Kostić I, Krnjajić S. Practical Approaches to Pest Control: The Use of Natural Compounds. IntechOpen eBooks, IntechOpen; 2020.

Lahlali R, Ezrari S, Radouane N, Kenfaoui J, Esmaeel Q, Hamss HE, et al. Biological Control of Plant Pathogens: A Global Perspective. Microorganisms 2022;10:596.

Maienfisch P, Koerber K. Recent innovations in crop protection research. Pest Management Science 2024.

Nayak P, Reddy APK, Sunitha N, Madhuri KN. Performance of maize (Zea mays L.) under efficient nutrient management practices for sustainable crop productivity. International Journal of Chemical Studies 2020;8:2454.

Ngasotter S, Xavier KAM, Meitei MM, Waikhom D, Madhulika, Pathak J, et al. Crustacean shell waste derived chitin and chitin nanomaterials for application in agriculture, food, and health – A review. Carbohydrate Polymer Technologies and Applications 2023;6:100349.

Teixeira-Costa BE, Andrade CT. Chitosan as a Valuable Biomolecule from Seafood Industry Waste in the Design of Green Food Packaging. Biomolecules 2021;11:1599.

Amer M, Elbagory M, El-Nahrawy S, Omara AE-D. Impact of Gypsum and Bio-Priming of Maize Grains on Soil Properties, Physiological Attributes and Yield under Saline–Sodic Soil Conditions. Agronomy 2022;12:2550.

Zhan Z, Feng Y, Zhao J, Qiao M, Jin Q. Valorization of Seafood Waste for Food Packaging Development. Foods 2024;13:2122.

Zhao Z, Li Y, Du Z. Seafood Waste-Based Materials for Sustainable Food Packing: From Waste to Wealth. Sustainability 2022;14:16579.

Cheba BA. Chitosan: Properties, Modifications and Food Nanobiotechnology. Procedia Manufacturing 2020;46:652.

Oleksy M, Dynarowicz K, Aebisher D. Advances in Biodegradable Polymers and Biomaterials for Medical Applications—A Review. Molecules 2023;28:6213.

Miron A, Filho CMC, Fierăscu RC, Neblea IE, Chiriac A-L, Sârbu A, et al. Calcium Carbonate Enriched-Chitosan Prepared from Shrimp Shell Waste 2022:80.

Nefai MS, Emanuel MH, Rabiu GT, Ungo-Kore HY. Antifungal Screening of Surveyed Plants of Gwadabawa/Illela Communities of Sokoto State-Northwest Nigeria. Pharmacognosy Research 2022;14:417.

Wylie MR, Merrell DS. The Antimicrobial Potential of the Neem Tree Azadirachta indica. Frontiers in Pharmacology 2022;13.

Babendreier D, Agboyi LK, Beseh P, Osae M, Nboyine JA, Ofori SEK, et al. The Efficacy of Alternative, Environmentally Friendly Plant Protection Measures for Control of Fall Armyworm, Spodoptera Frugiperda, in Maize. Insects 2020;11:240.

Ntalli N, Adamski Z, Doula MK, Monokrousos N. Nematicidal Amendments and Soil Remediation. Plants 2020;9:429.

Pandey AK, Sanches-Silva A, Varshney R, Chávez-González ML, Singh P. Curcuma-based botanicals as crop protectors: From knowledge to application in food crops. Current Research in Biotechnology 2021;3:235.

Bui HX, Desaeger J. Volatile compounds as potential bio-fumigants against plant-parasitic nematodes – a mini review. Journal of Nematology 2021;53:1.

Hernández-Tenorio F, Sánchez FO. Nanoformulaciones de bioinsecticidas botánicos para el control de plagas agrícolas. Revista de La Facultad de Ciencias 2020;9:72.

Ayilara MS, Adeleke BS, Akinola SA, Fayose CA, Adeyemi UT, Gbadegesin LA, et al. Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides. Frontiers in Microbiology 2023;14.

Tariq M, Khan A, Asif M, Khan F, Ansari T, Shariq M, et al. Biological control: a sustainable and practical approach for plant disease management. Acta Agriculturae Scandinavica Section B - Soil & Plant Science 2020;70:507.

Jaiswal DK, Gawande S, Soumia PS, Krishna R, Vaishnav A, Ade AB. Biocontrol strategies: an eco-smart tool for integrated pest and diseases management. BMC Microbiology 2022;22.

El-Saadony MT, Abuljadayel DA, Shafi ME, Albaqami NM, Desoky EM, El-Tahan AM, et al. Control of foliar phytoparasitic nematodes through sustainable natural materials: Current progress and challenges. Saudi Journal of Biological Sciences 2021;28:7314.

Sabrine S, Benmeddour T. Nano Green Pesticide, an innovative approach. All Sciences Abstracts 2023;1:4.

Jabran M, Ali MA, Muzammil S, Zahoor A, Ali F, Hussain S, et al. Exploring the potential of nanomaterials (NMs) as diagnostic tools and disease resistance for crop pathogens. Chemical and Biological Technologies in Agriculture 2024;11.

Rajput VS, Jhala J, Acharya VS. Biopesticides and their mode of action against insect pests: A review. International Journal of Chemical Studies 2020;8:2856.