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Commercializing The Value Chain For Biochar And Insect-Composted Organic Fertilizer (ICOF) In Kenya: An Empirical Literature Review

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ABSTRACT
This review article examines the commercialization of Biochar and Insect Composted Organic Fertilizer (ICOF) within the Kenyan context, emphasizing their economic viability and potential for profitability. Both Biochar and ICOF present considerable environmental and agricultural benefits, such as enhanced soil fertility, reduction of waste, and carbon sequestration. Nevertheless, several challenges impede their broader adoption, including increased production costs, inadequate infrastructure, restrictive policies, and market uncertainties. The review consolidates existing literature on the economic feasibility of Biochar and ICOF, analysing the roles of key stakeholders in the value chain, such as farmers, producers, distributors, and retailers. It identifies growth opportunities through government initiatives supporting green technologies, rising demand for sustainable agricultural practices, and synergies with agroforestry. Although financial assessments suggest potential profitability, the successful commercialization of Biochar and ICOF necessitates investments in research, infrastructure development, quality control standards, regulatory frameworks, market accessibility, and the establishment of supportive policies. Research on Biochar and ICOF production in Kenya is inadequate in key areas, including infrastructure, market access, economic viability, profitability and distribution in rural regions. Cost analyses specific to Kenya and localized financial studies are also inadequate.

Keywords: Biochar, Insect-Composted Organic Fertilizer, Value Chain

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INTRODUCTION

The drive towards commercialization and the pursuit of financial sustainability plays a central role in shaping agricultural innovations, especially in developing nations such as Kenya. There has been tremendous progress towards sustainable agricultural practices in the recent years. Issues such as soil degradation, waste management and agricultural productivity have taken centre stage. Biochar and insect-composted organic fertilizers (ICOF) are some of the emerging technologies which could potentially provide a solution to soil degradation and waste management. Biochar, which is nothing more than charcoal produced from pyrolysis, has proved to improve soil health and also sequester carbon [1]. ICOF is a method of converting organic waste into high quality fertilizers using larvae of black soldier flies, which are efficient and environmentally friendly methods of converting food waste into high quality fertilizer [2].

Biochar and ICOF technologies can be beneficial for smallholder farmers in Kenya as they make soil fertility better and minimize the use of synthetic fertilizers, thus contributing to sustainable waste management [3]. Despite the benefits of both technologies to the environment as well as to the economy, there is still a considerable research gap on their commercial viability in Kenya. Thus, this article fills that gap by reviewing the existing literature on the commercialization of Biochar and ICOF in Kenya to assess the profitability of their production and sale.

RESEARCH PROBLEM

Financial feasibility studies have been conducted in many countries on Biochar and ICOF production. Kizito and Muwanga [24] examined the feasibility of producing Biochar from food and beverage waste in Kenya, focusing on the TakaChar technology. The results showed that Biochar production could be a profitable venture, especially in urban areas where waste management and agricultural productivity are pressing concerns. They found out that although Biochar's initial investment costs are higher than those of synthetic fertilizers, the long-term financial benefits include improved soil fertility, increased agricultural yields, and environmental sustainability through carbon sequestration.

Furthermore, Biochar's ability to reduce dependency on chemical fertilizers and improve soil water retention made it a promising investment. Not many studies have explored the integration of Biochar and ICOF with other sustainable agricultural practices like agroforestry or conservation tillage. Future research could investigate the potential benefits of combining these technologies with some of the well-established practices already used by Kenyan farmers. Such studies as those by [2] and[3]. indicate that waste management plays a crucial role in Biochar and ICOF production, but little is known about how local waste management systems in Kenya can be effectively utilized to supply feedstock for these technologies. Research may attribute to optimizing waste collection, processing, and logistics to embrace sustainable supply chains and profitability.

