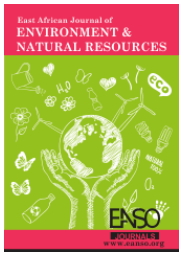
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Original Article

Multidimensional Evaluation of Natural Pesticides for the Control of Maize Armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Western Burundi: Efficacy and Lessons Learned

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Agroecology, Armyworm, Natural pesticides, Plant extracts, Tithonia diversifolia.

ABSTRACT

The use of natural pesticides is a sustainable approach for the control of pests. This study evaluates the efficacy of two locally available biopesticides: sand–ash mixture and extract of Tithonia diversifolia to control the fall armyworm (Spodoptera frugiperda) of maize. Field experiments were implemented across two agro-ecological zones: Imbo plain and Mumirwa in 134 farms. The experimental design used was a randomised complete block design, in which each household constituted a block. Results showed that the two natural pesticides significantly reduced pest impact and improved maize yield compared to farmers' conventional practices, including chemical insecticide use under local conditions. The most effective treatment for the sand–ash mixture was the weekly application, with the 50% sand and 50% ash proportion, where the yield was significantly higher. For Tithonia diversifolia extract, the highest concentration (4 L in 9 L of water) produced the best yield and reduced pest incidence and severity. Farmers and researchers largely converged on optimal treatments, although preferences varied slightly based on ease of use and resource availability. Beyond pest control, Tithonia diversifolia extract also improved plant vigour and grain quality, while the sand–ash mixture provided a low-cost control option. The effectiveness of these natural pesticides compared to chemical pesticides observed in some experiments is understandable in the local context, where underdosing of chemical pesticides is very frequent, and farmers' knowledge is limited. However, limitations such as labour intensity for sand–ash mixture and limited availability of Tithonia diversifolia were identified. Farmers proposed practical solutions, including domestication of Tithonia diversifolia and the design and development of an application tool for the

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ash–sand mixture. Overall, the study demonstrates that natural pesticides offer effective, sustainable, and transferable alternatives to chemical pesticides, and highlights the value of participatory action research in accelerating technology adoption in smallholder farming systems.

APA CITATION

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INTRODUCTION

Intensive agriculture characterised by the extensive use of chemical inputs has already demonstrated its limitations (Gosme et al., 2010; Pathak, 2018). Increased application of chemical pesticides has detrimental effects on the environment (Bondareva & Fedorova, 2021; Edwards, 1975; Isgren & Andersson, 2021; Walder et al., 2022), as well as on food safety and consumer health (Adewunmi & Fapohunda, 2018; Ahouangninou et al., 2012; Bonner & Alavanja, 2017; de Bon et al., 2014). Mineral inputs also negatively affect soil health (Barabasz et al., 2002; Menino et al., 2022), thereby progressively undermining the sustainability of agricultural productivity with time. In addition to these impacts, the high cost of agrochemical inputs reduces the profitability for smallholder farmers, often with limited resources, as these inputs represent a substantial share of production costs (Germaine Furaha et al., 2016). Moreover, such reliance fosters dependency on extended supply chains based on imports, where input prices are volatile.

Meanwhile, sustainable and agroecological practices for integrated pest and disease management (Arjjumend et al., 2021; Berlitz et al., 2021; Gitahi et al., 2021; Green et al., 2017; Grzywacz et al., 2014; Gupta & Dikshit, 2010) have recently been developed and promoted by research, others are still under investigation, while some originate from farmers' own practices. For the control of pests and diseases, the use of (i) plant extracts (Green et al., 2017), (ii) beneficial organisms (Arjjumend et al., 2021; Nimbeshaho et al., 2024), and (iii) adapted agronomic practices (Midega et al., 2018) are proposed as a component of integrated management strategies that avoid reliance on synthetic pesticides. These biopesticides are diverse. For instance,

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biopesticides derived from *Tithonia diversifolia* (Mexican sunflower) have been widely studied in Africa for their effectiveness against a range of agricultural pests, due to bioactive compounds such as sesquiterpene lactones and flavonoids (Moshi et al., 2013). Leaf extracts from *Tithonia* spp. have demonstrated significant insecticidal and fungicidal activity, particularly against aphids, caterpillars, and certain soil-borne pathogens (Ogendo et al., 2003). In East Africa, their use is embedded within an agroecological approach aimed at reducing dependence on chemical pesticides while valorising local resources (Kweka et al., 2016). Other plant extracts are also widely used, including those derived from *Azadirachta indica* (Neem), which are among the most well known. They contain azadirachtin, a compound that acts as an insecticide, antifeedant, and insect growth regulator (Isman, 2006). Extracts from *Tephrosia vogelii* are used against insect pests and livestock ectoparasites due to their toxic rotenoids (Gaskins et al., 2014). *Lantana camara* exhibits insecticidal and repellent properties against several vegetable crop pests (Sharma et al., 2005). Similarly, *Allium sativum* (garlic) and *Capsicum* spp. (chilli pepper) are used in extract form for their repellent and antifungal effects in traditional farming systems (Grange & Ahmed, 1988).

