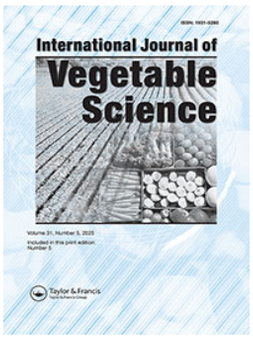

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Assessment of biopesticide adoption in vegetable production among smallholder farmers in Zimbabwe

Cosmas Parwada[a], Albert Gumbo[b], and Edith Matema[c]

[a]Department of Agronomy and Horticulture, Faculty of Agriculture, Environment and Natural Resources Management, Midlands State University, Gweru, Zimbabwe; [b]Department of Lands and Water Resources Management, Faculty of Agriculture, Environment and Natural Resources Management, Midlands State University, Gweru, Zimbabwe; [c]Department of Agribusiness Management, Faculty of Agriculture and Health Sciences, Women's University in Africa, Marondera, Zimbabwe

ABSTRACT

The increasing application of chemical pesticides in vegetable production among Zimbabwean smallholder farmers has raised concerns about environmental degradation, pesticide hazards, and pesticide resistance. Despite the availability of biopesticides as an adequate substitute, their adoption is characterized by low adoption levels. This study estimated the determinants of adoption of biopesticides among Zimbabwean smallholder vegetable farmers. A cross-sectional survey was conducted among 250 farmers who were randomly chosen through stratified random sampling in Mashonaland East and Manicaland provinces. Structured questionnaires were used to gather information, which was analyzed using descriptive statistics and logistic regression. Results showed that only 32% of farmers used biopesticides due to inadequate awareness (65%), unaffordable prices (48%), and inadequate extension support (56%). Regression analysis showed that access to training (OR = 3.2, $p < .01$), market incentives (OR = 2.5, $p < .05$), and the level of education of farmers (OR = 1.8, $p < .05$) significantly influenced adoption. Conclusively, limited farmer knowledge, financial constraints, and ineffective institutional support remain the primary barriers to wider adoption of biopesticides. We recommend to reinforce farmer education programs, support subsidies for biopesticides, and upgrade extension services to promote sustainable pest management.

KEYWORDS

Biopesticides; smallholder farmers; adoption; sustainable agriculture

Introduction

The extensive application of man-made pesticides in Zimbabwean vegetable production operations leads to significant risks to environmental as well as health safety. As indicated by Fusar Poli and Fontefrancesco (2024a), the use of chemical pesticides causes soil degradation, contamination of water bodies, and biodiversity loss, as well as exposing farmers and consumers to toxic residues. This is particularly alarming in Zimbabwe, where smallholder

CONTACT Cosmas Parwada cparwada@gmail.com Department of Agronomy and Horticulture, Faculty of Agriculture, Environment and Natural Resources Management, Midlands State University, P. Bag 9055 Gweru, Zimbabwe

farmers, who account for over 70% of agricultural producers (Food and Agriculture Organization, 2022), tend to apply such chemicals without adequate protective equipment. The challenge arises where there remains insistence on the application of synthetic alternatives despite growing evidence of long-term hazards and the availability of acceptable biopesticide alternatives. Biopesticides, like microbial pesticides, plant-incorporated protectants, and biochemical pesticides, give precise pest control with no collateral damage to artificial chemicals (Li et al., 2022).

The slow adoption of biopesticides by Zimbabwean smallholders is a multifaceted interrelation of technical, economic, and institutional constraints. The Niche Research (2023) explains that although biopesticides are environmentally better, farmers' lower perceived efficacy, slower action rate, and lower shelf life of biopesticides deter farmers from experiencing current pest pressure. In the Zimbabwean situation, among the additional challenges are low availability of products in rural settings, higher upfront capital expenditure compared to traditional pesticides, and low technical support for efficient utilization (Yılmaz et al., 2025). Economic uncertainty in the nation also amplifies the challenges since farmers use short-term pest control over long-term environmental benefits during times of cash flow constraints. Moreover, the existing extension system of agriculture that is meant to facilitate technology transfer is under-equipped and at times lacks up-to-date information on accessible biopesticide alternatives and their application (Li et al., 2022).