Although financial analyses like those by [4] have been conducted, there's a need for more comprehensive, long-term financial modelling that considers the unique conditions in Kenya. Research could explore how market changes, policy shifts, and scaling up production might affect the financial sustainability of these technologies over time. There is a notable gap in research regarding the infrastructure and market access for Biochar and ICOF production in Kenya, particularly in rural areas, where distribution networks, storage facilities, and market channels need further exploration. Cost analysis specific to Kenya is also lacking, requiring localized financial studies to assess the economic viability of these technologies.

Adoption of Biochar as a soil amendment is slow around the world, due mainly to lack of field-scale data on crop response, soil quality, and environmental footprint. Mukherjee & Lal [5] note that Biochar has been touted as some sort of panacea for improving soil quality, sequestering carbon, and increasing agricultural yields but studies from laboratories and greenhouses have however produced quite inconclusive results and extremely at times contradictory results. Negative attributes for Biochar include unfavourable changes in soil properties and reduced crop yields with the evidence including reduced yields in several crops namely rice, wheat, maize, lettuce, and tomato; Biochar-amended soils also have shown increased gaseous emissions of CO_2, CH_4, and N_2O.

SIGNIFICANCE OF THE STUDY

This study is important because it looks closely at how Biochar and insect-composted organic fertilizer (ICOF) can be turned into viable commercial products in Kenya, where both research and financial assessments on these technologies are still limited. Synthesizing existing research offer policymakers, investors, and development practitioners' actionable guidance for designing interventions that promote sustainable agriculture, unlock new market opportunities, and support inclusive green growth.

LITERATURE REVIEW

Theoretical Framework

The commercialization of biochar and insect-composted organic fertilizer (ICOF) can be understood through several established theories in economics and finance. Coase [6] in his **Theory of the Firm**, illustrates why firms exist and how they weigh the trade-offs between production costs and potential profits. Applied to biochar and ICOF, this theory explains the motivation for producers to optimize operations and seek efficiency in order to remain competitive within the agricultural sector. Complementing this perspective, Brealey, Myers, and Allen [7] through **Capital Budgeting and Investment Theory**, provide practical tools for evaluating investment viability. Financial techniques such as Net Present Value, Internal Rate of Return, and Payback Period enable investors and policymakers to determine whether ventures in sustainable fertilizer production can yield worthwhile long-term returns relative to the resources committed.

Barney [8] in the **Resource-Based View theory** ,emphasizes the role of unique and hard-to-replicate resources in building sustainable competitive advantage. In the Kenyan context, Biochar and ICOF represent such distinctive inputs, enabling firms to innovate and differentiate themselves within the fertilizer market. The societal contributions of biochar and ICOF are best framed through Pigou [9] in his **Public Goods and Externalities Theory**. This perspective highlights how benefits such as improved soil fertility, carbon sequestration, and waste reduction extend beyond individual producers to the wider community. Because markets often undervalue such positive spillovers, public policies and incentives become critical in promoting commercialization. Adoption trends are further explained by Rogers [10] in the **Diffusion of Innovation Theory**, which describes how new technologies are gradually taken up depending on factors such as cost, perceived effectiveness, and institutional support. This is particularly relevant in understanding how Kenyan farmers and agribusinesses integrate sustainable fertilizers into their practices.

The coordination challenges that arise across the value chain are captured by Williamson [11] in his **Transaction Cost Economics Theory**. This theory explains how transaction costs occur when multiple stakeholders such as farmers, processors, distributors, and retailers interact within a production system. Reducing these costs through effective contracts, reliable infrastructure, and supportive institutions can enhance both efficiency and profitability. Collectively, these theories provide a comprehensive framework for analysing the financial feasibility, competitive dynamics, and broader societal implications of commercializing sustainable fertilizers in Kenya.

