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ENHANCING CROP RESISTANCE TO ROOT NEMATODES THROUGH ADVANCED BREEDING TECHNIQUES

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ABSTRACT

This study aimed to evaluate the effectiveness of using nematode-resistant maize and cassava in Nigeria to improve farmers' sustainability and reduce pest pressures. Nematodes significantly impact global crop yield and availability, necessitating the development of resistant cultivars to reduce yield losses and reliance on chemical control measures. Field experiments were conducted in Agbor-Nta, Nigeria, using Resistant Variety A and Resistant Variety D developed from CRISPR-Cas9 and Marker Assisted Selection. The study found that Resistant Variety A reduced nematode count by 80%, increased yields, and higher net profits. Resistant Variety D also showed reasonable nematode control and economic returns, significantly reducing the nematode population to 12 per gram, achieving a 76% reduction. The adoption rate of CRISPR-Cas9 developed Resistant Variety A reached 50% by 2024. The study underscored the importance of advanced breeding technologies in producing nematode-resistant crops for farming sustainability and economies. The application of germplasm from CRISPR-Cas9 and MAS techniques successfully improved genetic improvement, reduced pest pressures, and enhanced yields. These findings align with efforts to improve agricultural sustainability by promoting reliable crop types to maintain food supply and economic stability in agricultural-dependent areas.

Keywords: Genetic improvement, marker-assisted selection, plant breeding and genetics, plant pests and diseases, sustainable agriculture.

INTRODUCTION

The root nematodes are considered to be among the most devastating pests to crops all over the world, causing magnitude reduction to the yield quantity and quality and as currently affecting Nigerian agriculture where most of the farmers depend on the sales of their produce for their livelihood. These are minuscule parasitic worms that live in the soil, and they fix themselves on the root systems of plants, thus denying the plants their chance of getting a good supply of nutrients and water, consequently stunting their growth, reducing their productivity, and in the extreme, causing plant death (Akinsanya et al. 2020; Olajide et al. 2022; Oyetunde et al. 2022). The conventional control measures such as chemical nematicides are usually costly, have adverse effects on the environment and sometimes inefficient. Thus, research on a more effective and permanent remedy to eradicate root nematode infections is quite limited; thus, the need for other strategies. With the help of the new biotechnological approaches like CRISPR-Cas9, marker-assisted selection (MAS), and conventional breeding methods, it becomes possible to develop resistance in the crops against these pests. Such resistant varieties are known to lessen the nematode populations in the ground, increase production, and increase the eventual revenues out of farming practices.

This study applies developed nematode-resistant varieties of two staple crops in Nigeria namely, maize and cassava. To support the evidence on the efficiency and advantages of these approaches the research was based more on the differences in yield, nematodes, economic value and the farmers' adoption rates of resistant and non-resistant type of varieties. However, the aim is to satisfy the demand in the long term and at a reasonable price for safe and efficient control of root nematode pests in order to increase cropping frequency and improve farmers' yield. Parasitic nematodes have risen to becoming a threat to agriculture, especially in the developing regions where most of the farmers are involved in producing crops like maize and cassava, which they depend on both for food and income (Coyne et al. 2018; Abiola, 2020).

Some of the common practices that have been practiced in the management of root nematodes include; control methods including crop rotation, application of organic matter to the soil, and use of nematicides. Crop rotation helps starve nematodes by breaking their life cycle, while organic inputs like composts and green manures act as nematode repellents (Soares et al. 2022). However, these techniques have limitations in terms of efficiency and cost-effectiveness. Chemical nematicides, while effective, are environmentally harmful and expensive for smallholder farmers (Chen et al. 2020; Egbadzor & Sakyi, 2021).

Genetic resistance through breeding crop varieties resistant to diseases is a sustainable and long-term method for managing root nematodes. Researchers have identified resistant genes in numerous crops that can be utilized through conventional breeding and advanced biotechnological methods. Broad-spectrum resistance (BSR) genes, which confer resistance against multiple pathogen species, are particularly valuable for crop breeding (Li et al. 2020). Yet, there is a problem in transferring these resistance genes into high-yielding cultivars because of gene–gene interactions and the genetic basis of the traits; long-lasting resistance generally involves multiple genes (Dinglasan et al. 2022).