These adoption issues can only be resolved by adopting a systemic strategy on both the supply and demand sides. On the supply side, localized production of biopesticides at the local level is required to improve affordability and accessibility, along with quality control measures. On the demand side, there must be widespread farmer education programs that demonstrate the economic effectiveness of biopesticides through cost–benefit analysis and field demonstrations. Successful models of other developing countries, such as Kenya's adoption of push-pull technology (Khan et al., 2023), show that having biopesticides promoted within broader general IPM programs has more success than promoting them as a silver bullet. For Zimbabwe, this would align the promotion of biopesticides with support programs in place for agriculture and building incentive systems that make sustainable pest management economically attractive to smallholders facing multiple-production constraints.

Zimbabwean smallholder farmers are confronted with a vicious cycle of challenges that substantially inhibit their capacity to embrace sustainable farming technologies such as biopesticides. According to Lantero et al. (2023), these farmers work under a limited environment typified by disjointed extension services, unstable input markets, and poor access to credit facilities. The exorbitant price of farm inputs is especially

prohibitive, with many smallholders expending more than 40% of their cost of production in pest control efforts (ZIMSTAT, 2024). The economic stress usually compels farmers to rely on quick and cheap solutions such as synthetic pesticides at the expense of more durable but costly substitutes. Moreover, the lack of efficient market linkages and price incentives for sustainably produced crops offers limited economic incentive to farmers to move toward biopesticides, thus creating a cycle of chemical addiction.

The slow take-up of biopesticides in Zimbabwe is the opposite of what has occurred in other African countries, which identifies huge gaps in the agricultural innovation system in the country. Chikoye et al. (2023) identify a set of Zimbabwe-specific challenges that include deeply rooted myths about the performance of biopesticides among extension agents and farmers. Most farmers consider biopesticides to be 'weak' compared to synthetic chemicals, unaware that the effectiveness of many biopesticides depends on precise timing and proper application practices. The research also identifies systemic issues in product distribution, where biopesticides are rarely available in local agro-dealer outlets, resulting in long-distance journeys by farmers to procurement points (Yılmaz et al., 2025). Also, the absence of local success stories and demonstration plots means that most farmers never get to experience biopesticides' benefits firsthand, unlike in countries like Kenya where field schools have really boosted adoption rates (Grillo et al., 2021).

A thorough understanding of these adoption barriers is essential to the design of targeted interventions that can tackle Zimbabwe's particular context. Research gaps exist with respect to the need for a more in-depth examination of gender dimensions in biopesticide adoption because women farmers would likely have further barriers to accessing information and resources (Marrone, 2024). There is little documentation also on how Zimbabwe's changing climatic trends might affect biopesticide efficiency and farmer perceptions. Effective intervention design must tackle these multifaceted challenges through a holistic system that brings together farmer education, input subsidy reform, and market incentive mechanisms. Malawi's National Agricultural Policy (2023) might be emulated, as it managed to increase the uptake of biopesticides by linking it to climate-smart agriculture incentives and establishing local production centers in a bid to improve accessibility and affordability. These holistic strategies would overcome Zimbabwe's adoption barriers as well as further serve larger sustainable development aims. This study seeks to assess the extent of uptake of biopesticides and identify determinants of influence among smallholder vegetable producers in Zimbabwe. Specifically, it focuses on socio-economic factors, institutional services, and farmer beliefs affecting adoption. Findings will be used to inform policy guidelines toward the advancement of sustainable agricultural practices.

Materials and methods

Study area and sampling

The study focused on Mashonaland East and Manicaland provinces, Zimbabwe. Masholand East is one of Zimbabwe's most productive vegetable-producing regions that collectively contribute over 60% of the country's horticultural output (ZIMVAC, 2024). These provinces were strategically selected to reflect Zimbabwe's diverse agro-ecological environments, with Mashonaland East (Natural Regions II and III) possessing comparatively high rainfall levels (650–800 mm annually) and extensive smallholder irrigation schemes. Using a stratified random sampling procedure, 250 smallholder vegetable farmers (125 per province) were drawn by a multi-stage process whereby farmers were first divided by district (total six districts), second by farm size (<1 ha or small; 1–2 ha or medium), and finally by random selection from updated lists provided by Agritex offices and local farmer organizations in order to provide representative gender (52% male and 48% female) and production systems (62% irrigated and 38% rain-fed) proportionally within the sample (FAO, 2024). This strict sampling design enabled the gathering of diverse experiences and uptake patterns with statistical relevance for the target population of smallholder vegetable farmers in these target areas.