Biochar Production and Properties

Biochar is produced through a process called pyrolysis, which involves heating organic material in the absence of oxygen. This process creates a stable, carbon-rich substance that can be used to improve soil health. The feedstocks for Biochar production are often agricultural residues, like leftover crop materials [1]. Studies have shown that Biochar can boost soil fertility, improve moisture retention, and help sequester carbon, offering notable environmental benefits [12] It has also been found to increase soil pH, reduce greenhouse gas emissions, and enhance crop yields [13]. In Kenya, Biochar production mainly relies on agricultural waste from crops such as maize, sugarcane, and tea, making it a valuable solution for both waste management and soil improvement [13].Biochar has a wide range of applications, including its use in energy generation, as a soil amendment, and in carbon sequestration. The characteristics of Biochar, such as its chemical composition, physical traits, and reactivity, are influenced by both the type of feedstock used and the pyrolysis process itself, particularly the temperature at which it is produced [14].

Biochar has the potential to generate economic value in a variety of ways. One of the most promising opportunities comes from the global carbon market, where Biochar can earn carbon credits because it helps sequester carbon dioxide [12]. In Kenya, Biochar has been shown to improve soil health by making essential nutrients more available and encouraging plant growth [13].This dual benefit as both a soil amendment and a potential source of carbon credits makes Biochar an appealing product for international markets [15].However, the viability of Biochar production in Kenya depends on factors like the availability of feedstocks and the cost of acquiring the necessary pyrolysis equipment [16].Biochar's ability to sequester carbon and boost soil fertility has generated growing interest in its commercial potential. Biochar holds promise for applications in wastewater treatment and environmental cleanup, further driving its appeal for commercial production [17].Gopinath et al [18] emphasize that successful commercialization of Biochar will require optimization of feedstock and processing conditions, along with thorough techno-economic analyses and life cycle assessments. The authors suggest exploring regeneration and reuse of spent char, as well as its potential applications in soil improvement, microbial fuel cells, and plant growth, to enhance both sustainability and economic viability.

Insect-Composted Organic Fertilizer (ICOF)

Insect-composted organic fertilizer (ICOF) is made by using black soldier fly larvae to break down organic waste. These larvae transform waste materials like food scraps into nutrient-rich compost and protein, which can then be used as organic fertilizer or animal feed [2]. ICOF holds great potential in Kenya, helping to address both food waste management and the growing need for organic fertilizers [3].It's packed with essential nutrients like nitrogen, phosphorus, and potassium, making it a valuable alternative to synthetic fertilizers [3].

ICOF offers several environmental benefits, such as reducing organic waste and decreasing reliance on synthetic fertilizers, which can harm the environment [19], [20] , [21]. Its economic potential is tied to the global demand for organic fertilizers, which are becoming more popular due to their eco-friendly properties. Additionally, the larvae themselves can be sold as animal feed, providing an extra revenue stream for ICOF producers. However, scaling up ICOF production is still a challenge, due to factors like feedstock availability, high startup costs, and market access [2]. From a financial perspective, ICOF production can be very profitable, as it relies on low-cost feedstock (organic waste) to create a high-value product (fertilizer and protein for animal feed), with growing market demand [22]. Challenges remain in scaling up production, particularly with large-scale waste processing and ensuring consistent product quality.

Value Chain Analysis

The value chains for both Biochar and ICOF involve several key players, including farmers, producers, distributors, and retailers. For Biochar, farmers provide agricultural residues, which are then processed by producers using pyrolysis units. The final Biochar product is either sold to farmers or agricultural companies, or used to generate carbon credits [23],[1]. In the case of ICOF, the value chain includes waste collectors who supply organic waste, insect larvae producers who convert the waste into fertilizer and insect protein, and marketers who distribute the finished products to farmers, cooperatives, and retailers [3].

