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Investigating the Efficacy of Chilli Pepper Extract in Controlling Pest and Promoting Sustainable Spinach Production

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Abstract

The study aimed to evaluate the efficacy of chilli pepper extract (*Capsicum spp*.) as a botanical pesticide in managing pest populations and enhancing the sustainability of spinach (Spinacia oleracea) cultivation. Three treatment levels of chilli extract concentrations were selected based on previous studies and empirical evidence from integrated pest management (IPM) research. The concentrations used were 5% and 10% chilli extract solutions, prepared by blending dried chilli powder with water and allowing the mixture to steep before filtration. Each treatment, along with a control (water spray), was replicated three times in a randomized complete block design (RCBD) under field conditions. Results demonstrated a significant reduction in pest incidence across all treatments when compared to the control. The 10% chilli extract treatment was most effective, leading to an average 72% reduction in aphid and leaf miner populations. The 5% treatment followed closely with a 61% reduction, while the control treatment recorded a 45% decrease. In terms of plant growth and yield, spinach plots treated with 10% and 5% chilli extract produced significantly higher biomass and marketable yield compared to the control. The 10% treatment led to the highest average fresh weight per plant, suggesting that pest control effectiveness translated to improved crop performance. The positive results underscore the role of locally available, plant-based solutions in promoting resilient and sustainable food systems, especially in smallholder and resource-limited agricultural settings.

Keywords: Spinach Production, Chili Extract, Pest Management, Bio-Pesticides, Sustainable Agriculture

Introduction

Spinach (*Spinacia oleracea,* L.), as an annual plant with a short growth cycle, is considered as one of the most common leafy vegetable crop, which belongs to the subfamily Chenopodiaceae and family Amaranthaceae (Biemond *et al.*, 2015). Spinach is a highly desirable leafy vegetable with a good cooking adoptability, a high nutritive value and many important vitamins and minerals (Nishihara *et al*., 2001).

Spinach has been consumed for thousands of years. It is believed that spinach made its way into Indian and Asian cooking through Arab traders who carried it to Asia from the Middle East. In the 11th and 12th centuries, spinach became a popular vegetable in Spain, and from there it diffused to Germany, Italy, England, and France. It has been used in salads, soups, in baked dishes with cheese, yogurt, and in tortellini. In the early 19th century, American colonists introduced spinach to North America. At least three varieties were grown by 1806.

Spinach comes in a variety of leaf types and textures. Planting a range of different types makes salads more interesting. There are many good varieties for sale in local gardening outlets and through seed catalogs. Most grow well in Lusaka province. Varieties suited to local conditions include Bloomsdale, Melody, Teton, and Olympia, Space and Fordhook giant. Vegetables like Spinach are grown in Zambia not just for food but serve as a source of income. There are Zambians that grow vegetables in their background either for food or commercial purpose.

Vegetable growing particularly in Lusaka province has existed for over several years and has been done with the vegetable crops such as rape, cabbage, spinach and okra among others. These vegetable crops are well adapted for the temperate climate of such a region and has been known to yield well per unit area of land.

Spinach is extremely perishable and will deteriorate quickly in warm conditions, with an accelerated loss of the carotenoid content which contributes to its nutritional value. Spinach is ideally maintained in storage close to 32°F or 0°C, with high

humidity levels.
Spinach does not compete well with weeds. Weed control is particularly important during establishment. Closely spaced plants help control weeds. Cultivate shallowly and avoid root pruning to ensure uninterrupted growth.
Because of the increasing demand for the vegetable among the local consumers, there is need to focus most on these vegetables with high nutritional content and market demand. Other than that, the adaptability of the vegetable in the known climate of Zambia makes it among the most profitable vegetables that farmers could chose to grow. It is a hardy vegetable that is quite tolerant to a wide range of environmental conditions and it is for this reason that the research discussed Spinach as a vegetable choice that may, in the near future, monopolize local markets in Zambia.