In molecular biology and recombinant DNA technology there are new prospects for creating crops that are resistant to nematodes. CRISPR-Cas9 assessment provided big changes in resistance genes in non-resistant crops (Borrelli et al. 2018). MAS also speeds up the breeding process through employing molecular markers linked to the resistance or desirable characteristics to identify bigger populations and attained high-performing genotypes (Arruda et al. 2016).

These advanced methods have been effectively implemented in several crops through several case studies below. For instance, maize has been rigorously bred to produce resistance to root nematodes, through conventional breeding and the molecular techniques improving the yields and decreasing the nematode populations (Kagoda et al. 2011). Likewise, MAS has supported the identification and release of suitable cassava varieties that have resistance to the root-knot nematodes thus increasing yields and income of growers.

There is so much that can be gained economically and socially in the use of nematode-resistant varieties in the case of smallholder farmers. Studies reveal that all these varieties enhance the protection of yields, the decrease in chemical use and ultimately food security and income (Fanning et al. 2018). Nevertheless, these varieties' use is conditioned by awareness, seed accessibility, and the perceived advantages and potential threats by the farmers (Ruzzante et al. 2021).

From the analysis of the literature, it can be deduced that there is a need to increase the application of the improved breeding techniques in combination with conventional control methods in the enhancement of sustainable management of root nematodes. The effectiveness of these measures requires further analysis, the availability of resistant varieties, and the willingness of farmers to adopt these practices. This research will aim at determining the possibility of applying nematode-resistant maize and cassava derived through breeding processes including CRISPR-Cas9, MAS and normal breeding to enhance the resistance of and productivity in Nigerian crops.

In particular, the objectives of the paper are as follows: To analyze the yield parameters of the CRISPR-Cas9, MAS, and conventional-bred nematode-resistant maize and cassava genotypes developed under the nematode-infested environment for nematode populations, yield, and biomass; to collect data concerning the pre- and post-yield nematode population density of the above-mentioned genotypes.These objectives aim to offer a comprehensive understanding of the benefits and challenges associated with applying nematode-resistant crop varieties, eventuallysubscribing to sustainable agricultural practices and improved livelihoods for farmers.

Related Works

Many researchers have stressed combating root nematode problems associated with crop production. A study by Arita et al. (2020) noted that the conventional control measures of crop rotation and chemical nematicides were not effectively combating infestations by nematodes. These methods, while effective, could be more efficient when it comes to scaling up and ensuring the sustainability of the interventions, especially in the developing world where most smallholder farmers are found, particularly in sub-Saharan Africa. In this context, investigation of genetic resistance has revealed some effectiveness; Pascual et al. (2023) also mentioned some of the specific resistance genes, for instance, Mi-1 in tomato plants, which gives primary ideas of plant-nematode interactions.

The techniques of inbreeding have gone a long way in developing this area. Borrelli et al. (2018) showed that using CRISPR-Cas9 for targeted gene editing has boosted the cultivation of resistant crop varieties. Another modern technique that has been efficiently used is Marker-Assisted Selection (MAS), which has helped speed up the breeding process (Arruda et al., 2016). Arim et al. (2006) also showed evidence of higher yields and reduced populations of nematodes in maize and *Canavalia ensiformis* or *Mucuna pruriens* intercrop. Many studies, including those by Mooney et al. (2022) and Barker (2017), have identified the economic and social effects of adopting resistant varieties.

Theoretical Framework

This study uses the IPM framework to control pests in crops using an efficient, sustainable, and economically and environmentally sound approach. It covers the nematode problem holistically, focusing on genetic resistance and the use of germplasm technologies like CRISPR-Cas9 and MAS. The diffusion of innovations helps evaluate farmers' adoption of nematode-resistant varieties, based on perceived benefits, compatibility with organizational practices, simplicity, ease of testing, and easy observation. Understanding these factors is crucial for formulating tactics for propagating resistant varieties and optimizing returns. The study emphasizes the importance of understanding these factors to effectively manage pests in agriculture.

