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EFFICACY OF MORINGA SEED CAKE ORGANIC AMENDMENT ON IMPROVING SOIL FERTILITY, CROP PRODUCTIVITY, AND DISEASE MANAGEMENT ON AGRICULTURAL CROPS: A REVIEW

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ABSTRACT

The excessive and long-term use of chemical fertilizers has resulted in soil degradation, environmental pollution, and a decline in soil biological health. The positive effects of seed cakes as an organic nutrient source have recently emerged as an effective strategy for restoring soil health and sustainability. Their application not only improves soil fertility but also supports microbial activity, thereby promoting resilient and productive agro ecosystems. Additionally, the recycling of agro industrial by products such as seed cakes aligns with circular economy principles and reduces dependence on synthetic inputs. In this context, Moringa seed cake has rich nitrogen supplement along with phosphorus and potassium. However in the Moringa oil extraction factory they did not commercially utilize this valuable gold. Therefore, this review aims to create greater awareness among the scientific and farming communities about the role of moringa seed cake in improving soil physicochemical and biological properties, enhancing crop productivity, and managing soil borne pathogens and plant-parasitic nematodes.

Keywords: Microbial activity; Moringa seed cake; organic fertilizers; plant parasitic nematodes; seed cake; soil health; sustainable agriculture.

Introduction

By 2050, the world's population is projected to reach 9.1 billion, and feeding nearly 10 billion people will be a tremendous and herculean task. To meet this demand, global food production must increase by approximately 56% to 70% (FAO, 2026). However, several researchers have shown that although synthetic fertilizers have significantly increased food production, their prolonged use has led to soil nutrient imbalance, depletion of soil organic carbon, reduced microbial diversity, and environmental contamination (Tilman *et al.*, 2002; Lal, 2015; FAO, 2017). Sustainable agriculture emphasizes eco-friendly nutrient sources that restore soil fertility while minimizing environmental impacts and greenhouse gas emissions (Drinkwater & Snapp, 2007; Smith *et al.*, 2008; Paustian *et al.*, 2016). In the present scenario, organic amendments derived from plant and oilseed residues

are increasingly recognized for their role in improving soil structure, enhancing nutrient cycling, and promoting biological activity (Palm *et al.*, 2001; Edmeades, 2003).

Several researchers suggest that organic manures improve soil health, soil fertility, and overall crop growth, with particular emphasis on physical, chemical, and biological characteristics. Physical properties of soil include texture, structure, bulk density, porosity, and moisture content, all of which influence water retention, aeration, and root growth (Weil & Brady, 2017). Soil texture is determined by the proportions of sand, silt, and clay, while soil structure refers to the arrangement of soil particles into aggregates that affect infiltration and root penetration. Chemical properties such as soil pH, organic matter content, nutrient availability, and cation exchange capacity (CEC) play a major role in soil fertility and

plant growth (Tynchenko *et al.*, 2024). Soil pH affects nutrient solubility and microbial activity, whereas organic matter improves soil structure, water-holding capacity, and nutrient supply. Essential nutrients including nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients are required for plant development, and CEC indicates the soil's ability to retain and exchange nutrients. Biological properties involve soil microorganisms, fauna, and enzyme activity, which are responsible for nutrient cycling, organic matter decomposition, and maintaining soil health (Mazzola, M. (2004). Microorganisms such as bacteria and fungi decompose organic residues, while soil fauna like earthworms enhance soil aeration and aggregation. Overall, soil properties are critical for determining soil productivity, environmental sustainability, and effective soil management practices.

Moringa seed cakes are residual materials obtained after oil extraction in moringa processing



Fig. 1 : *Moringa oleifera* tree, pods, seeds and seed cake obtained after oil extraction.

Nutrient composition and mineralization of moringa seed cakes

Moringa seed cakes vary widely in nutrient composition depending on crop species, extraction method, and processing conditions (Shivakumar *et al.*, 2011; Chivenge *et al.*, 2011). Groundnut cake is particularly rich in nitrogen (6.0–8.0%), phosphorus (1.0–1.5%), and potassium (1.3–1.8%), while mustard cake also contains substantial amounts of nitrogen (4.5–6.0%) and phosphorus (1.8–2.2%). In contrast, neem (N: 4.0–5.5%, P: 0.8–1.0%, K: 1.0–1.5%), pongamia (N: 3.5–4.5%, P: 0.5–0.9%, K: 1.0–1.3%), and mahua cakes (N: 2.5–3.5%, P: 0.6–1.0%, K: 1.2–1.6%) contain moderate nutrient levels along with biologically active secondary metabolites (Shivakumar *et al.*, 2011). Moringa (N: 3.0–4.5%, P: 0.8–1.2%, K: 1.2–1.8%), castor (N: 4.5–6.0%, P: 1.5–2.0%, K: 1.0–1.5%), sesame (N: 5.0–6.5%, P: 2.0–2.5%, K: 1.0–1.4%), and jatropha seed cakes (N: 4.0–5.0%, P: 1.0–1.5%, K: 1.0–1.4%) also contribute appreciable amounts of macro and micronutrients (Emmanuel *et al.*, 2011a; Gadheshari & Malam, 2021). These values