In addition, ash and sand are traditional methods widely used in agriculture for pest control, particularly in smallholder systems in Africa. On one hand, ash acts as a desiccant and can damage the insect cuticle, thereby reducing survival and reproduction (Stathers et al., 2002). It is also used to protect stored grains against weevils and other storage pests. On the other hand, sand can create a physical barrier that prevents pests from accessing crops or seeds, while also reducing oviposition sites and movement (Golob et al., 2002).

The use of biopesticides offers considerable advantages. They present lower risks to users during handling (Zhang & Lu, 2007), have positive environmental effects (Berlitz et al., 2021; Grzywacz et al., 2014), and contribute to enhanced food safety. Furthermore, biopesticides can be produced with relatively low investment and, in some cases, directly at the farm level. Their environmental and food safety benefits, reduced risks to users, capacity for on-farm production, and lower propensity to induce resistance in pests and pathogens underscore their importance in sustainable agricultural systems.

The outbreak of fall armyworm (*Spodoptera frugiperda*) in Africa has resulted in a marked increase in the use of chemical insecticides by farmers seeking to mitigate yield losses. However, this intensification of chemical control has frequently led to the development of insect resistance, alongside environmental and public health concerns (Day et al., 2017). The use of farm-derived natural pesticides represents a cost-effective alternative for the management of *Spodoptera frugiperda*, while reducing environmental impacts. Nevertheless, their adoption remains limited, with agrochemical pesticides still widely used. This low adoption of natural pesticides is largely attributable to insufficient knowledge regarding their efficacy, as well as the lack of standardised formulations and inadequate dissemination of application techniques among farmers (Isman, 2006).

Action research remains a key approach for promoting the use of biopesticides, given its numerous advantages. It enables (i) the co-construction of knowledge with local stakeholders, ensuring adaptation to the local context (Lewin, 1946; Reason & Bradbury, 2008); (ii) the strong contextualization of solutions, thereby enhancing their relevance and effectiveness (Kemmis & McTaggart, 2005); (iii) greater ownership and adoption of innovations, which reduces resistance to change and strengthens confidence in outcomes (Stringer, 2014); and (iv) the strengthening of local capacities through mutual learning between researchers and communities, fostering the progressive autonomy of stakeholders in addressing their own challenges (O'Brien, 1998). Within this action research framework, two natural pesticides, namely a sand–ash mixture and *Tithonia diversifolia* extract, were evaluated in Burundi, specifically in the former provinces of

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Bujumbura, Bubanza, and Cibitoke, for the control of fall armyworm on maize. The objectives were i) to evaluate the effect of the application of the sand–ash mixture, under different mixture proportions and application frequencies, on the incidence and severity of fall armyworm infestations in maize crops and ii) to determine the effectiveness of different concentrations of *Tithonia diversifolia* extract in reducing the incidence and severity of fall armyworm infestations in maize.

The research hypotheses were (i) When applied at an appropriate mixture proportion and optimal frequency, the sand–ash mixture significantly reduces the incidence and severity of fall armyworm infestations in maize, and ii) The application of *Tithonia diversifolia* extract at an optimal concentration reduces the incidence and severity of fall armyworm infestations in maize.

METHODOLOGY

Site Description

The experiments were conducted in two agro-ecological zones of Burundi, namely the Imbo Plain and the Mumirwa region, between October 2023 and February 2024, as well as between October 2024 and February 2025. The climatic and edaphic characteristics are detailed in Table 1.

Table 1: Climatic and Edaphic Characteristics of the Two Agro-Ecological Zones.