Data collection and analysis

Primary data were collected through face-to-face interviews with the assistance of structured questionnaires. Variables included farmers' socio-economic profiles, biopesticide knowledge, access to extension services, and adoption behavior. Adoption determinants were examined using binary logistic regression and descriptive statistics. Primary data were collected through face-to-face interviews using a pre-tested structured questionnaire. There were four broad sections in the questionnaire: the study applied a mixed-methods rigorous approach in quantifying the uptake of biopesticides by smallholder vegetable farmers in Zimbabwe. Primary data were collected through face-to-face interviews with the assistance of a pre-tested structured questionnaire administered to 30 farmers to validate and ensure reliability. The instrument captured four most critical dimensions: (1) socio-economic characteristics (farm size, demographics, income level), (2) awareness and knowledge of biopesticides (perception, information source, perceptions of effectiveness), (3) institutional support (availability of credit, attendance at training, access to extension), and (4) adoption behavior and barriers (current practices, adoption drivers, and hindrances). A multi-stage sampling design was used, first stratifying farmers by district

(Mashonaland East and Manicaland) and farm size category (small: <1 ha, medium: 1–2 ha), and then, randomly sampling 250 participants from official agricultural office registries to achieve representative coverage of the target population.

Quantitative analysis employed both descriptive and inferential statistical techniques. Descriptive statistics (means, percentages, and frequencies) summarized the sample population and adoption trends, and cross-tabulations examined bivariate relationships between major variables. Binary logistic regression was modeled as adoption determinants, with a dichotomous-dependent variable (adopter = 1, non-adopter = 0) regressed on three predictor categories: socio-economic (education, age, income), institutional (extension access, training), and perceptual (cost, efficacy beliefs).

The model was expressed as:

$$Log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$$

Where p = probability of adoption, $\beta 0$ = intercept constant and $X_1 \ldots X_n$ = predator variables.

Model goodness-of-fit was ascertained through the Hosmer–Lemeshow test ($\chi^2 = 7.24$, $p = .405$), and multicollinearity tests ensured all VIF values < 5, hence no high correlation between independent variables. Ethical practices included the obtaining of informed consent, participant anonymity, and data security through the application of password-protected systems. This complex methodology ensures the results of the study to be statistically significant and policy-relevant in promoting sustainable pest management practices within Zimbabwe's smallholder agriculture systems.

Results

Most of the farmers (63.2%) aged between 30 and 50 years had an average experience of farming for 12.4 years (Table 1). Over half (51.2%) had less than 1 hectare of land cultivated, which indicates small-scale farming. Tomatoes (36.8%) and leafy vegetables (31.2%) were the most cultivated vegetables.

Only 36.8% could define biopesticides appropriately, indicating low awareness. Extension services (38.0%) were the prominent source of information (Table 2). 48% perceived biopesticides to be less effective than chemicals.

Just 35.2% had undergone IPM training. 83.2% had no access to subsidies for biopesticides (Table 3).

12% of the respondents had no choice but to use biopesticides. The high cost of (48%) and the lack of knowledge (65.2%) were major hindrances (Table 4).

Table 1. Demographic and farm characteristics of smallholder farmers ($N = 250$).

Variable	category	frequency	percentage	mean
Age (years)	<30	42	16.8	46.2
	30–50	158	63.2	
	>50	50	20.0	
Gender	Male	132	52.8	
	Female	118	47.2	
Educational level	No formal	35	14.0	
	Primary	102	40.8	
	Secondary	85	34.0	
	Tertiary	28	11.2	
Household size	1–3	68	27.2	4.5
	4–6	145	58.0	
	>6	37	14.8	
Farm size (ha)	<1	128	51.2	1.8
	1–2	89	35.6	
	>2	33	13.2	
Farming experience (yrs)	<5	55	22.0	12.4
	5–15	135	54.0	
	>5	60	24.0	
Main vegetables grown	Tomatoes	92	36.8	
	Leaf vegetables	78	31.2	
	Onions	45	18.0	
	Other	35	14.0	
Monthly income ($USD)	<50	112	44.8	
	50–100	95	38.0	
	>100	43	17.3	

Table 2. Farmers' knowledge and sources of information on biopesticides.

Variable	Response	Frequency	Percentage
Heard of biopesticides	Yes	163	65.3
	No	87	34.8
Correct definition	Yes	92	36.8
	No	158	63.2
Main source of information	Extension services	95	38.0
	Fellow farmers	68	27.2
	NGOs	45	18.0
	Media	42	16.8
Perceived effectiveness	More effective	55	22.0
	Less effective	120	48.0
	Equally effective	75	30.0

Table 3. Institutional factors affecting biopesticide adoption.