units and are rich in essential and micronutrients. However, many extraction units do not process this seed cake into valuable organic manure due to less awareness about the valuable gold (Fig 1.). Moringa seed cake enhances microbial growth in soil, particularly *Aspergillus niger* and *Pseudomonas fluorescens*, which are key microorganisms involved in mineralization and nitrification processes (Ramteke, 2024). Additionally, moringa seed cake is abundant in nitrogen, organic carbon, phosphorus and potassium, along with secondary and micronutrients. Beyond their fertilizing value, moringa seed cakes contain bioactive compounds that influence soil microbial communities and help suppress soil-borne pathogens and nematodes (Karmelreetha & Muthukumar, 2020; Mazzola, 2004). This review integrates existing research to provide a comprehensive understanding of the agronomic, biological, and protective roles of moringa seed cakes in soil–plant systems.

indicate that moringa seed cake possesses nutrient concentrations comparable to other commonly used organic amendments, highlighting its potential as an effective organic nutrient source. Recent analyses confirm these levels while highlighting micronutrients and bioactive compounds that aid mineralization. A 2025 Zambian study reported Moringa Seed Cake boosting soil nitrogen uptake by 4.79%, phosphorus by 0.72%, and potassium by 3.44% in smallholder systems (Coelho *et al.*, 2024).

Nutrients from seed cakes are released gradually through microbial mineralization, ensuring sustained nutrient supply to crops and improved nutrient synchrony (Palm *et al.*, 2001; Gentile *et al.*, 2009). This slow-release pattern reduces nutrient losses through leaching and volatilization and enhances nutrient use efficiency compared to inorganic fertilizers (Osman *et al.*, 2009; Vanlauwe *et al.*, 2015). Long-term application increases soil organic carbon stocks and improves soil fertility (Six *et al.*, 2004; FAO, 2017).

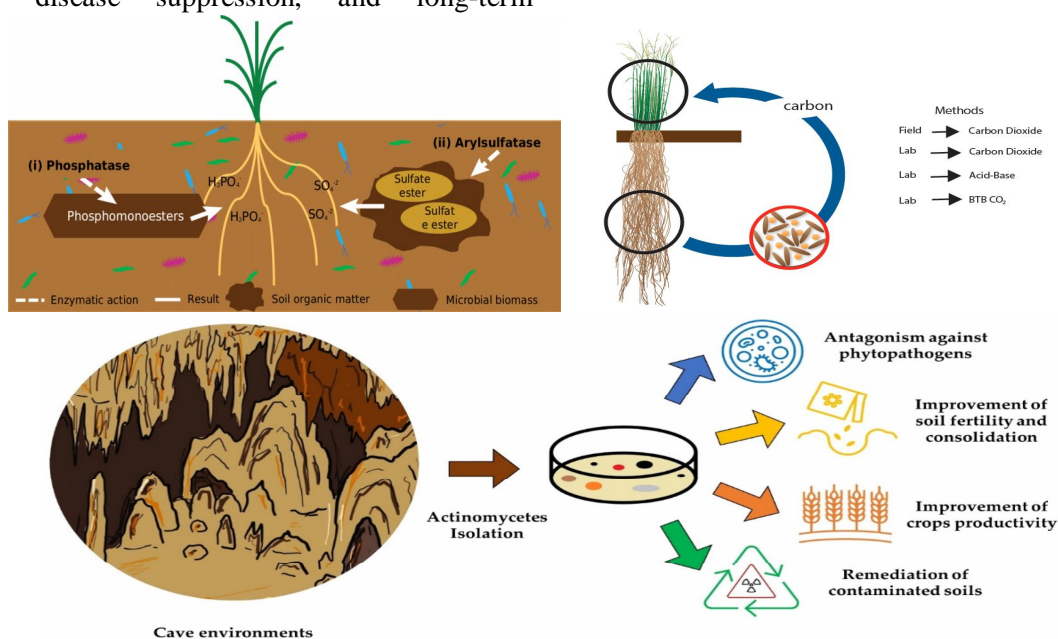
Table 1 : Nutrient contents of various seed cakes