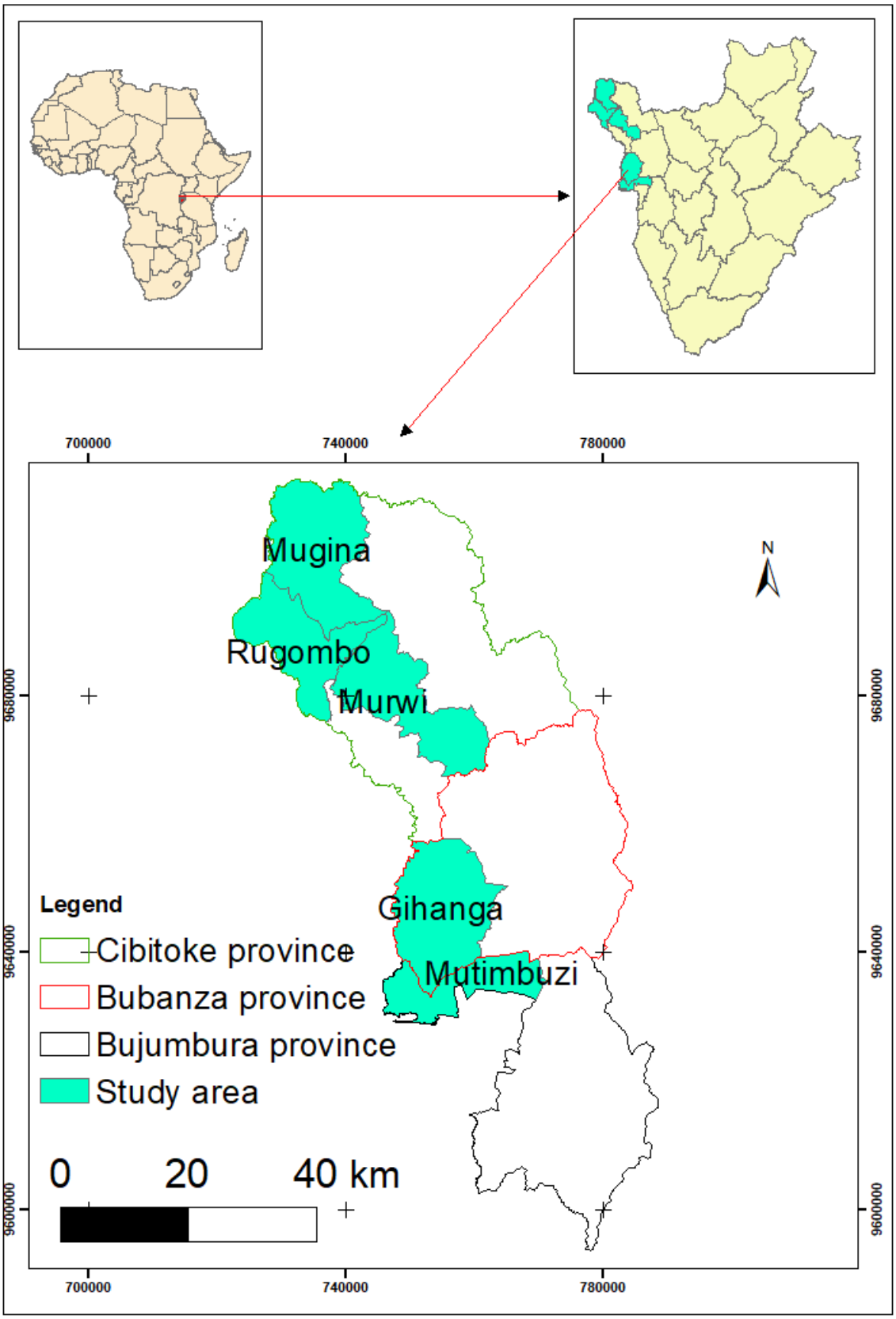
Characteristics	Imbo Plain	Mumirwa
Altitude (Baramburiye et al., 2010)	770-1100 m	1100-1750 m
Annual mean temperature (Baramburiye et al., 2010)	23-29 °C	18-28 °C
Annual rainfall (Baramburiye et al., 2010)	800-1100 mm	1100-1900 mm
Dominant soils according to the classification INEAC (Sottiaux et al., 1988)	Cambisols, Ferralsols, vertisols, Regosols	Ferrisols, Feralsols and Regosols
Average soil pH_{water}, (Musonerimana et al., 2025)	6.05	5.22
Average Soil organic carbon (Musonerimana et al., 2025)	1.79 %	2.56 %
Total N (Musonerimana et al., 2025)	0.20 %	0.24 %
Average of available P (Musonerimana et al., 2025)	6.38 ppm	4.12 ppm
Average exchangeable K (Musonerimana et al., 2025)	0.40 cmolc/kg	0.32 cmolc/kg
Average exchangeable Ca (Musonerimana et al., 2025)	5.96 cmolc/kg	2.65 cmolc/kg
Average of exchangeable Mg (Musonerimana et al., 2025)	2.82 cmolc/kg	1.19 cmolc/kg

In the agro-ecological zone of the Imbo Plain, the communes of Mutimbuzi in Bujumbura Province, Gihanga in Bubanza Province, and Rugombo in Cibitoke Province were selected. In the Mumirwa region, the communes of Mugina and Murwi, both in Cibitoke Province, were chosen. Figure 1 shows the location of these communes. The communes of the Mumirwa are close to the Imbo Plain and therefore have characteristics similar to those of the plain.

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Figure 1: Location of the Selected Communes



In these communes, six cooperatives' members of CAPAD were involved, namely:

- Kazoza keza from Gihanga ;
- Kerebuka Dukore from Gihanga ;