MATERIALS AND METHODS

The study dwells on enhancing the resistance of crops to root nematodes through a field survey of Nigerian crop varieties. Among the selected crops for the investigations were maize and cassava; these crops are essential income-generating crops in Nigeria. The following breeding methods and experimental procedures were employed: The used breeding methods and experimental procedures included the following:

Crop Varieties and Breeding Techniques: The five crop varieties were 2 of the maize samples genetically modified through CRISPR-Cas9 and traditional breeding methods, maize samples developed from a non-GM breeding process, cassava samples engineered for resistance to the disease through a marker-assisted selection process, and non-resistant cassava samples. The resistant varieties were obtained from The International Institute for Tropical Agriculture, (IITA) Ibadan where they have been genetically improved.

Field Trials: the study was carried out in farmlands in Agbor-Nta, a suburb of Agbor metropolis, which lies on latitude 6.11877^0 N and longitude 6.18026^0 E, with an average annual temperature of 27^0 C (80.6 ^{0}F) and average annual rainfall ranging from 1,894 mm to 2,392mm. During the field trials established in areas infested with nematodes, comparative experiments were conducted on the yield of resistant and non-resistant varieties. The design adopted in the experiment was the completely Randomised Complete Block Design (RCBD) with three replications of the varieties applied. Anchored fertilization, irrigation, pest management, and other agronomic practices were applied to manage the plots.

Yield Analysis: At the end of every growing season, the total yield per plot was measured and given in kilograms per hectare (kg/ha). The yield data set up the outcome of the resistant and non-resistant cultivars planted under nematode stress. Moreover, the root nematodes were categorized into ten subgroups ranging from 1 to 10 depending on the level of infection, as the plant that rated one was free of root nematodes. In contrast, the plant rated ten was highly infested with root nematodes.

Soil Nematode Population: A soil sample was taken from each plot to count the root nematode population before planting and after harvest. Adult nematodes were obtained using the Baermann funnel technique, and the numbers of nematodes were estimated microscopically. The number of nematodes per gram of soil was determined before and after the experiment, and the percentage reduction was calculated from the variety.

Economic Analysis: The cost per variety of production and net profit at the market price was determined. This cost entails seed, fertilizer, pesticide, labor, and other inputs. The market price was assessed using the rates set in the local market. Net profit was calculated using total revenue, which was yield multiplied by the market price minus the cost of production.

Farmer Adoption Rates: To establish the extent of adoption of nematode-resistant varieties, a series of face-to-face interviews with local farmers was conducted over a period of five years, including the period of three years before the study was conducted. Questionnaires were administered to farmers, and their perceptions of the varieties and the proportion of farmers who adopted each variety were then established annually. The adoption factors included yield performance, resistance levels, and economic returns.

These methods gave an overview of the different crops' yields, nematode population, economic effects, and adoption rates, which means that advanced breeding could increase crop resistance against root nematodes.

RESULTS

Table 1 presents a comparative yield analysis of different maize and cassava varieties, highlighting their resistance levels and the extent of root nematode infestation they experienced. Resistant Variety A (maize), developed using the CRISPR-Cas9 genetic editing technique, demonstrated the highest yield at 4500 kg/ha. This variety also exhibited a high resistance level, reflected in a low nematode infestation rating of 2. Such results underscore the effectiveness of

CRISPR-Cas9 in enhancing crop resistance and boosting yield under nematode pressure.

Oba Super 10, a maize variety developed through traditional breeding methods, yielded 4200 kg/ha. This variety showed a medium resistance level with a nematode infestation rating of 4, indicating that traditional breeding methods can produce reasonably resistant and high-yielding varieties, although less effective than advanced genetic techniques like CRISPR-Cas9. In stark contrast, Non-resistant C (maize), a standard commercial variety, had the lowest yield of 3000 kg/ha and a high nematode infestation rating of 8. This variety's poor performance underscores the vulnerability of non-resistant crops to nematode attacks, resulting in significantly lower yields. For cassava, Resistant Variety D, developed using marker-assisted selection (MAS), achieved a high yield of 4400 kg/ha and a nematode infestation rating of 3. This demonstrates the potential of MAS in producing highly resistant and productive cassava varieties. Similarly, TMS 419, a standard commercial cassava variety, yielded only 3200 kg/ha and had a high nematode infestation rating of 7. This further illustrates the disadvantage of non-resistant varieties in nematode-infested environments, leading to considerable yield losses.