Sl. No	Seed cake	Nitrogen (%)	Phosphorus (%)	Potassium (%)	References
1.	Moringa	3.0–4.5	0.8–1.2	1.2–1.8	Ramteke <i>et al.</i> , 2024
2.	Groundnut	6.0–8.0	1.0–1.5	1.3–1.8	Tandon, 2016
3.	Mustard	4.5–6.0	1.8–2.2	1.0–1.3	Brady & Weil, 2017
4.	Neem	4.0–5.5	0.8–1.0	1.0–1.5	Prasad <i>et al.</i> , 2014
5.	Pongamia	3.5–4.5	0.5–0.9	1.0–1.3	Ghosh <i>et al.</i> , 2012
6.	Mahua	2.5–3.5	0.6–1.0	1.2–1.6	Das & Mandal, 2015
7.	Castor	4.5–6.0	1.5–2.0	1.0–1.5	Singh <i>et al.</i> , 2018
8.	Sesame	5.0–6.5	2.0–2.5	1.0–1.4	Rao <i>et al.</i> , 2013
9.	Jatropha	4.0–5.0	1.0–1.5	1.0–1.4	Openshaw, 2000

Effects on soil microbial activity and enzyme functions

The effects on soil microbial activity and enzyme functions about the moringa seed cake were illustrated in Fig 2. It act as carbon rich substrates that stimulate soil microbial growth and activity, leading to enhanced microbial biomass and diversity (Elnasikh *et al.*, 2011; Nannipieri *et al.*, 2012). However, research on moringa seed cake is relatively limited. Several researchers reported that increased populations of bacteria, fungi, and actinomycetes by the application of neem, groundnut, and sesame cakes (Elnasikh *et al.*, 2011; Zhang *et al.*, 2016). Enhanced microbial activity is associated with increased enzymatic activities such as dehydrogenase, urease, phosphatase, and nitrate reductase, which play key roles in nutrient transformation and cycling (Burns *et al.*, 2013; Dick, 2011; Zhang *et al.*, 2016). Neem seed cake, in particular, enhances microbial biomass while suppressing harmful organisms due to its secondary metabolites (Karmelreetha & Muthukumar, 2020; Oka, 2010). Improved microbial balance contributes to soil resilience, disease suppression, and long-term

productivity (Mazzola, 2004; Reganold & Wachter, 2016). Application of moringa seed-derived amendments increased urease (22.54% over control) and phosphatase (33.28% over control) activities while improving ammonium-nitrogen and available potassium, indicating stimulated microbial processes in soil (Harman, 2004). However, detailed quantitative assessments of bacterial, fungal, and actinomycetes populations remain scarce, emphasizing the need for further investigation. Nevertheless, available evidence suggests that moringa seed cake can similarly promote soil enzyme activity and microbial population growth, demonstrating effects comparable to those of other organic amendments. Moringa Seed Cake stimulates microbial biomass, including *Aspergillus niger* and *Pseudomonas fluorescens*, increasing dehydrogenase and phosphatase activities by 22-33%. New research shows 25-50% rises in microbial enzyme activity and 15-30% in soil organic matter after MSC application. In citrus orchards, MSC combined with vermicompost enhanced microbial respiration and aggregate stability (Coelho *et al.*, 2024).

**Fig. 2 :** Mechanism of microbial stimulation and enzyme activity enhancement by organic amendments

Impact on soil physical and chemical properties

Incorporation of moringa seed cakes into soil significantly improves physical properties (Fig 3.) by enhancing aggregate stability, increasing porosity, and improving water-holding capacity while simultaneously reducing bulk density (Bronick & Lal, 2005; Giller *et al.*, 2009). The addition of organic residues promotes the formation of stable soil aggregates through microbial binding agents and polysaccharides, thereby improving soil tilth and structural resilience (Six *et al.*, 2004). Increased aggregate stability protects soil organic carbon from rapid mineralization and enhances resistance to compaction and erosion (Lal, 2015). Such improvements facilitate deeper root penetration, better aeration, and enhanced microbial activity, ultimately supporting efficient nutrient uptake and plant growth. Moreover, improved soil structure reduces surface crusting and minimizes erosion, contributing to long-term soil sustainability (Bronick & Lal, 2005).

The addition of moringa seed cake also increases soil organic matter (SOM) content, which plays a critical role in improving soil physical quality. Higher SOM improves soil friability, reduces penetration resistance, enhances moisture retention in sandy soils, and improves drainage in clay soils (Brady & Weil, 2017). Organic amendments further enhance soil biological activity, increasing earthworm populations and microbial biomass carbon, both of which contribute to improved soil aggregation and nutrient cycling (Giller *et al.*, 2009). Enhanced biological activity accelerates the decomposition process and promotes the stabilization of organic carbon fractions, thereby improving long-term soil fertility (Six *et al.*, 2004; Lal, 2015).