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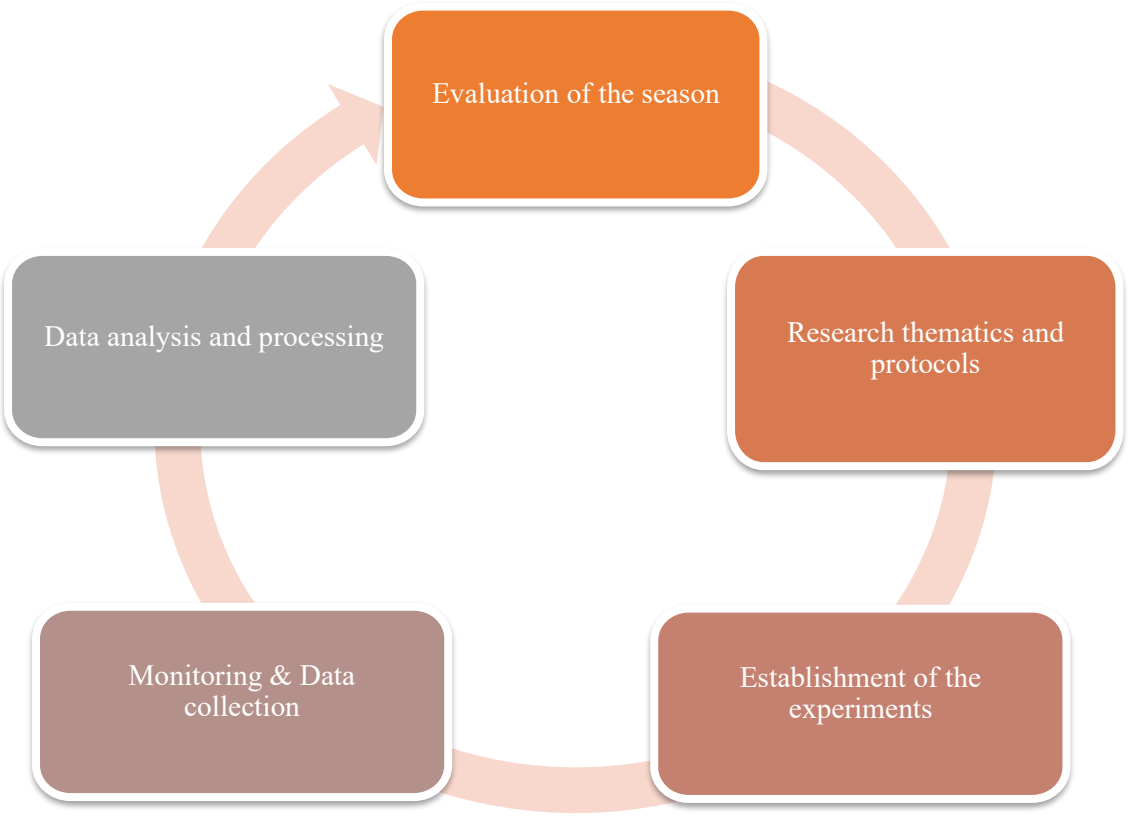
- Girumwete Dukore from Mutimbuzi ;
- Murimyi Girijambo from Mugina ;
- Dukoribirama Manege from Murwi ;
- Urumuri rw'abarimyi from Rugombo.

Action Research Process

The action research was conducted in an inclusive and participatory method, with strong involvement of farmers. Initially, discussions with farmers were held at the beginning of the action research. These discussions focused on the main diseases and pests in the area, the constraints encountered in their management, the available resources, and the prioritisation of interventions. In terms of prioritisation, the fall armyworm affecting maize was identified as the pest that most negatively impacts local production and which is particularly difficult to manage.

As this pest is commonly controlled using agrochemical insecticides, innovations involving the use of natural pesticides were proposed and discussed with the farmers. Following these discussions, protocols were developed by the researchers and submitted to the farmers for validation. The validation primarily concerned the size of the elementary plots in order to avoid unnecessary use of farmland. After validation of the protocols, each cooperative voluntarily selected the protocol(s) with which they wished to align. Consequently, the number of participants differed across experiments depending on the farmers' level of interest. Furthermore, farming practices varied among farmers, as each participant maintained their usual management practices in order to avoid any potential reduction of yield in the control plots. Participants were informed about the objectives and procedures of the study before providing their consent. Confidentiality of the information collected from farmers was respected throughout the research process. The cycle of the process is summarised in Figure 2.

Figure 2: Cycle of the Action Research Process over a Single Season



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Description of the Implemented Protocols

The experimental design used was a randomised complete block design, in which each household constituted a block. The experimental plot size was consistently 9 m² (3 m × 3 m).

a) Use of sand – ash mixture for the control of maize fall armyworm

The first experiment focused on application frequency. For this experiment, a mixture composed of 50% sand and 50% ash (by volume) was used. The following treatments were established:

- T0: farmers' practices;
- T1: application of the mixture once per week;
- T2: application of the mixture once every two weeks;
- T3: application of the mixture once every four weeks.

This protocol was replicated in 75 households. To obtain fine particles, each of the two ingredients is sieved through a 1 mm mesh sieve. The retained fraction is discarded and not used. A quantity of 10 g of the mixture was applied per plant to the still-unexpanded leaves at the apex of the plant. This 10 g dose corresponds to approximately two Coca-Cola bottle caps. Data on incidence, severity, yield, and 1 000-grain weight were collected. Qualitative data were also collected, namely (i) user appreciation and (ii) the transferability of the tested technology.