Problem Statement
The intensification of agricultural production to meet global food demands is critically challenged by the pervasive threat of crop pests, which can lead to substantial yield losses and economic damage, particularly for smallholder farmers with limited resources. Conventional reliance on synthetic chemical pesticides, while often effective, has precipitated a cascade of detrimental consequences, including the evolution of pest resistance, the detrimental effects on non-target beneficial organisms like pollinators and natural predators, and the contamination of soil and water resources, thereby undermining the ecological foundations of agricultural sustainability (Sharma *et al*., 2019). This creates an urgent need for the development and integration of effective, economical, and environmentally benign pest management strategies that are accessible to resource-limited farming communities. Botanical pesticides, derived from plants with inherent insecticidal properties, present a promising alternative, as they are typically biodegradable, have multiple modes of action that can delay resistance, and can be produced from locally available materials, thus aligning with the principles of integrated pest management (IPM) and contributing to more resilient and sustainable food production systems (Isman, 2020) [40].

Purpose of the Study
The purpose of the study is to provide means and techniques that will not only be utilized by small scale farmers but by commercial farmers as well with the understanding that the knowledge of innovative use of chili will foster less adverse impacts on the environmental and the biodiversity. Furthermore, the research aims to produce an entirely new perspective on the subject of disease management by making use of readily available cheap and biologically friendly means of treating fungal and bacterial infections in Spinach plants.

Research Objectives
Main Objective
Investigate the efficacy of chilli pepper extract in controlling pests and promoting sustainable spinach production.

Specific Objective
1. To evaluate the impact of chilli pepper extract treatments on the growth parameters of spinach, including plant height, number of leaves, and canopy diameter, in comparison to an untreated control.
2. To determine the efficacy of different concentrations of chilli pepper extract (5% and 10%) against spinach pests by comparing the pest population among treatments.
3. To identify the optimal concentration of chilli pepper extract with produces improvements in crop yields for smallholder farmers.

Hypothesis
HO: There is a significant difference on the growth parameters of spinach, including plant height, number of leaves, and canopy diameter, in comparison to an untreated control.
HI: There is no significant differences on the growth parameters of spinach, including plant height, number of leaves, and canopy diameter, in comparison to an untreated control.
HO: There is significant difference in the efficacy of different concentrations of chilli pepper extract (5%, 10%, and 15%) against spinach pests among treatments.
HI: There is no significant difference in the efficacy of different concentrations of chilli pepper extract (5%, 10%, and 15%) against spinach pests among treatments.
HO: There is a significant difference in the optimal concentration of chilli pepper extract which produces improvements in crop yield s for smallholder farmers.
HI: There is no significant difference in the optimal concentration of chilli pepper extract which produces improvements in crop yield s for smallholder farmers.

Theorectical Framework
Sustainable Agriculture Theory
Organic production of spinach provides an outline of cultural and pest management practices and includes topics that have an impact on improving plant health and reducing pest problems and disease problems. The effective growing of Spinacia oleracea requires a close and preliminary understanding of the different parameters that would pose a challenge in the production and postproduction operations. It is with this respect that a means of understanding such an enterprise is proposed through the theory of sustainable agriculture. Sustainability aims at ensuring a reliable, effective and economically viable means of crop and vegetable production.
Stability of the food supply is broadly related to the environmental conditions that allow for sustainable food production and encourage productivity as well as to the economic conditions that allow for sustainable supplies at reasonable prices.
Plant based extracts form the basis of the many agricultural applications in modern society. They are used in various fields such as food additives, aromas, perfumes, cosmetics as well as agrochemicals, R, Ditz *et al*. (2017). According to FAO, the worldwide trade volume of the plant extracts was about 1 trillion USD in 2003/2004 and the annual growth rates between 6% and 8% were reported for plant based phytopharmaceuticals and agro chemicals.
Although the plant-based extracts are widely accepted by the consumers, they are in stiff competition due to the increasing shift towards chemical defined activities. In the right sense, a lot of farmers are drawing further away from sustainable growing of vegetables and crops into a more rapidly growing chemical age. This however poses a lot of

risks to the consumers and to the bio geophysical environment.

In the field of agriculture, it is generally accepted that botanical plant derived extracts serve a variety of purposes such as in herbicide production and agrochemical production. Some of the products used by small scale farmers around Zambia are not necessarily certified. And it is for this reason that mass production of such products is challenged and this can also be owed to the lack of financial support and investments. The quantities used in these local products vary because most of the farmers understand the level of ingredients that will produce an effective reaction.