Chemically, the application of moringa seed cake enhances soil nutrient availability, with available nitrogen increasing to 280–350 kg ha⁻¹, available

phosphorus to 18–30 kg ha⁻¹, and available potassium to 220–320 kg ha⁻¹, along with improved levels of exchangeable calcium (4.0–6.5 cmol kg⁻¹) and magnesium (1.2–2.5 cmol kg⁻¹). These improvements are accompanied by soil pH buffering toward near-neutral conditions (pH 6.5–7.5) and an increase in cation exchange capacity to 12–20 cmol kg⁻¹, reflecting enhanced nutrient retention and availability (Osman *et al.*, 2009; Agegnehu *et al.*, 2016). Increased CEC is largely attributed to the formation of humic substances and the addition of negatively charged organic colloids that improve the soil's capacity to adsorb and exchange nutrient cations (Brady & Weil, 2017). The decomposition of moringa seed cake releases organic acids and humic substances that help moderate soil reaction, typically maintaining pH within a favorable range of 6.5–7.5 for most crops (Agegnehu *et al.*, 2016). These organic compounds can also chelate micronutrients such as iron, zinc, copper, and manganese, enhancing their availability and preventing deficiencies in calcareous or alkaline soils (Lal, 2015). Additionally, organic amendments contribute to improved phosphorus solubilization through microbial activity and organic acid production, reducing phosphorus fixation in highly weathered soils (Giller *et al.*, 2009). Additionally, the application of organic amendments can help regulate soil electrical conductivity by improving salt distribution and leaching, with EC values often stabilizing around 0.8–1.5 dS m⁻¹, which is considered suitable for optimal crop growth (Osman *et al.*, 2009). Improved soil structure and organic matter content also reduce nutrient losses through runoff and volatilization, thereby improving nutrient use efficiency and long-term soil productivity (Blanco-Canqui & Lal, 2008). Collectively, these physical and chemical improvements highlight the potential of moringa seed cake as an effective organic amendment for sustaining soil fertility and productivity.

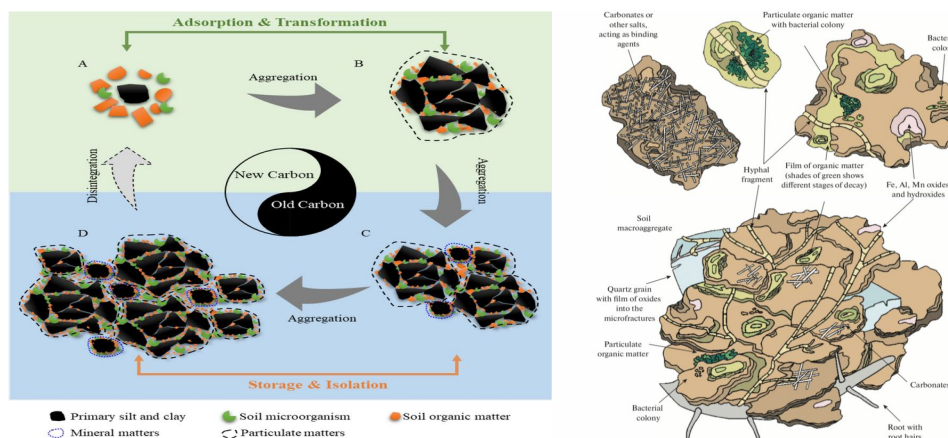


Fig. 3 : Improvement in soil aggregation and porosity following organic amendment application.

Influence on crop growth and productivity

Numerous field studies have demonstrated the positive effects of moringa seed cakes on crop growth and yield due to improved nutrient availability, enhanced microbial activity, and better soil physical conditions (Edmeades, 2003). Organic amendments promote synchronized nutrient mineralization, which matches crop nutrient demand more effectively than sole inorganic fertilization, thereby improving nutrient use efficiency (Chivenge *et al.*, 2011). Increased microbial activity enhances nitrogen mineralization, phosphorus solubilization, and production of plant growth-promoting substances such as auxins and cytokinins, which collectively stimulate root proliferation and shoot development (Vanlauwe *et al.*, 2015). Chivenge *et al.*, (2011) reported that organic amendments increase crop yields by 15–35% compared to unfertilized plots, primarily through sustained nutrient release and improved soil health. Application of neem, pongamia, and mahua cakes significantly increased grain yields of finger millet to approximately 2.5–3.2 t ha⁻¹ and enhanced total biomass production to 5.5–7.0 t ha⁻¹ (Shivakumar *et al.*, 2011; Tiyagi *et al.*, 2001). These improvements are attributed not only to direct nutrient supply but also to reduced nitrogen losses through volatilization and leaching, improved root architecture, and enhanced photosynthetic efficiency.