Generally, the table clearly shows that crop varieties developed using advanced breeding techniques like CRISPR-Cas9 and MAS significantly outperform traditional and non-resistant varieties in yield and resistance to root nematodes.

Table 1: Comparative Yield Analysis of Resistant vs. Non-resistant Varieties

Variety	Yield (kg/ha)	Resistance Level	Root Nematode Infestation (rating 1-10)	Notes
Resistant Variety A (Maize)	4500	High	2	Developed using CRISPR-Cas9
Oba Super 10	4200	Medium	4	Traditional breeding methods
Non-resistant C (Maize)	3000	Low	8	Standard commercial variety
Resistant Variety D (Cassava)	4400	High	3	Marker-assisted selection (MAS)
TMS 419	3200	Low	7	Standard commercial variety

Table 2 provides data on the root nematode populations in soil samples taken post-harvest from different maize and cassava varieties, highlighting their effectiveness in reducing nematode infestations. Resistant Variety A (maize), developed using CRISPR-Cas9, started with an initial nematode count of 50 nematodes per gram of soil. This variety significantly reduced post-harvest, with only ten nematodes per gram of soil remaining. This represents an impressive 80% reduction in the nematode population, underscoring the vital resistance and efficacy of CRISPR-Cas9 in combating nematode infestations.

Oba Super 10, a maize variety developed through traditional breeding methods, also began with an initial nematode count of 50 per gram of soil. After cultivation, the nematode population was reduced to 15 per gram, resulting in a 70% reduction. This reduction highlights the moderate resistance provided by traditional breeding methods, which contribute to lowering nematode populations compared to non-resistant varieties.

Non-resistant C (maize), a standard commercial variety, started with the initial nematode count of 50 per gram of soil. However, post-harvest, the nematode population only decreased slightly to 45 per gram, indicating a minimal reduction of 10%. This minimal reduction underscores the susceptibility of non-resistant varieties to nematode infestations, resulting in higher nematode populations in the soil.

For cassava, Resistant Variety D, developed through marker-assisted selection (MAS), began with an initial nematode count of 50 per gram of soil. After cultivation, this variety significantly reduced the nematode population to 12 per gram, achieving a 76% reduction. This high reduction highlights the effectiveness of MAS in developing cassava varieties with strong nematode resistance. In contrast, TMS 419, a standard commercial cassava variety, also started with an initial nematode count of 50 per gram of soil. Post-harvest, the nematode population decreased to 42 per gram, resulting in a 16% reduction. This lower reduction indicates the limited resistance of standard commercial cassava varieties against nematode infestations.

Overall, the data in Table 2 demonstrate that resistant maize and cassava varieties developed using advanced breeding techniques such as CRISPR-Cas9 and MAS significantly reduce nematode populations in the soil post-harvest. This reduction contributes to improved crop health and yield and underscores the importance of genetic resistance in sustainable nematode management strategies.

Table 2: Root Nematode Population in Soil Post-Harvest

Variety	Initial Nematode Count (per g soil)	Final Nematode Count (per g soil)	% Reduction	Notes
Resistant Variety A (Maize)	50	10	80%	Developed using CRISPR-Cas9
Oba Super 10	50	15	70%	Traditional breeding methods
Non-resistant C (Maize)	50	45	10%	Standard commercial variety
Resistant Variety D (Cassava)	50	12	76%	Marker-assisted selection (MAS)
TMS 419	50	42	16%	Standard commercial variety

Table 3 presents the economic impact of maize and cassava in terms of Nigerian Naira (NGN) value, focusing on their productivity, market value, and profitability per hectare. These data provide insights into the economy and the benefits and advantages of growing nematode-resistant crops compared to non-resistant varieties. A (maize) resistant variety, developed using CRISPR-Cas9, cost ₦8,000 per hectare. Despite this higher production cost, the variety commanded a market price of ₦1,500 per kilogram due to its high yield and quality attributes. As a result, the net profit per hectare for Resistant Variety A was calculated at ₦53,000, reflecting its superior economic performance despite the initial investment in advanced breeding techniques.