Katarzyna G, *et al* (2021) explains the theory underlying plant extracts in those plants, due to the high content of various bio active compounds are the main raw material for production of various useful bio-products like the bio stimulants and bio pesticides. He further explains that different plant parts such as seeds, stems, and the roots can be cultured and used in the production of organic compounds. It is imperative therefore to consider developing new efficient and environmentally friendly methods of growing both vegetables and crops without solely relying on chemical compounds. Plant based compounds are new, natural and multi- compound products that would potentially bring about the redefinition of the existing conventional methods of agriculture production. This plant derived extracts possess antifungal, antimicrobial, antiparasitic, antiprotozoal, antioxidant, medicinal, aromatic, and anti-inflammatory properties, Ertarin *et al*, (2015).

Other natural products should be considered, such as chili extracts then studied, and assessed and the importance of plant extract will be concluded to improve agricultural sustainability and in particular crops quality and quantity. Primary and secondary plant metabolites affect important biological activities influencing plant physiological responses, Barrajón-Catalán *et al*., (2014) [10] and plant phenotype. Several previous studies reported the effects.

A variety of plants can be used to produce natural extracts. The biomass availability and wide abundance are the main selection criteria. Farmers or other growers (environmental agriculture) choose plants that grow near their farms, Mkenda *et al*., (2015), Tembo *et al*., (2018). Additionally, the farmers know about their effectiveness (traditional recipes passed on for generations), the content of bioactive compounds and safety, (Pavela, 2016). An additional advantage of plant biomass is its low cost. Conversion of plant biomass into extracts, showing the action of biostimulants of plant growth or biopesticides, can be crucial for poor farmers in developing countries who cannot afford synthetic biostimulants.

The chili extracts will be prepared into a liquid form organic pesticide and this is modeled around the understanding that the potent content of bioactive compounds will safely act of the present pathogen to disrupt the functioning and consequently stop their reproduction capability. *Erwinia carotovora* is a soil bacterium that affects vegetables, such as carrots [*Daucus carota* subsp. *sativus* (Hoffm.) Arcang.], potatoes (*Solanum tuberosum* L.), cucumbers (*Cucumis sativus* L.), onions (*Allium cepa* L.), tomatoes (*Lycopersicon esculentum* Mill.), lettuce (*Lactuca sativa* L.), and green peppers (*Capsicum annuum* L.). Crops can be infected in the field as well as during storage. Affected tissues become soft and watery, turning slimy and foul-smelling. This disease known as bacterial soft rot is caused by *E. c.* subsp. *atroseptica* (van Hall) Dye, and *E. carotovora* subsp. *carotovora* Jones, Basim, E., and Basim, H. (2000).

Jones, N.L., Shabib, S., and Sherman, P.M. (1997) further explain the theory that discusess fatty acids and plant extracts that over the years, antimicrobial properties of substances of natural origin have been recognized, including those derived from animals, plants, and microorganisms. It is known that spices and aromatic herbs have different properties, in addition to those for which they are grown. Furthermore, due to their bacteriostatic, bactericidal, and fungicidal properties, certain species increase the useful life of foods, and some even prevent food spoilage by their antioxidant activity.

Many of the plant compounds of the solanacea family are related to capsaicin, the flavor and pungent principle in hot peppers, which are present in different concentrations. They are also called capsaicinoids and are synthesized by the phenylpropanoid pathway, Dorantes *et al*., (2000). Emperical studies on the subject reported antibacterial effects of capsaicin from hot pepper.

Materials and Methods

Location and Site

The study area is located in Zimba district of Southern province between latitudes 17 to 18 S and 26 to 28 E. Zimba district covers an area of 5,245 to 5,480 square kilometres and shares district boundaries with Kalomo in the north and east, Choma and Sinazongwe in the east, Kazungula in Southwest. According to agro- ecological conditions, based on temperature and moisture supply, the area lies in Region II of Zambia. This region receives a total annual rainfall of between 800 to 1000mm a mean yearly temperature of 20.4^{0}C. The dominant soils include Acrisols and Luvisols soils which are typicalmoderately leached, medium to strongly acid with sandy top soils overlying loamy subsoil. They also include portions of moderately weathered, moderate to slightly acidic red to strong brown soils derived from limestone, Victor Shitumbanuma *et al* (2021).