Similarly, moringa seed cake has been reported to improve maize growth, with grain yields rising to about 4.5–6.0 t ha⁻¹ and stover yields reaching 6.5–8.5 t ha⁻¹, largely due to improved nutrient supply and stimulated soil biological activity (Emmanuel *et al.*, 2011). Improved soil aggregation and moisture retention further contribute to better crop performance under rainfed conditions, reducing moisture stress during critical growth stages (Edmeades, 2003). Residual application effects further benefit succeeding crops by maintaining available nitrogen above 250 kg ha⁻¹ and supporting higher system productivity, thereby emphasizing the importance of moringa seed cakes in crop rotation and integrated nutrient management systems (Tiyagi *et al.*, 2001). This residual nutrient contribution reduces dependence on synthetic fertilizers and enhances system productivity and profitability. Integrated nutrient management approaches that combine moringa seed cake with reduced rates of inorganic fertilizers have been shown to optimize nutrient synchronization, improve agronomic efficiency, and sustain long-term soil

fertility (Vanlauwe *et al.*, 2015). Beyond nutrient supply, its bioactive compounds may support chlorophyll formation, improve leaf area development, and increase harvest index, ultimately contributing to higher economic returns for farmers. Overall, moringa seed cake is not just a nutrient source—it acts as a soil conditioner, a biological stimulant, and a sustainable input that supports consistent crop growth and improved productivity. Its use offers a practical pathway toward maintaining soil health while enhancing crop yields in both rainfed and irrigated farming systems.

Management of soil-borne fungi

Soil-borne fungal diseases are one of the major hidden threats to crop production, often attacking plant roots and reducing yield long before visible symptoms appear. The incorporation of moringa seed cake into soil offers a natural and eco-friendly approach to managing these pathogens (Fig 4.). During decomposition, moringa seed cake releases several bioactive compounds including phenolics, fatty acids, glucosinolates, and sulfur-containing compounds that exhibit antifungal properties (Khan *et al.*, 1974). These compounds create an unfavorable environment for many harmful fungi, thereby reducing their survival and infection potential.

Similar effects have been observed with other oilseed cakes such as neem, mustard, castor, and mahua, which have demonstrated significant suppression of diseases caused by *Fusarium*, *Rhizoctonia*, *Macrophomina*, *Sclerotium*, and *Pythium* species (Tiyagi *et al.*, 2001; Karmelreetha & Muthukumar, 2020). These pathogens are commonly responsible for root rot, wilt, damping-off, and collar rot diseases in many crops. The suppressive effect is often attributed to toxic metabolites released during decomposition as well as to improved soil biological balance.

Beyond direct antifungal action, moringa seed cake also works indirectly by strengthening the soil's natural defense system. The addition of organic matter stimulates beneficial microorganisms, particularly antagonistic fungi and bacteria such as *Trichoderma* spp. and fluorescent *Pseudomonas*. These beneficial microbes compete with pathogens for space and nutrients, produce antibiotics that inhibit fungal growth, and sometimes parasitize the harmful fungi themselves (Harman *et al.*, 2004; Mazzola, 2004).

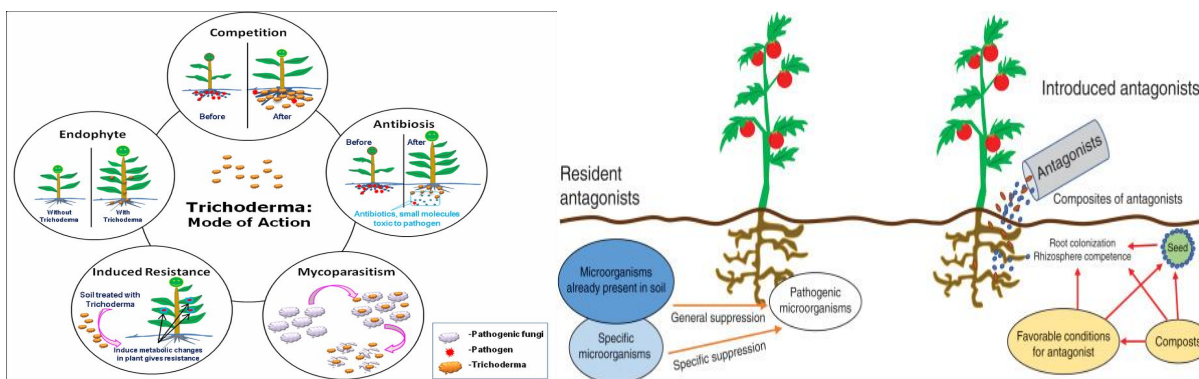


Fig. 4 : Suppression of soil-borne pathogens through bioactive compounds and microbial antagonism.

Role in the management of plant-parasitic nematodes

Plant-parasitic nematodes are microscopic roundworms that attack plant roots and silently reduce crop productivity (Fig. 5.). Although invisible to the naked eye, they are responsible for substantial yield losses worldwide by interfering with root function, nutrient uptake, and water absorption (Sikora *et al.*, 2018). Infested plants often show stunted growth, yellowing, wilting, and poor root development. In severe cases, root-knot nematodes cause characteristic galls that severely restrict root efficiency.