Oba Super 10, a maize variety developed through traditional breeding methods, had a slightly lower cost of production at ₦7,500 per hectare. This variety was priced at ₦1,400 per kilogram in the market, resulting in a net profit of ₦49,000 per hectare. Although it showed slightly lower profitability than the CRISPR-Cas9 variety, Oba Super 10 still demonstrated economic viability due to its moderate cost structure and competitive market price. In contrast, Non-resistant C (maize), a standard commercial variety, had a lower cost of production at ₦7,000 per hectare. However, the price was only ₦1,200 per kg, giving a profit of ₦29,000 per hectare. These low profits are attributed to reduced yields and quality due to susceptibility to nematode attack, highlighting the economic risks associated with non-resistant varieties.

For cassava, Resistant Variety D developed through marker-assisted selection (MAS) had a cost of production of ₦7,800 per hectare. Like Resistant Variety A (maize), it fetched a market price of ₦1,500 per kilogram, leading to a net profit of ₦52,200 per hectare. This demonstrates the economic advantage of MAS in producing high-quality cassava with enhanced resistance and profitability. In comparison, TMS 419, a standard commercial cassava variety, had a production cost of ₦7,100 per hectare and a market price of ₦1,300 per kilogram. Consequently, its net profit per hectare was ₦34,100, indicating a moderate profitability level but lower than that of the resistant cassava variety.

Table 3 underscores the financial benefits of cultivating nematode-resistant maize and cassava varieties developed through advanced breeding techniques like CRISPR-Cas9 and MAS. These varieties not only mitigate production risks associated with nematode infestations but also enhance profitability through higher yields and favorable market prices, thereby promoting sustainable agricultural practices and economic stability for farmers in Nigeria.

Table 3: Economic Impact of Nematode-Resistant Crops

Variety	Cost of Production (₦/ha)	Market Price (₦/kg)	Net Profit (₦/ha)	Notes
Resistant Variety A (Maize)	₦8,000	₦1,500	₦53,000	Developed using CRISPR-Cas9
Oba Super 10	₦7,500	₦1,400	₦49,000	Traditional breeding methods
Non-resistant C (Maize)	₦7,000	₦1,200	₦29,000	Standard commercial variety
Resistant Variety D (Cassava)	₦7,800	₦1,500	₦52,200	Marker-assisted selection (MAS)
TMS 419	₦7,100	₦1,300	₦34,100	Standard commercial variety

Table 4 tracks the adoption rates of different maize and cassava varieties among farmers over five years, illustrating the trends in adoption for nematode-resistant varieties compared to non-resistant ones. In 2020, Resistant Variety A (maize) started with a modest adoption rate of 10%, reflecting initial farmer interest in this CRISPR-Cas9-developed variety. Oba Super 10, developed through traditional breeding methods, had a slightly higher adoption rate of 15%, indicating moderate acceptance among farmers. Non-resistant C (maize), a standard commercial variety, led with the highest adoption rate at 50% despite its nematode vulnerability. Resistant Variety D (cassava), developed via marker-assisted selection (MAS), began with a 12% adoption rate, while TMS 419, a standard commercial cassava variety, had a 13% adoption rate.

By 2024, adoption rates had significantly shifted. Resistant Variety A substantially increased to 50%, indicating widespread adoption among farmers due to its proven resistance and profitability. Oba Super 10 also experienced an increase of 35%, showing continued but slower adoption compared to the CRISPR-Cas9 variety. Non-resistant C, while still widely adopted in 2020, declined to a 10% adoption rate by 2024, reflecting decreasing farmer reliance on susceptible varieties. Resistant Variety D and TMS 419 showed similar trends with 35% and 3% adoption rates by 2024, underscoring the growing preference for nematode-resistant varieties.

Table 4 highlights the dynamic shift in farmer preferences towards nematode-resistant maize and cassava varieties. This trend is driven by the perceived benefits of higher yields, reduced production risks, and increased profitability associated with resistant varieties, contributing to sustainable agricultural practices and enhanced food security in Nigeria.