Varietal Information

The Spinach variety of choice was Swiss chard seeds that were bought from Zimba Agric stores. Spinach (*Spinacia oleracea)* is a vegetable that is rich with chlorophyll that will be selected as the plant material in this study. Spinach is an annual plant with short growth cycle between 25 – 30 days after transplanting and is commonly grown in the summer or rainy season. It takes approximately three months for the complete life cycle of Spinach until harvesting.

Chilli Extract Prepareation

The chili was first crushed and pounded working them into a paste. The paste was the n placed on a fine muslin cloth bringing the sides together making a cloth bag enclosing the paste. The cloth bag was later placed in water to cover the bag overnight. Thereafter soaking, squeeze the juice from the bag with hands protected by rubber gloves or plastic bags, for the final mix and added water and 5g bar soap. Checked if the mix contained plant materials which may block the sprayer, strain through a metal strainer. Added water to achieve final volume and poured into the sprayer for use. (Mani. M & Grahame J, 2021).

Land Preparation and Planting

The land on study site was cleared of all crop residues from previous production and then prepared mechanically using hand hoes to till the soil, rakes to level the beds and measuring tapes for accurate measurement of the planting beds. Raised seed beds to a height of 15 to 30 cm, measuring 2 x 2 meters each were prepared, making a total of 12 seed beds. Water was then applied to the seedbeds to increase its moisture content and stabilize the soils.

Irrigation

The plots was irrigated using horse pipes and watering cans. Water was supplied to the seed beds at the time of planting. The watering continued up until the seeds emerge from the soil.

Fertilization

Veg mix B was applied at planting up to 4 up after planting, 2.5grams per plant. Veg top 24 was applied 21 days after planting at the rate of 2 grams per plant. Veg top 24 every 2 weeks three times to make 4 top dressing applications.

Experimental Design and Schematic Diagram

The study was modelled around the complete randomized design and there were three treatments replicated three times. The treatments were assigned codes T1, T2 and T3 for which T1 was Spinach grown without any pesticide applied and this was the control, T2 was Spinach grown with the application of the chili extract of 10% and finally T3 represented Spinach grown with he application o he chilli extract of 5% The Spinach seed was sown at a depth of 5 mm with an inter row spacing of 5cm.

Data Collection

Data was systematically collected ensuring data quality. The effect of the treatments on the plant development of spinach was measured by taking the plant height, number of leaves, canopy diameter and leaf length. The plant height of the spinach was measured from the medium surface until the top of the plant top while the number of leaves were counted each week. The canopy diameter was measured from one leaf tip to the other end the leaf length was measured from the bottom to the tip of the leaves. The fresh weight and root length were measured at the end of the study.

Statistical Analysis

The effect of each treatment on the growth parameter i.e., plant height, number of leaves, canopy diameter, leaf length, fresh weight and root length of the spinach were analyzed using Statistical Analysis Software (SAS). Analysis of Variance (ANOVA) was performed to find significant effect of different growth parameters. Mean comparison using Least Significant Difference (LSD) test at $P < (0.05)$ was employed for mean comparison. Differences were considered significant when the P value was < 0.05.

Harvesting

Individual leaves were picked as needed at the end of the growth period, from the outside of the plant, but was taken to leave enough for the plant to be able to photosynthesize as the leaves did not all mature at the same time. Harvesting was done by cutting the leaves to avoid damage to the root system. Harvesting started right before the spinach plants showed signs of seeding.