Moringa seed cake has shown promising potential as a natural and environmentally friendly option for managing these pests. When incorporated into soil, it undergoes decomposition and releases several bioactive compounds, including ammonia, fatty acids, and other toxic metabolites that are harmful to nematodes (Akhtar & Alam, 1993; Oka, 2010). The release of ammonia during organic matter breakdown is particularly important, as it creates localized conditions in the soil that reduce nematode survival and egg hatching.

Research has reported significant reductions in populations of *Meloidogyne incognita* (root-knot nematode), *Rotylenchulus reniformis* (reniform nematode), and *Tylenchorhynchus* spp. following application of moringa seed cake (Tiyagi *et al.*, 2001). Lower nematode populations translate into healthier root systems, improved nutrient uptake, and ultimately better crop performance. In many cases, treated plants show stronger root growth and reduced gall formation compared to untreated controls.

In addition to its direct toxic effects, moringa seed cake also improves soil health in ways that indirectly

suppress nematodes. Increased organic matter enhances microbial activity, encouraging the growth of beneficial microorganisms such as predatory fungi and bacteria that feed on or compete with nematodes. Some soil microbes produce enzymes that degrade nematode eggs or release metabolites that inhibit their movement and reproduction. This biological balance strengthens the soil's natural suppressive capacity over time (Oka, 2010).

Neem cake is another well-known organic amendment for nematode management. Its effectiveness is largely attributed to azadirachtin and related limonoid compounds, which disrupt nematode feeding behavior, inhibit egg hatching, and interfere with development and reproduction (Chitwood, 2002; Oka, 2010). Similar bioactive principles in moringa and other oilseed cakes contribute to their nematicidal potential, making them valuable components of integrated pest management (IPM) systems.

An additional advantage of using moringa seed cake is that it simultaneously improves soil fertility while controlling nematodes. Unlike synthetic nematicides, which may provide short-term suppression but can harm beneficial organisms, organic amendments enhance soil structure, nutrient cycling, and biological diversity. This dual function pest suppression and soil improvement makes moringa seed cake a sustainable option for long-term nematode management.

Overall, incorporating moringa seed cake into crop production systems offers a practical and eco-friendly strategy to reduce nematode populations, protect root health, and improve crop yields while maintaining soil ecological balance.

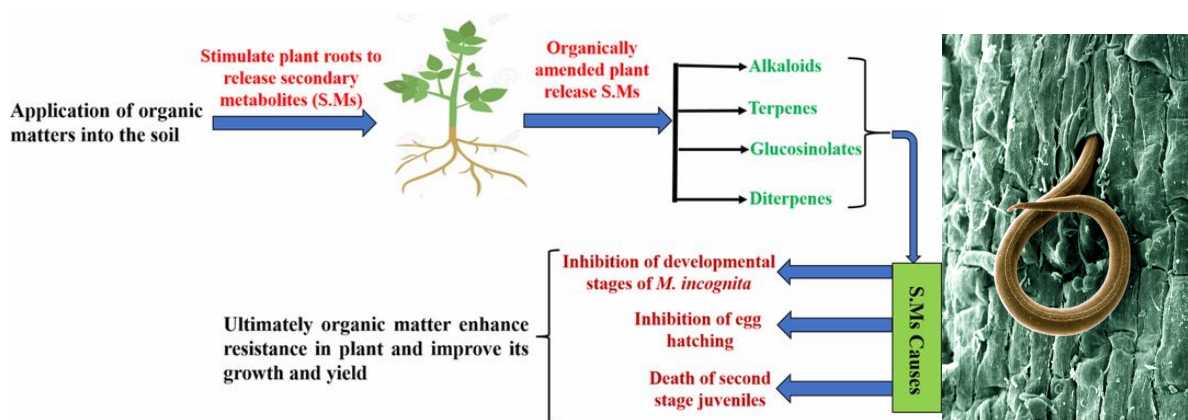


Fig. 5 : Reduction of root-knot nematode infestation following application of organic seed cake

Environmental and socio-economic benefits

The use of organic amendments such as moringa seed cake extends far beyond improving crop yield it contributes meaningfully to environmental protection, climate resilience, and farmer livelihoods. Over the past few decades, researchers have clearly demonstrated that regular application of organic materials plays a vital role in reducing environmental degradation while enhancing long-term soil health. One of the most important environmental benefits is the improvement of soil organic carbon (SOC). SOC is widely recognized as a key indicator of soil quality and a critical component in climate change mitigation. Continuous addition of organic inputs has been shown to increase SOC by approximately $0.2\text{--}0.6 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (Lal, 2004; Smith *et al.*, 2008). This means that soils not only become more fertile but also act as carbon sinks, capturing and storing atmospheric carbon dioxide. Organic amendments promote carbon stabilization by improving soil aggregation. When stable aggregates form, carbon becomes physically protected within micro-aggregates, reducing its exposure to decomposition and limiting carbon losses to the atmosphere (Six *et al.*, 2004). In simple terms, healthier soils help “lock away” carbon for longer periods.