Variable	Category	Frequency	Percentage
Received extension visits	Yes	145	58.0
	No	105	42.0
Frequency of visits (if yes)	<1 per year	60	24.0
	1–2 per year	65	26.0
	>2 per year	20	8.0
Attended IPM training	Yes	88	35.2
	No	162	64.8
Access to credit	Yes	75	30.0
	No	175	70.0
Subsidy availability	Yes	42	16.8
	No	208	83.2

Table 4. Adoption rates and challenges.

Variable	Category	Frequency	Percentage
Current pest control method	Chemical only	140	56.0
	Biopesticides	30	12.0
	Mixed	80	32.0
Reason for non-adoption	High cost	120	48.0
	Lack of awareness	163	65.2
	Poor availability	105	42.0
	Doubt efficacy	90	36.0

Table 5. Factors influencing biopesticide adoption (Binary logistic regression).

Variable	β	S.E	Odds ratio	p-value
Age	−0.2	0.08	0.89	0.142
Educational level	0.45*	0.21	1.57	0.032
Farm size	0.30	0.18	1.3	0.096
Extension access	0.85**	0.34	2.34	0.012
IPM training	1.15**	0.29	3.16	0.001
Perceived cost	−0.72*	0.31	0.49	0.020
Constant	−2.10	0.75	–	0.005

Hosmer–Lemeshow test: $\chi^2 = 7.24$ (p = .405); Nagelkerke $R^2 = 0.42$

Training (OR = 3.16, $p < .01$) and access to extension (OR = 2.34, $p < .05$) had strong impacts on adoption. High perceived cost reduced the probability of adoption (OR = 0.49, $p < .05$) (Table 5).

Discussion

Low use of biopesticides (12%) by Zimbabwean smallholder vegetable farmers is consistent with the findings of similar studies in SSA, e.g., Bayeck (2023), which also documented such challenges in Malawi and Zambia. The most significant barriers identified – are costliness and ignorance – reflect systemic issues in the region's agricultural systems. Most smallholder farmers operate on thin margins, and the upfront price of biopesticides renders them inaccessible compared to conventional chemical alternatives, perceived as cheaper and more convenient. Second, the lack of adequate information on the benefits of biopesticides, such as long-term soil fertility and reduced chemical resistance, works to discourage their use, encouraging continued reliance on synthetic pesticides e.g. lambda-cyhalothrin, deltamethrin, and imidacloprid.

The persistence of knowledge gaps is particularly concerning as it underlines inefficiencies in agricultural extension systems. Even though extension services constituted the principal source of information (38%), coverage and frequency were inadequate, as only 35.2% of farmers received any IPM training. This confirms Sylvestre et al. (2023), who determined that institutional support weakness and fragmented dissemination of sustainable farming techniques are hindrances to biopesticide adoption. Barring special education campaigns that highlight the economic and environmental advantages of

biopesticides, misconceptions about their efficacy (48% believed they were less effective than chemicals) will continue to drive farmer choice.

These challenges can be overcome through a multi-faceted strategy. Subsidies or cost-sharing arrangements might alleviate financial limitations, as in Kenya (Dogara et al., 2022). Concurrently, strengthening extension services through community-based training and participatory farm field schools might improve knowledge transfer. Market incentives such as premium prices for crops raised using biopesticides might also promote adoption. Without these interventions, the transition to sustainable pest management in Zimbabwe's smallholder systems will remain slow, with lasting implications for environmental and human health.

The study categorically demonstrates the changing influence of training in adopting biopesticides, with farmers having undergone training being three times more likely to adopt such environment-friendly options compared to those who had not undergone training. The strong correlation (OR = 3.16, $p < .01$) indicates the fundamental role played by knowledge dissemination in modifying agricultural practices. The impact of training was particularly pronounced when it included hands-on demonstrations of biopesticide preparation and application, together with clear economic comparisons showing long-term cost savings. These results are in line with those of Fusar Poli and Fontefrancesco's (2024b) research in Greece, where they concluded that practical, farmer-oriented training programs were far more effective than traditional lecture-based extension approaches in promoting sustainable pest management. The current study also reveals that training overcame psychological hurdles because farmers who were well-trained were less likely to consider biopesticides ineffective (22% versus 48% in non-trained groups).