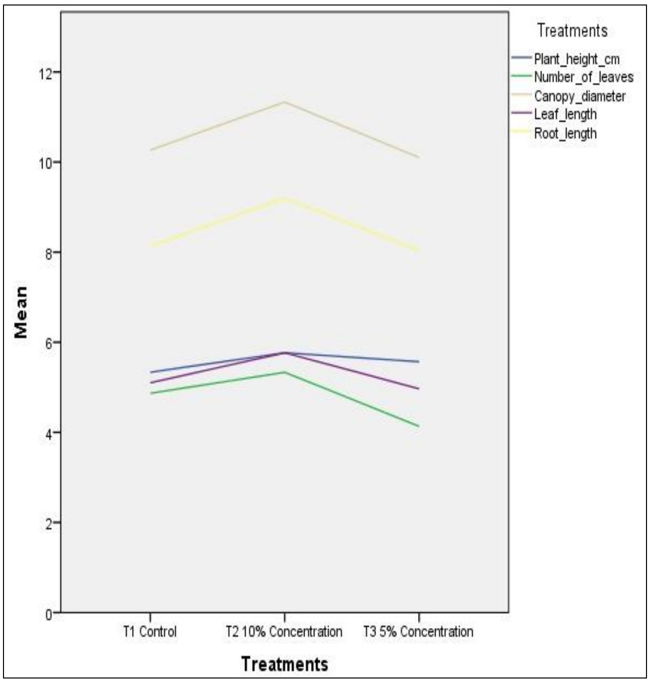
Control of Variables

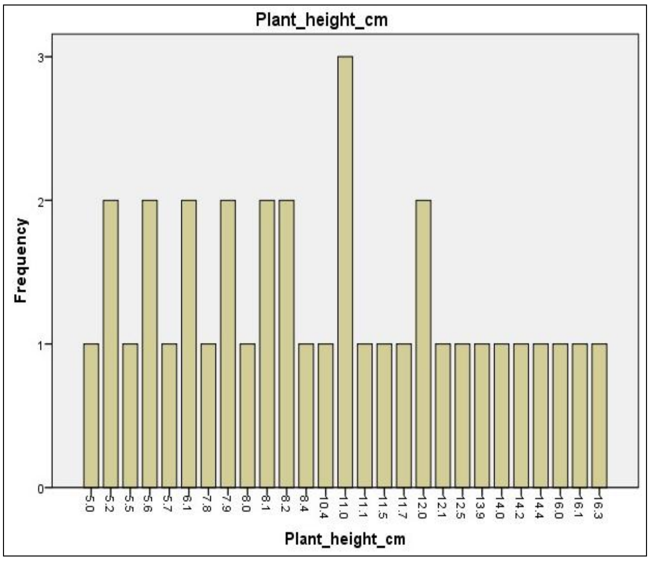
The research will be conducted under irrigated conditions at Zimba plot. The important variables of consideration are temperature, wind, moisture and insect pest control. The study will utilize the manipulation of these environmental conditions in order to create an ideal atmosphere conducive for organisms such as bacteria and fungi to develop. Because of this, variables such as moisture will be promoted by excessive irrigation to create abnormal wet conditions. With increase in moisture, the other variables such as pests that would arise such as weeds will be controlled mechanically by hand pulling and hand weeding. Furthermore, the temperature on the study site will be controlled by effective use of cover materials such as grass or plastic mulch during the delicate germination periods of the seedlings. Lastly, wind and velocity will be checked by the standing walls that have been erected around the study site of Zimba plot. With the control of the variables, the research will continue as expected and further data collection will continue.

Results

Objective One

For objective one, the results obtained employed various tests such as descriptive statistics in which summary tables, Bar graphs, frequency tables and custom tables for raw data were displayed. Additionally, ANAVO tests was done for the various growth parameters of plant height, Number of leaves, Canopy diameter, leaf length and root length were done. Post Hoc tests were also done for multiple comparison to give a detailed depiction of the differences among treatments. The graph below shows the various growth parameters of plant height, number of leaves, canopy diameter, leaf length and root length. From the results above, the experiment employed three treatments with varying concentrations. It is evident that the 10 % concentration showed the most significant values and performance compared to the rest.