Another important environmental advantage is the reduced dependence on synthetic fertilizers. Excessive use of chemical fertilizers often leads to nutrient leaching, groundwater contamination, soil acidification, and greenhouse gas emissions such as nitrous oxide. By integrating organic sources like moringa seed cake, fertilizer requirements can be reduced by 25–50% while still maintaining soil fertility and crop productivity (Agegnehu *et al.*, 2016). This balanced approach lowers input costs and minimizes environmental risks (Edmeades, 2003; Giller *et al.*, 2009).

Organic amendments also revitalize soil biological life. They provide energy-rich substrates for soil microorganisms, creating a more active and diverse microbial community. Studies report microbial biomass carbon values ranging from $250\text{--}600 \text{ mg kg}^{-1}$ in organically amended soils, significantly higher than in soils relying solely on chemical fertilizers (Chivenge *et al.*, 2011). Enhanced microbial activity improves nutrient mineralization, supports enzymatic functions, and strengthens natural nutrient cycling processes (Vanlauwe *et al.*, 2015). A biologically active soil is more resilient to stress, recovers faster from disturbances, and supports sustainable agricultural production. From a socioeconomic perspective, moringa seed cake offers practical advantages, particularly for smallholder farmers. As a by-product of moringa oil extraction, it represents an opportunity to recycle agro-industrial waste into a valuable soil amendment. This recycling reduces environmental waste while providing a locally available and cost-effective nutrient source (Emmanuel *et al.*, 2011b). Farmers who utilize such organic inputs often reduce their expenditure on synthetic fertilizers and pesticides, thereby improving profit margins.

Furthermore, improved soil fertility and enhanced carbon sequestration contribute to climate-resilient farming systems. Soils enriched with organic matter retain more moisture, withstand drought better, and support stable crop yields under variable climatic conditions (Lal, 2015). By reducing greenhouse gas emissions and increasing carbon storage, organic amendments such as moringa seed cake also contribute to global climate mitigation efforts (Paustian *et al.*, 2016). In essence, moringa seed cake serves multiple roles it enriches soil, strengthens ecological balance, reduces environmental pollution, lowers production costs, and supports long-term agricultural sustainability. Its adoption aligns well with climate-smart agriculture principles, offering both

environmental protection and economic benefits for farming communities.

Challenges and future perspectives

In the current agricultural landscape, organic amendments such as farmyard manure, compost, green manures, and various oilseed cakes have been extensively studied and promoted for improving soil fertility and sustaining crop productivity. Their benefits in enhancing soil organic matter, nutrient cycling, and biological activity are well documented (Lal, 2004; Agegnehu *et al.*, 2016). However, despite the recognized nutritional richness and multifunctional properties of *Moringa oleifera*, research specifically examining moringa seed cake as a soil amendment remains comparatively limited. Most scientific efforts have focused on commonly available materials like neem cake or compost, leaving moringa seed cake relatively underexplored as a reliable and scalable organic input.

This research gap is particularly relevant in regions such as Tamil Nadu, where moringa is widely cultivated and oil extraction units generate considerable quantities of seed cake as a by-product. In many cases, this residual biomass is underutilized or treated as low-value waste. From a sustainability perspective, this represents a missed opportunity. Recycling moringa seed cake into agricultural systems could support circular economy principles, reduce waste disposal issues, and provide farmers with a locally available nutrient source (Reganold & Wachter, 2016).

Nevertheless, broader adoption of organic amendments including moringa seed cake faces practical challenges. One major limitation of traditional organic inputs is variability in nutrient composition. Differences in raw material source, processing methods, storage conditions, and decomposition stages often lead to inconsistent nutrient content and unpredictable crop responses (Elbl *et al.*, 2016). Farmers may hesitate to adopt such materials widely when yield outcomes are uncertain.

Additionally, some oilseed cakes, such as jatropha, contain toxic or phytotoxic compounds that can adversely affect seed germination, root development, or soil microbial communities if not adequately processed. The presence of anti-nutritional factors in certain organic residues further complicates their safe application (Sikora *et al.*, 2018). In many regions, the absence of standardized recommendations regarding application rates, timing, and integration with chemical fertilizers creates confusion and limits farmer confidence.

In contrast, moringa seed cake presents several promising attributes that warrant deeper investigation. Its relatively low carbon-to-nitrogen (C:N) ratio promotes faster decomposition and quicker nutrient mineralization compared to high-carbon residues. This allows crops to access nutrients more readily while still benefiting from gradual improvements in soil organic matter. Organic inputs with balanced nutrient release patterns are known to enhance nutrient use efficiency and support sustained crop growth (Vanlauwe *et al.*, 2015). Moreover, the addition of moringa-derived organic matter can improve soil aggregation, increase microbial biomass, and enhance soil enzymatic activity key indicators of soil health (Six *et al.*, 2004; Chivenge *et al.*, 2011).