Since some participants reported that the 50% sand and 50% ash mixture caused leaf scorching in maize, a second experiment was conducted to evaluate different sand-to-ash ratios. The treatments were as follows:

- T1: 75% sand + 25% ash
- T2: 50% sand + 50% ash
- T3: 100% sand

The quantity per plant, the application method, and the data collected were the same as in the previous experiment. This protocol was replicated in 30 households.

b) Use of *Tithonia diversifolia* extract to control maize armyworm

Tithonia diversifolia extract was produced in each cooperative using 25 kg of young *Tithonia diversifolia* leaves in 200l of water. The mixture was left to mature for 15 days.

The treatments applied were as follows:

- T0: farmers' practices;
- T1: 1 L of *Tithonia diversifolia* extract in 9 L of water;
- T2: 2 L of *Tithonia diversifolia* extract in 9 L of water;
- T3: 4 L of *Tithonia diversifolia* extract in 9 L of water.

The first application was carried out when the maize plants were at the four-leaf stage. Subsequent applications were conducted when symptoms were observed on at least one plant. On average, four applications were performed until crop maturity. The mixture was sprayed onto the leaves in the same manner as synthetic agrochemical insecticides.

Collection of Qualitative and Quantitative Data

The collection of quantitative data was carried out by cooperative facilitators (support and extension staff of the cooperatives). Regarding the farmers' perception and the transferability of each technology, a questionnaire was administered to the different users during group work sessions. Scores were assigned by consensus.

Statistical Analysis

First, a one-way ANOVA was performed to test differences between agro-ecological zones. Since no significant differences were observed between the agro-ecological zones, both zones were analysed jointly. Data analyses, as well as comparison of means using Tukey's test, were

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conducted using R version 4.3.2. The significance level was 5%.

RESULTS

Use of the Sand + Ash Mixture for Controlling Maize Fall Armyworm

Frequency of Application

Significant differences ($p \leq 0.05$) were observed for yield among all control treatments (farmers' practice), except for DUDU Fenos (fenitrothion). Differences in incidence and severity were not statistically significant (Table 2). For the control treatment with Rocket (lambda-cyhalothrin), the highest yield was recorded for the sand + ash treatment applied weekly, with a yield of 4.1 kg/9 m². The other treatments showed values close to those of the control. For the control treatment with DUDU Fenos, although yield differences were not statistically significant, the highest yield was also observed with the weekly application of the sand and ash mixture. For farmers who did not apply any intervention in the control plot, the treatments with weekly application and biweekly application showed higher yields, with 5.1 kg/9 m² and 4.0 kg/9 m², respectively. The monthly application showed yield values close to those of the no-intervention treatment. For farmers who manually removed the larvae, the highest yield was observed under the treatment with weekly application of the sand + ash mixture, with a value of 4.0 kg/9 m². Overall, the highest yields were recorded with the weekly application of the sand + ash mixture.

Table 2: Incidence, Severity, and Yield of Maize for Different Frequencies of Application of the Sand + Ash Mixture Compared to the Farmers' Practices for the Control of Maize Fall Armyworm. Values are the mean ± standard error of the mean.

Treatments and farmer's practices	Incidence	Severity	Yield (kg/9 m²)
Comparison with Rocket (N=5)			
T0: Rocket, chemical insecticide	0.1±0.1	1.2±0.1	3.3±0.2a
T1 : weekly	0.1±0.1	1.2±0.1	4.1±0.2b
T2 : biweekly	0.1±0.1	1.2±0.1	3.2±0.2a
T3 : monthly	0.2±0.1	1.2±0.1	3.1±0.2a
P-value	0.829^{NS}	0.964^{NS}	**0.008****
Comparison with DUDU FENOS (N=32)			
T0: DUDU Fenos, chemical insecticide	1.2±0.1	1.7±0.1	4.6±0.2
T1 : weekly	1.0±0.1	1.6±0.1	4.9±0.2
T2 : biweekly	0.9±0.1	1.7±0.1	4.7±0.2
T3 : monthly	0.8±0.1	1.6±0.1	4.3±0.2
P-value	0.164^{NS}	0.758^{NS}	0.384
Comparison with no intervention (N=14)			
T0: No intervention	0.8±0.2	1.6±0.1	3.4±0.2a
T1 : weekly	0.7±0.2	1.5±0.1	5.1±0.2cb
T2 : biweekly	0.7±0.2	1.4±0.1	4.0±0.2b
T3 : monthly	0.6±0.2	1.4±0.1	3.5±0.2a
P-value	0.839^{NS}	0.487^{NS}	**<0.0001*****
Comparison with larvae removed manually (N=16)			
T0: Larvae removed manually	0.2±0.0	1.2±0.0	3.2±0.1a
T1 : weekly	0.3±0.0	1.2±0.0	4.0±0.1b
T2 : biweekly	0.2±0.0	1.12±0.0	3.1±0.1a
T3 : monthly	0.1±0.0	1.1±0.0	3.1±0.1a
P-value	0.107^{NS}	0.161^{NS}	**<0.0001*****

Significance codes: 0 < *** ; < 0.001 < ** ; < 0.01 < * ; < 0.05; NS: not significant.

Sand – Ash Proportions

Treatment T2 (50% sand + 50% ash) recorded the highest yield. The application of equal proportions of sand and ash was the most effective mixture (Table 3).