The dramatic training effect highlights the urgency of scaling up capacity-building initiatives in Zimbabwe's agricultural extension system. However, the study also uncovered significant gaps in the current training coverage, where only 35.2% of the interviewed farmers had received any official IPM or biopesticide training. The limited coverage means that most of the extension capacity is in particular areas or among certain groups of farmers, depriving many of them of access to vital information. Chikoye et al. (2023) further noted that Zimbabwe's extension services often overlook the most vulnerable smallholders, such as women and remote farmers. For the greatest impact, programs in the future need to adopt decentralized, participatory training methods with farmer field schools and peer-to-peer networks of learning. Such approaches can be very powerful when hybridized with mobile technology platforms to facilitate learning and maintain support, as immensely successfully done in Kenya's biocontrol adoption programs (Onwujiogu et al., 2022). Investment in comprehensive, equitable training systems would not only increase adoption of biopesticides but also forge long-term resilience within smallholder farming communities.

The findings strongly suggest that targeted policy intervention through subsidies and comprehensive awareness campaigns would go a significant distance in promoting biopesticide adoption among Zimbabwe's smallholder farmers. Given that 48% of the non-adopters cited prohibitive cost as the primary barrier, carefully crafted subsidies would bridge the price difference between biopesticides and conventional chemical alternatives. These subsidies can be in the form of direct input vouchers, like what was successfully piloted with Zambia's Farmer Input Support Programme (FISP), or tax incentives to local producers of biopesticides to lower their production cost. Subsidies alone would never suffice, however, without simultaneous efforts to create sustainable market frameworks. Policy makers could consider setting up public–private partnerships to implement local clusters for biopesticide production that will increase availability (a constraint faced by 42% of the farmers) as well as creating rural employment opportunities. This multifaceted approach has succeeded with India's National Mission on Sustainable Agriculture where increased usage by a 35% margin for the last 5 years among the smallholders has resulted from these measures (Khan et al., 2023).

Complementary awareness interventions must fill the very deep knowledge gaps uncovered in the study, where 65.2% of farmers lacked fundamental knowledge on biopesticides and 48% considered them to be less effective. Such campaigns must employ more than one mode of communication like radio (reaching 92% of rural Zimbabweans), mobile platforms, and participatory demonstration plots. Emulating Malawi's Agricultural Extension Services' 28% rise in sustainable practice uptake by community-based learning (FAO, 2022), Zimbabwe can coordinate lead farmers to be trained as biopesticide champions per district. Policy actions need to compel national extension curricula and agriculture college courses to incorporate biopesticide training to institutionalize it. Furthermore, linking these awareness campaigns with market incentives – e.g., certification schemes or premium pricing for crops grown with biopesticides – could create a virtuous cycle of adoption. Rwanda's Green Revolution strategy provides an interesting example, whereby similar policy packages increased adoption of sustainable inputs by 40% among smallholders (FAO, 2024). By combining smart subsidies with innovative awareness and market linkage interventions, Zimbabwe can surmount the current adoption limitations while building a more climate-resilient and sustainable agricultural sector.

Conclusion and recommendations

This study indicates that Zimbabwean smallholder vegetable farmers' adoption of biopesticides remains urgently low at 32%, constrained primarily by three interlinked factors: the prohibitively high costs (48% of the respondents), the considerable knowledge gaps (65.2% unaware of the

benefits of biopesticides), and restricted extension services (only 35.2% trained). These findings are aligned with broader regional studies indicating that cost and information constraints continue to perpetuate chemical pesticide dependency in sub-Saharan Africa. The logistic regression results particularly underscore the potential to change through training interventions, such that trained farmers are 3.16 times more likely adoption odds ($p < .01$), such that knowledge transfer remains the significant initial step for overcoming psychological as well as technical obstacles to adoption.

To catalyze change, policymakers should implement a three-pronged intervention strategy. First, there should be the establishment of targeted subsidy programs to eliminate cost barriers, potentially modeled on Kenya's successful plant protection subsidy program that increased biopesticide use by 22% among smallholders. Second, extension systems should be strongly strengthened through the application of participatory training approaches like farmer field schools, which have proven effective in neighboring Zambia. Third, there must be established market incentives by way of premium pricing mechanisms and certification schemes for sustainably sourced produce, based on Rwanda's experience in the agricultural transformation strategy. These intervention measures must run concurrently since from our findings single-faceted interventions have low effectiveness. Training without subsidies, for instance, can lead to abuse, while training without incentives does not alleviate economic viability challenges. By putting this cumulative strategy into practice, Zimbabwe can overcome current adoption challenges while creating a more sustainable, climate-resilient food system aligned with both national food security initiatives and global environmental treaties.

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Authors contribution

All authors have contributed equally to this work.

Data availability statement

The datasets during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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