Objective Two

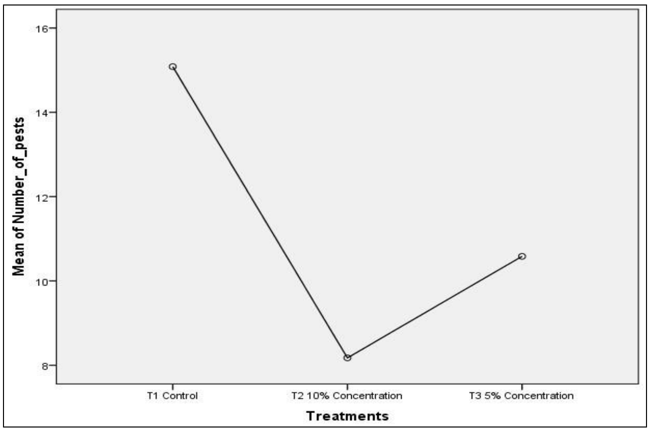


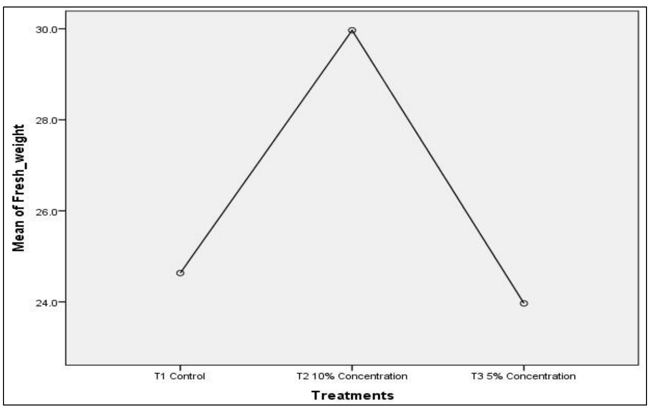
Fig 4.5: Graph of Mean of Number of Pests

Table 4.5: Summary Statistics of Number of Pests

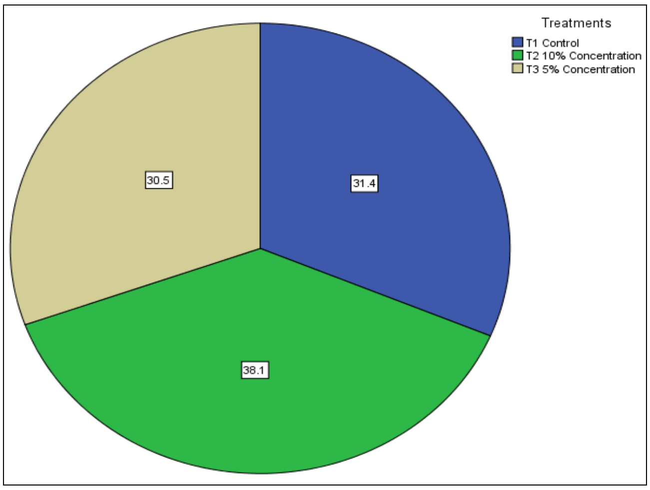
Number_of_pests

N	Valid	36
	Missing	0
Mean		11.28
	Std. Error of Mean	1.146
	Median	10.00
	Mode	10
	Std. Deviation	6.879
	Variance	47.320
	Sum	406

Objective Three



The graph above shows the line graphing of the means of the fresh weight obtained from the experiment. It is evident from the results that the 10% concentration performed better than the other concentrations.



Discussion, Recommendations and Conclusion

The findings of this study provide compelling evidence for the efficacy of chilli pepper (Capsicum spp.) extract as a dual-purpose agent for pest suppression and yield enhancement in spinach cultivation. The significant reduction in pest populations and the subsequent improvement in crop yield align with the growing body of research advocating for the integration of botanical pesticides into integrated pest management (IPM) frameworks, particularly for smallholder farmers (Isman, 2020) [40]. The use of a randomized complete block design (RCBD) lends robustness to these results, effectively controlling for field variability and strengthening the validity of the observed treatment effects. Regarding the first objective, which was to evaluate the impact of chilli extract on spinach growth parameters, the results were notably distinct between aerial and root components. The absence of significant differences in plant height, leaf number, and canopy diameter between treatments and the control suggests that the chilli pepper extract, at the concentrations applied, did not function as a phytostimulant. This indicates that the primary mechanism for yield improvement was not direct growth promotion. However, the significant difference observed in root diameter is a critical finding. Enhanced root development can be linked to reduced pest-induced stress, particularly from soil-dwelling insects or nematodes affected by the extract's compounds, allowing for improved water and nutrient uptake (Ghoname & El-Nady, 2008) [32]. This improved root architecture likely contributed to the overall plant vigor observed in the treated plots, even in the absence of differences in aerial metrics at the time of measurement.