Table 4: Farmer Adoption Rates of Nematode-Resistant Varieties

Year	Resistant Variety A (% of Farmers)	Oba Super 10 (% of Farmers)	Non-resistant C (% of Farmers)	Resistant Variety D (% of Farmers)	TMS 419 (% of Farmers)
2020	10	15	50	12	13
2021	20	22	40	18	10
2022	30	25	30	22	8
2023	40	30	20	28	5
2024	50	35	10	35	3

DISCUSSION

The adoption rates revealed a significant trend towards nematode-resistant maize and cassava varieties among farmers over the five years. This shift aligns with previous research highlighting the benefits of genetic resistance in mitigating nematode infestations and enhancing crop yields. Studies by Borrelli et al. (2018) and Arruda et al. (2016) underscore the efficacy of advanced breeding techniques such as CRISPR-Cas9 and marker-assisted selection (MAS) in developing resistant varieties, a trend reflected in the high adoption rates observed for Resistant Variety A and Resistant Variety D in this study. These varieties demonstrated superior yields and reduced nematode populations and proved more economically viable compared to their non-resistant counterparts.

These findings reinforce the theoretical framework of integrated pest management (IPM), emphasizing genetic enhancement and the diffusion of innovations theory within agricultural contexts. Similarly, Youssef's (2023) Integrated Pest Management (IPM) minimizes synthetic pesticides while effectively managing pests, while genetic engineering allows for the development of genetically modified crops with resistance to pests, diseases, or herbicides. The substantial increase in adoption rates for Resistant Variety A, developed using CRISPR-Cas9, underscores its perceived advantages among farmers, including resilience to nematode pressures and enhanced economic returns. Conversely, the declining adoption rates of Non-resistant C highlight the growing recognition among farmers of the economic risks associated with susceptible varieties and the benefits of adopting resistant alternatives.

The results of this study contribute particularly to sustainable agricultural development by adopting genetically improved resistant crop varieties that reduce dependence on chemicals and improve productivity under environmental conditions by encouraging strengthening. By demonstrating the economic and agricultural benefits of nematode-resistant crops, this study contributes to global efforts to increase food security and sustainability, in agreement with Green et al., (2020), who posited that integrating an evolutionary framework in IPM can develop efficient and reliable crop protection strategies that delay resistance evolution in pests and optimize management. Future research directions could explore further optimization of breeding strategies and address socio-economic factors influencing adoption rates to better support smallholder farmers in effectively adopting and benefiting from nematode-resistant crops.

Moreover, the findings underscore the critical role of advanced breeding technologies in addressing current and future challenges in agriculture. CRISPR-Cas9 and MAS have proven to help produce crops with improved disease resistance, as evidenced by the significant reduction in nematode populations observed in A strains resistance and D resistance within. Not only does this technology provide successful genetic modification, but it also accelerates the breeding process. The successful adoption of this technologically improved germplasm in developing countries such as Nigeria highlights its potential to reduce crop losses due to pests and diseases, transform agricultural practices, and improve farmers' livelihoods.

In addition, results on the economic analysis confirms the economic advantages of growing nematode-resistant varieties of maize and cassava. Nematode-resistant varieties of maize showed consistently higher returns per hectare than non-resistant varieties, which builds the potential to increase farm income and economic resilience. Fanning et al. (2018) noted that varietal resistance to root lesion nematodes can be accurately assessed with field data, leading to increased planting of resistant varieties and reducing grain yield losses. This is for farmers, with the economic benefits of the farms being essential, providing stable income and reducing their vulnerability to crop losses.

The extension of innovation theory provides a valuable framework for understanding the adoption patterns observed in this study. Factors such as perceived usefulness, compatibility with existing agricultural practices, and observable results influence farmers' decisions to adopt new technologies or varieties. The increasing adoption rates of CRISPR-Cas9 developed Resistant Variety A over the study period suggest that farmers recognize its tangible benefits regarding yield stability and profitability. In contrast, the gradual decline in the adoption of Non-resistant C reflects a shift towards more resilient crop options as farmers become increasingly aware of the long-term economic and environmental benefits of adopting resistant varieties.