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Table 3: Yield and Yield Parameters of Maize under the Use of Different Proportions of Sand and Ash for the Control of Maize Fall Armyworm. Values are the mean ± standard error of the mean (N=30).

Treatment	Germination rate (%)	1000 grains weight	Number of plants/plot	Yield (kg/9 m²)
T1 :75% sand + 25% ash	97.8±0.1	488.5±1.1	31±0.1	3.5±0.0a
T2 : 50% sand + 50% ash	97.8±0.1	491.5±1.2	31±0.1	3.8±0.0b
T3: 100% sand	97.7±0.1	487.2±1.1	31±0.1	3.4±0.0a
P value	0.88^{NS}	0.98^{NS}	0.79^{NS}	0.04*

Significance codes: 0 < *** ; < 0.001 < ** ; < 0.01 < * ; < 0.05; NS: not significant.

Use of *Tithonia diversifolia* Extract for Controlling Maize Fall Armyworm

For the control treatment, where larvae were removed manually, significant differences were observed for yield. Incidence and severity values did not differ significantly (Table 4). For the control treatment with DUDU Fenos application, significant differences were observed for both incidence and severity. Incidence and severity decreased with increasing doses of *Tithonia diversifolia* extract. The highest yields were observed with the highest dose of *Tithonia diversifolia* extract, with values of 4.3 kg/9 m² and 4.7 kg/9 m² for the control treatments with manual larval removal and DUDU Fenos, respectively. It should be noted that, for the latter, yield differences were not statistically significant.

Table 4: Incidence, Severity, and Yield of Maize for Different Doses of *Tithonia diversifolia* Extract Compared to the Farmers' Practices for the Control of Maize Fall Armyworm. Values are the mean ± standard error of the mean.

Treatments and farmer's practices	Incidence	Severity	Yield (kg/9 m²)
Comparison with larvae removed manually (N=5)			
T0 : larvae removed manually	0.7±0.3	1.4±0.1	3.5±0.3a
T1 : 1 L *Tithonia diversifolia* extract in 9 L of water	0.5±0.3	1.3±0.1	3.6±0.3a
T2 : 2 L *Tithonia diversifolia* extract in 9 L of water	0.6±0.3	1.4±0.1	3.9±0.3ab
T3 : 4 L *Tithonia diversifolia* extract in 9 L of water	0.7±0.3	1.3±0.1	4.3±0.3b
P-value	0.914^{NS}	0.917^{NS}	**0.028***
Comparison with DUDU FENOS (N=24)			
T0 : DUDU Fenos	1.3±0.1c	1.8±0.05c	4.5±0.2
T1 : 1 L *Tithonia diversifolia* extract in 9 L of water	1.2±0.1b	1.7±0.05b	4.7±0.2
T2 : 2 L *Tithonia diversifolia* extract in 9 L of water	1.0±0.1a	1.6±0.05b	4.5±0.2
T3 : 4 L *Tithonia diversifolia* extract in 9 L of water	0.9±0.1a	1.5±0.05a	4.7±0.2
P-value	**0.003****	**<0.0001*****	0.628^{NS}

Significance codes: 0 < *** ; < 0.001 < ** ; < 0.01 < * ; < 0.05; NS: not significant.

Convergence in the Choice of Effective Treatments

Researchers and farmers reached a consensus on the most effective treatment regarding the frequency of application of the sand – ash mixture and the appropriate dose of *Tithonia diversifolia* extract to be used (Table 5). The best treatments were the weekly application of the sand + ash mixture, and the optimal dose of *Tithonia diversifolia* extract was 4 L in 9 L of water.

However, divergence was observed for the experiment related to the sand-to-ash mixing proportions. Quantitative data showed that the 50% sand + 50% ash mixture produced higher yields, whereas farmers recommended the 75% sand + 25% ash mixture.

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Table 5: Selection of the Best Treatments by Farmers and Results from Quantitative Analysis (shaded in grey).

Treatments	Best treatment based on quantitative data analysis	Best treatment according to farmers' qualitative assessment
Use of sand and ash for the control of maize fall armyworm: frequency of application		
T0: Farmer's practice		
T1 : weekly		
T2 : biweekly		
T3 : monthly		
Use of sand and ash for the control of maize fall armyworm: Proportion of the mixture		
T1 :75% sand + 25% ash		
T2 : 50% sand + 50% ash		
T3: 100% sand		
Use of *Tithonia diversifolia* extract for the control of maize fall armyworm		
T1: Farmer's practice		
T2: 1 L *Tithonia diversifolia* extract in 9 L of water		
T3: 2 L *Tithonia diversifolia* extract in 9 L of water		
T4: 4 L *Tithonia diversifolia* extract in 9 L of water		

Advantages, Limitations, and Proposed Solutions to Address the Limitations

Table 6 presents farmers' assessments of the different technologies that were tested. For the control of maize fall armyworm using the sand + ash mixture, farmers made the following observations: (i) the product is readily available, (ii) it is effective against the pest. However, (iii) the dosage per plant is difficult to standardise, and excess application can cause leaf scorching, and (iv) application to each plant is highly labour-demanding.