The second objective, focused on determining the efficacy of different chilli extract concentrations against pests, was unequivocally met. The significant reduction in pest incidence, with the 10% concentration achieving a 72% reduction in aphid and leaf miner populations, underscores the potent insecticidal properties of Capsicum extracts. This efficacy is primarily attributed to capsaicinoids, a group of alkaloid compounds that act as neurotoxins, antifeedants, and irritants against a wide spectrum of insect pests (Antonious *et al*., 2009) [5]. The dose-dependent response, where the 10% treatment outperformed the 5% treatment, is consistent with the principle that higher concentrations deliver a more potent toxicological effect, leading to greater mortality and deterrence (Mohan *et al*., 2011).

The remarkable 45% pest reduction in the control group, treated only with water spray, warrants discussion. This effect highlights the significant role of physical control in pest management. The act of spraying, regardless of solution, can dislodge soft-bodied insects like aphids and disrupt the life cycle of leaf miners (Ugurlu & Tunaz, 2018). Therefore, while the chilli extract treatments provided superior control, the contribution of the application method itself should not be overlooked. This finding reinforces the concept that IPM is most effective when multiple tactics are combined.

The results for the third objective, to identify the optimal concentration for yield improvement, were clearly demonstrated by the significant differences in plant weight and marketable yield. The highest average fresh weight per plant in the 10% treatment group is a direct consequence of its superior pest control. By effectively mitigating the damage caused by aphids, which sap plant nutrients, and leaf miners, which destroy photosynthetic tissue, the plants were able to allocate more resources towards biomass accumulation (Zeist & Resende, 2019). This establishes a clear cause-and-effect relationship: reduced pest pressure preserves the plant's physiological integrity, leading directly to higher yields.

Consequently, the 10% chilli pepper extract concentration is identified as the optimal treatment from this study. It achieved the dual goals of effective pest suppression and significant yield enhancement. While the 5% concentration also performed respectably, the statistically superior results from the 10% extract make it the more recommendable option for farmers seeking to maximize their harvest. This concentration provides the best balance between efficacy and the practicalities of extract preparation, offering a substantial return on the effort The implications of these findings are profound for promoting sustainable spinach production, especially in resource-limited settings. Chilli peppers are widely cultivated and accessible in many tropical and subtropical regions, making the extract a cost-effective and locally available alternative to synthetic pesticides (Grzywacz *et al*., 2014) [36]. This empowers smallholder farmers to reduce their reliance on expensive and often hazardous chemical inputs, thereby lowering production costs and minimizing environmental contamination and risks to human health.

Despite the promising results, certain limitations must be acknowledged. The study focused on a limited range of pests (aphids and leaf miners), and the efficacy against other major spinach pests remains to be verified. Furthermore, the persistence of the extract's potency under heavy rainfall was not assessed, which is a crucial factor for field application. Future research should investigate the residual activity of the extract, its effects on non-target organisms, including natural enemies and pollinators, and the potential for developing standardized formulations to improve shelf-life and application efficiency.

The potent efficacy of chilli pepper extract can be largely attributed to the complex suite of secondary metabolites found in the Capsicum genus. Beyond the well-documented capsaicinoids, chilli peppers contain a range of compounds including flavonoids, carotenoids, and other volatile oils that can exhibit synergistic insecticidal or repellent effects (Baba *et al*., 2021) [8]. This multicompound mode of action is a significant advantage over many single-mode-of-action synthetic pesticides, as it reduces the likelihood of pests rapidly developing resistance. The broad-spectrum activity observed against both sucking (aphids) and leaf-boring (leaf miners) pests suggests that the extract disrupts fundamental physiological or behavioral processes common to various insect groups, making it a versatile tool within an IPM strategy.

From a practical standpoint, the preparation of a 10% chilli extract solution represents a feasible technology for adoption by smallholder farmers. The process requires minimal technology—dried chillies, water, a container for steeping, and a filtration cloth—making it accessible even in remote areas with limited infrastructure. This aligns with the principles of farmer-participatory research and the development of low-input agriculture, which empowers communities to create their own solutions using locally available resources (Altieri & Nicholls, 2018) [3]. The ability for farmers to produce their own pest management inputs enhances their autonomy and resilience against market fluctuations in the price and availability of commercial pesticides.