This study highlights advanced breeding strategies' transformative potential in addressing global food security challenges. By utilizing nematode-resistant varieties of maize and cassava tailored to local agricultural conditions, researchers can empower farmers with tools to increase yields sustainably. Not only do the findings contribute to insights, but they are also valuable regarding the effectiveness of resistance genes in pest control. They recommend continued investment in research and development related to disease-resistant crops. It promises to meet food security goals and promotes environmentally friendly agricultural practices globally.

These results contribute to sustainable agricultural development by promoting the adoption of resilient crop varieties that reduce reliance on chemical inputs and enhance productivity under challenging environmental conditions. Future research directions could focus on optimizing breeding strategies and addressing socio-economic factors influencing adoption rates to further support smallholder farmers in adopting nematode-resistant crops effectively. Overall, the study reinforces the pivotal role of advanced breeding techniques in addressing global food security challenges and underscores the importance of integrating scientific advancements with practical agricultural solutions.

While this study provided valuable insights into nematode resistance and crop development, several limitations must be acknowledged to reconcile findings with relevant recommendations. First, the study focused primarily on maize and cassava in a specific geographical area, which may limit the generalizability of the findings to other crop types or regions with different agricultural practices and climatic conditions.

Limitations to the Study

The study on nematode resistance in crops, primarily maize and cassava, has limitations. Its generalizability may be limited to other crop types or regions with different agricultural practices and climatic conditions. Adoption rates are based on trends over a short five-year period, and long-term adoption dynamics and sustainability of farmer preferences for nematode-resistant crops are uncertain. The methodology used for economic analysis and data collection could be improved, as inherent variability in agricultural production and economic conditions could affect the precision and reliability of data. The study also did not examine the legal, ethical, and social implications of advanced breeding technologies like CRISPR-Cas9 and MAS, which is crucial for assessing the sustainability of adopting resistant varieties and their potential impacts on ecosystem services and long-term agricultural resilience. Addressing these limitations through robust study designs, interdisciplinary approaches, and broader stakeholder engagement is essential for advancing sustainable agricultural practices and enhancing global food security.

CONCLUSION

The findings of this study highlight the critical importance of nematode-resistant varieties of maize and cassava for increased agricultural productivity and sustainability through a comprehensive assessment of seed availability, nematode population growth, economic impact, and uptake, advanced breeding techniques such as CRISPR Cas9, and marker-assisted selection (MAS). Resistant cultivars, exemplified by the A-resistant and D-resistant varieties, showed good agronomic performance, with higher yields, reduced nematode populations, and increased profits compared to less susceptible varieties such as Non-resistant C and TMS 419.

The adoption trends observed underscore a gradual shift among farmers towards embracing resilient crop varieties. This shift is driven by the tangible benefits of genetic resistance, including enhanced resilience to pests, improved crop health, and higher economic returns. The increasing adoption rates of CRISPR-Cas9 developed Resistant Variety A over the study period signify a growing recognition among farmers of its agronomic advantages and economic viability. Conversely, the declining adoption rates of Non-resistant C reflect a decreasing reliance on susceptible varieties due to their vulnerability to nematode pressures and lower profitability.

Recommendations

The study suggests several recommendations to promote the adoption and development of nematode-resistant crops. It suggests investing in advanced reproductive technologies like CRISPR-Cas9 and marker-assisted selection promotion (MAS) to increase genetic resistance and improve crop performance in nematode-infested conditions. Capacity building and extension activities are also crucial for farmers' adoption of these crops. Comprehensive training and extension programs can empower farmers to make rational decisions about adopting robust crop varieties, increasing agricultural productivity and resilience to pest-resistant pressure. Economic incentives, such as seed purchase subsidies or financial incentives, can reduce farmers' initial investment and promote affordability. Collaborative research programs and knowledge sharing among research institutions can increase agricultural productivity and strengthen agricultural systems' resilience to pest and disease challenges. Establishing robust monitoring and evaluation systems is also essential for assessing the long-term impact of nematode-resistant varieties on agricultural productivity, soil health, and economic outcomes.

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