Regarding the use of *Tithonia diversifolia* extract, farmers acknowledged that the product was effective against the pest, that the harvested product was of better quality with larger maize grains, and that, following application, plants became greener, as if fertiliser was applied. The limitations were the limited availability of *Tithonia diversifolia* and the lengthy preparation time required.

When comparing the two technologies for controlling maize fall armyworm, the use of *Tithonia diversifolia* extract was considered less labour-intensive than the use of the sand + ash mixture.

Table 6: Assessment of the Technologies by the Farmers

Use of sand and ash for the control of maize fall armyworm		**Use of *Tithonia diversifolia* extract for the control of maize fall armyworm**	
Advantage	**Score[1]**	**Advantage**	**Score**
Sand and ash reduced the armyworm population.	++++	High effectiveness of the product against all insects	+++++
Better stem growth	++++	Vigorous green vegetative growth, as if the plants were fertilised	+++++
Good vegetative aspect	++++	Quality of the product: larger cobs	+++++
Increase in the yield.	++++		
Good quality of the product	++++		

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Use of sand and ash for the control of maize fall armyworm		**Use of *Tithonia diversifolia* extract for the control of maize fall armyworm**	
Advantage	**Score[1]**	**Advantage**	**Score**
Limitations	**Score[2]**	**Limitations**	**Score**
Labor-intensive work	+++	The duration of the action of protection is short.	+++
Sand is not readily available.	+++	Necessary to take protective measures during the application.	++
If ash is used in large quantities and there is no rainfall, the leaves turn brown.	++++	The preparation process is time-consuming.	++++
Difficult to determine the appropriate dosage	+++	*Tithonia* is not available everywhere.	++++
Proposed solutions			
Not to mix equally sand and ash, but increase the quantity of sand.		Install *Tithonia* in hedgerows.	
Design an instrument for the application of the product by dusting.		Apply the product simultaneously to prevent pests from taking refuge in neighbouring fields.	

[1]+ : Poor; + : Fair ; +++ : Moderate ; ++++ : Good ; +++++ : Excellent

[2]+ : low limitation; ++ : Acceptable ; +++ : Moderately limiting ; ++++ : Limiting ; +++++ : May hinder adoption

Transferability of the Tested Technologies

The sand-ash mixture was considered easily transferable by the farmers; however, it presented severe limitations in terms of labour intensity (Table 7). The *Tithonia diversifolia* extract presented limitations related to the availability of *Tithonia diversifolia*.

Table 7: Factors Affecting the Transferability of the Proposed Technologies

Factor of transferability of the technology	**Score sand-ash for the control of maize fall armyworm**	**Score *Tithonia diversifolia* extract for the control of maize fall armyworm**
Availability of the product[1]	+++++	++
Ease of the technique[2]	++++	+++++
Labor intensity[3]	+	+++
Ease of replication (training requirements for new users)[4]	+++++	+++++
Quality of the harvested product[5]	++++	++++
Effectiveness[6]	+++++	++++

[1]rare : +, little available :++, available :+++ ; widely available : ++++ and very available : +++++

[2]Very difficult: +; difficult: ++; feasible: +++; easy: ++++; very easy: +++++

[3]Very tiring: +; tiring: ++; moderately tiring: +++; not tiring: ++++; not at all tiring: +++++

[4]Very difficult: +; difficult: ++; feasible: +++; easy: ++++; very easy: +++++

[5]Poor quality: +; low quality: ++; medium quality: +++; good quality: ++++; very good quality: +++++

[6]Not effective at all: +; slightly effective: ++; moderately effective: +++; effective: ++++; very effective: +++++

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DISCUSSION

The application of the sand – ash mixture at a dosage of 10 g per maize plant reduced the impact of *Spodoptera frugiperda* on maize yield (Table 2) when applied weekly. This mixture proved to be more effective than chemical insecticides such as Rocket (lambda-cyhalothrin) applied at farmers' dosages and frequencies (Table 2). The insecticidal effects of sand and ash when applied individually have been reported by several authors (Golob et al., 2002; Stathers et al., 2002). Mixing these two components enhances their effect through the combination of their modes of action. The most effective mixing proportion was 50% sand + 50% ash (Table 3). Similarly, the use of *Tithonia diversifolia* extract at a concentration of 4 L in 9 L of water reduced the impact of *Spodoptera frugiperda* on maize yield and, in some cases, reduced pest incidence and severity (Table 3). The insecticidal properties of *Tithonia sp.* have been reported by other authors (Kweka et al., 2016; Ogendo et al., 2003), and it is also used in powdered form.

Comparing the effects of the sand + ash mixture and *Tithonia diversifolia* extract with farmers' practices, we may conclude that these natural pesticides are as effective as, or even more effective than, chemical insecticides (Tables 2 and 3). However, this must be interpreted within a context where farmers have limited financial resources (Ademola et al., 2017) and lower technical knowledge in pesticide use compared to other inputs (Singbo et al., 2015). This may lead to suboptimal application dosages and reduced spraying frequency. In all cases, pesticide doses and application frequencies are likely to be non-optimal. Sub-lethal pesticide use has also been reported in other African countries (Brevault et al., 2003; Reid & McKenzie, 2016). Thus, low-income levels and limited technical capacity in the use of chemical insecticides make local natural pesticides relatively more effective.