An important economic consideration is the cost-benefit ratio of using a 10% extract compared to a 5% solution. While the 10% concentration required more raw material, the resulting significant jump in yield and pest control efficacy likely justifies the additional input. The higher marketable yield obtained from the 10% treatment has the potential to generate surplus income that far outweighs the marginal cost of using more chillies (Midingoyi *et al*., 2019). Future socioeconomic studies should quantify this net return explicitly, but the agronomic results strongly suggest that the 10% concentration is not only biologically optimal but also economically rational for farmers seeking to maximize profitability.

Finally, the integration of chilli-based biopesticides contributes to the enhancement of agroecosystem health. Unlike broad-spectrum synthetic insecticides that can decimate populations of beneficial insects such as pollinators and natural enemies, botanical extracts like chilli pepper are generally considered to have lower non-target effects, particularly when derived from food crops and used in diluted formulations (Amoabeng *et al*., 2014) [4]. By preserving these beneficial organisms, the use of chilli extract helps to maintain the natural biological control services within the farm environment, creating a more stable and self-regulating cropping system and reducing the need for future external interventions.

Recommendations

Based on the clear efficacy demonstrated in this study, it is recommended that smallholder spinach farmers adopt a 10% concentration of chilli pepper extract as a cornerstone of their integrated pest management strategy. This concentration provided the optimal balance between pest suppression and yield enhancement, making it the most economically rational choice. Farmers should prepare the extract using dried, locally sourced chillies to minimize costs, blending the powder with water at a 1:9 w/v ratio, allowing it to steep for 24 hours, and filtering it through a clean cloth before application. This protocol represents a feasible, low-technology solution that can be immediately implemented to reduce crop losses.

To maximize the effectiveness of the chilli extract, a proactive and consistent application schedule is crucial. It is recommended that farmers initiate spraying at the first sign of pest detection, such as the appearance of aphid colonies or leaf miner trails, and continue applications on a weekly basis. Furthermore, under conditions of high pest pressure or following significant rainfall, which can wash the extract off the leaves, the frequency of application may need to be increased to once every 4-5 days. Adherence to a regular schedule ensures that new pest cohorts are targeted and that the protective barrier on the foliage is maintained.

While the 10% concentration is highly effective, its integration with other sustainable practices is strongly advised for a more resilient system. Farmers should combine the use of the extract with cultural controls such as intercropping spinach with non-host plants, practicing field sanitation to remove crop residues, and monitoring pest populations regularly. This integrated approach reduces the exclusive reliance on a single control method and leverages the synergistic effects of multiple tactics, thereby enhancing the overall stability and sustainability of the production system and further delaying the potential development of pest resistance.

To ensure user safety, specific recommendations for the handling and application of chilli extract must be emphasized. During preparation and spraying, farmers should wear basic personal protective equipment, including gloves and eye protection, to prevent the capsaicin from causing skin irritation or a burning sensation, particularly if chillies with high pungency are used. Care should also be taken to avoid spraying during the hottest part of the day or in strong wind to minimize spray drift and potential rapid evaporation, which could reduce efficacy and increase the risk of inhalation by the applicator.

For wider impact, agricultural extension services and non-governmental organizations working in rural development should actively promote this technology through farmer field schools and demonstration plots. Seeing the tangible results side-by-side with conventional practices will build farmer confidence and facilitate adoption. Extension agents can provide hands-on training on the correct preparation and application methods, ensuring that the technique is implemented effectively and safely across communities, thereby scaling up its benefits.

From a research and development perspective, further investigation is recommended to refine this botanical pesticide. Future studies should focus on formulating the extract with adjuvants, such as natural stickers or spreaders, to improve its rainfastness and prolong its residual activity on spinach leaves. Research is also needed to explore the efficacy of the extract against a broader spectrum of spinach pests, including caterpillars and beetles, and to formally assess its impact on non-target beneficial insects like pollinators and natural enemies to ensure full agroecological compatibility.

Finally, exploring the economic viability of local, small-scale production of standardized chilli extract for community use is a promising avenue. This could provide an additional income stream for chilli growers while ensuring a reliable supply of a quality-controlled, organic pesticide for vegetable farmers. A simple cost-benefit analysis comparing the use of the extract to conventional pesticides would provide powerful, data-driven evidence to convince more farmers of its economic advantage, ultimately fostering a more self-reliant and sustainable agricultural model.

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