Looking ahead, systematic and region-specific research is essential to unlock the full potential of moringa seed cake. Future studies should evaluate its performance across diverse soil types, agro-climatic zones, and cropping systems to establish scientifically validated guidelines. Long-term field experiments are particularly important to assess residual effects, carbon sequestration potential, and impacts on soil biological communities (Lal, 2015). Emphasis should also be placed on its integration within integrated nutrient management (INM) frameworks, where partial substitution of chemical fertilizers with organic inputs can reduce environmental risks while maintaining productivity (Agegnehu *et al.*, 2016).

An exciting future direction involves the development of fortified or enriched organic amendments. Enriched manures organic materials fortified with micronutrients, beneficial microorganisms, or bio-stimulants are increasingly recognized as innovative tools to combat nutrient deficiencies and soil degradation. Given its nutrient density and biodegradability, moringa seed cake could serve as an excellent base material for such formulations. For example, enrichment with phosphate-solubilizing bacteria or nitrogen-fixing microorganisms could further enhance its agronomic efficiency and disease-suppressive capacity (Sikora *et al.*, 2018; Vanlauwe *et al.*, 2015).

From a climate perspective, promoting moringa seed cake use aligns with climate-smart agriculture principles. Organic amendments contribute to soil carbon sequestration, improve moisture retention, and enhance resilience against drought and temperature stress (Lal, 2004; Paustian *et al.*, 2016). Healthier soils with higher organic matter content are better equipped to buffer climatic variability, thereby stabilizing crop yields in the face of changing environmental conditions.

Socioeconomically, wider utilization of moringa seed cake could generate additional value within local supply chains. Oil extraction industries could diversify income streams by marketing seed cake as an organic fertilizer. Smallholder farmers, in turn, could benefit from reduced input costs and improved soil fertility, enhancing long-term profitability (Reganold & Wachter, 2016). With appropriate extension support and policy encouragement, moringa seed cake could evolve from an underutilized by-product into a strategic resource for sustainable agricultural intensification.

In conclusion, while challenges related to standardization, awareness, and large-scale validation remain, the future prospects of moringa seed cake are highly promising. Through coordinated research, technological innovation, and farmer-centered outreach programs, it has the potential to emerge as a scientifically validated, environmentally sustainable, and economically viable organic amendment for diverse agricultural and horticultural systems.

Conclusion

This study highlights that moringa seed cake is far more than a simple organic fertilizer it is a multifunctional soil amendment capable of improving the physical, chemical, and biological health of soils. Its application enhances soil structure by improving aggregation, porosity, and water-holding capacity, while simultaneously enriching nutrient availability and stimulating beneficial microbial activity. These combined improvements create a more balanced and resilient soil environment that supports healthy root development and sustained plant growth.

One of the most valuable characteristics of moringa seed cake is its gradual nutrient release pattern. Unlike synthetic fertilizers that may supply nutrients rapidly but are prone to losses, moringa seed cake provides a more sustained and synchronized nutrient supply. This improves nutrient use efficiency and reduces leaching or volatilization losses. In addition, the presence of bioactive compounds contributes to the suppression of soil-borne fungal pathogens and plant-parasitic nematodes, offering a natural form of biological protection to crops. Its residual effects further benefit succeeding crops, making it particularly useful in crop rotation and integrated nutrient management systems.

Beyond productivity gains, moringa seed cake contributes to broader soil health restoration. By increasing soil organic matter and stimulating microbial diversity, it strengthens natural nutrient cycling processes and enhances soil resilience under

environmental stress conditions. These qualities position it as a valuable input for sustainable and climate-resilient agriculture.

However, while the available findings are promising, further systematic research is needed. Evaluations across diverse soil types, climatic regions, and cropping systems are essential to establish standardized application rates, management practices, and long-term impacts. Such research would help bridge existing knowledge gaps and build farmer confidence in its wider adoption.

Importantly, integrating moringa seed cake with complementary amendments such as biochar and fortified nutrients presents an exciting future direction. Biochar may enhance nutrient retention and carbon stabilization, while nutrient fortification or microbial enrichment could further improve agronomic efficiency. Such combinations have the potential to enhance nutrient use efficiency, promote carbon sequestration, and strengthen long-term soil health, thereby supporting environmentally sustainable agricultural systems.

In summary, moringa seed cake represents a promising, eco-friendly, and resource-efficient solution for improving soil fertility and crop productivity. With continued research, technological refinement, and field-level validation, it has the potential to become a key component of sustainable agricultural intensification and soil health management strategies.

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