The biopesticides evaluated in this study present several advantages. Being locally produced, they increase farmers' independence from imported inputs that are often costly and difficult to access (Isman, 2006; Belmain et al., 2012). The sand-ash mixture acts through mechanical action (Golob et al., 2002; Stathers et al., 2002), which reduces the risk of resistance development of the pests. In addition, *Tithonia diversifolia* extract not only controls pests, but it also acts as a fertiliser and strengthens plant growth (Table 6). The fertilising effect of *Tithonia sp.* has been reported in other studies (Jama et al., 2000; Nziguheba et al., 2002). These natural pesticides have a major advantage over chemical insecticides, which can lead to pest resistance (Georghiou, 1990; Sparks & Nauen, 2015) and may sometimes negatively affect plant growth and respiration (Lichtenstein et al., 1962). Furthermore, biopesticides are not polluting. Sand and ash are natural materials that do not degrade the environment when returned to it. Likewise, *Tithonia diversifolia* extract, being plant-based, degrades rapidly in nature. In contrast, one of the major constraints of chemical insecticides is environmental pollution and the associated risks to human health when users are not properly protected, as well as risks to consumers (Ahmad et al., 2020; Arjmandi et al., 2010).

The selection of the best treatments showed convergence between quantitative data analysis and farmers' assessment for two experiments, namely the application frequency of the sand + ash mixture and *Tithonia diversifolia* extract. However, for the sand–ash proportions experiment, quantitative data indicated that the best treatment was 50% sand + 50% ash, whereas farmers preferred the 75% sand + 25% ash mixture (Table 4). This suggests that when quantitative differences are small, farmers tend to choose the easiest treatment, as sand is more readily available than ash in the study area.

In addition to the pest control effects, the natural pesticides showed other benefits such as improved vegetative growth and increased ear size in the case of *Tithonia diversifolia* extract (Table 5). However, they also present some limitations, including the limited availability of *Tithonia sp.* for some sites and the labour-intensive nature of applying the sand - ash mixture, as each plant must be treated individually. Labour intensity and input availability are key determinants of

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technology adoption. Limited availability reduces farmers' flexibility and may increase costs, while high labour requirements are perceived as constraints even though practices are beneficial (Doss, 2006; Mignouna et al., 2011). Farmers proposed alternative solutions such as installing *Tithonia sp.* in non-cultivated areas or designing an application tool for the sand - ash mixture (Table 5).

The transferability of the evaluated biopesticides was considered high by farmers, despite the limitations mentioned above. Indeed, their preparation and use do not require advanced technical skills or knowledge, and new users can easily replicate the techniques without external assistance (Table 7). The action research approach saved time for research and accelerated adoption. In conventional approaches, there is often a significant gap between on-station research results and field adoption. Action research shortens the "research – dissemination – adoption" cycle (Reason & Bradbury, 2008), thanks to better problem identification, stronger knowledge of the field context, and faster feedback loops (Chambers, 1994; Pretty, 1995).

The study has the same limitations. In fact, it was conducted under real farming conditions, with farmers' specific socio-economic and environmental contexts. The availability of resources and the level of knowledge regarding the use of chemical pesticides may differ in other areas, which could make chemical pesticides more effective than the biopesticides used in this study. The natural pesticides were prepared by farmers themselves without any analysis of their active compounds or their concentrations. Without such analyses, it is difficult to standardise both the product and its application. In addition, the study was carried out in two agroecological zones that are relatively similar within Burundi. These combined conditions may limit the generalizability of the findings and call for further studies under laboratory conditions or in more diverse environments.

CONCLUSION

The results show that the sand–ash mixture (50% sand + 50% ash), as well as the *Tithonia diversifolia* extract, can be as effective, or even more effective, than some chemical insecticides used by farmers. It is therefore recommended to integrate these biopesticides into integrated pest management programs in order to reduce dependence on chemical pesticides and strengthen sustainable agriculture. These natural pesticides offer important advantages, including accessibility, low cost, and reduced environmental and human health detrimental impacts. However, their effectiveness must be interpreted in the socio-economic context of farmers, characterised by limited resources and low technical capacity in the use of chemical pesticides. Constraints related to resource availability, such as *Tithonia sp.*, and the labour-intensive nature of applying the sand-ash mixture may limit adoption. Nevertheless, farmers proposed appropriate solutions, such as the domestication of *Tithonia sp.* and the development of tools to facilitate application. The convergence between experimental results and farmers' preferences highlights the importance of incorporating practical criteria in technology selection. Moreover, the ease of preparation and use of these natural pesticides enhances their transferability to similar agricultural contexts. Finally, the action research approach facilitated the innovation and adoption process by directly involving farmers in experimentation and validation of solutions.

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