Much of the past research on Biochar and insect-based organic fertilizers (ICOF) has concentrated on analyzing the financial aspects of these technologies, including capital and operating costs, to assess their feasibility. Both Biochar and ICOF production require significant capital investments in infrastructure, such as pyrolysis equipment for Biochar and insect farming facilities for ICOF. These upfront costs can be a challenge for smallholder farmers and entrepreneurs .Operating costs for both technologies also include expenses related to feedstock procurement, labor, and equipment maintenance. For Biochar, the feedstock is agricultural waste, while ICOF requires organic waste collection and transportation [2]. Additionally, costs related to transportation, storage, and marketing must be considered, as they are crucial for ensuring financial sustainability and reaching end-users.

Revenue analysis for both Biochar and ICOF suggests that they can generate income through the sale of products like organic fertilizer, insect protein for animal feed, and carbon credits [3],[12]. Financial viability is typically assessed using indicators like Net Present Value (NPV), Internal Rate of Return

(IRR), and Payback Period, with sensitivity analyses conducted to account for fluctuations in feedstock costs, market prices, and government incentives. Beyond the financials, these technologies offer significant economic and environmental benefits, such as creating jobs, improving soil health, and sequestering carbon. These contributions align with Kenya's broader agricultural and environmental strategies, supporting sustainable development goals [13].

There are several challenges within the value chains, such as the limited availability and high cost of feedstock, limited access to financing, high capital investment needed for production infrastructure and limited market access for small-scale producers. Despite these challenges, the increasing demand for sustainable agricultural practices in Kenya and the rising popularity of organic fertilizers create opportunities for both Biochar and ICOF producers. Government policies supporting green technologies and waste management could help facilitate the commercialization of these value chains . .Additionally, there are opportunities to integrate Biochar and ICOF production with existing agricultural practices like agroforestry and integrated pest management. This could create synergies that boost profitability for producers while supporting more sustainable farming methods.

METHODOLOGY

The methodology for this review article involved conducting a thorough literature search across databases like Google Scholar, Scopus, and Web of Science. Studies were selected based on their focus on Biochar, ICOF, and the financial aspects of these technologies in Kenya. Key criteria for inclusion were peer-reviewed articles, case studies, and financial analyses. The data gathered included information on production methods, environmental and economic benefits, value chain dynamics, and financial performance indicators.

RESULTS AND DISCUSSION

Financial Feasibility of Biochar Production

The capital costs for Biochar production primarily involve the purchase of pyrolysis equipment, setting up processing facilities, and covering initial setup expenses, such as acquiring land and utilities. On the operational side, both Biochar and ICOF production incur costs related to feedstock procurement, labour, energy, and maintaining equipment. For Biochar, feedstock is typically sourced from agricultural waste, while ICOF relies on organic waste, which can add extra costs for collection and transportation [2]. Labor is another important cost factor, as skilled workers are required for both Biochar production and insect farming. Transportation, storage, and marketing costs also play a significant role in the financial picture. Having effective distribution channels, such as partnerships with agricultural retailers or cooperatives, is essential to ensure the products reach the end-users.

In Kenya, Biochar production often involves the pyrolysis of agricultural residues like maize cobs, sugarcane bagasse, and sawdust [13].The production process requires a pyrolysis unit, which can range from simple, small-scale kilns to more sophisticated, large-scale gasification systems. The choice of technology impacts both the efficiency of production and the overall cost structure.

Several studies have underscored the potential benefits of Biochar in improving soil health in Kenya. For example, Biochar has been shown to boost soil fertility, increase crop yields, and enhance water retention, benefits that can make a big difference for smallholder farmers [12]. Furthermore, Biochar production offers the added advantage of carbon sequestration, which contributes to climate change mitigation efforts [1]. The financial feasibility of Biochar production in Kenya has been the subject of multiple studies, which have explored costs, potential revenues, and overall profitability. Some research focuses on the economic viability of Biochar production using specific feedstocks, while others take a broader look at the financial landscape of the industry as a whole.

Munyasi et al. [13] conducted a study on the potential for Biochar production from agricultural residues in Kenya. The research found that while Biochar production could be financially feasible in the long run, the high initial capital costs for purchasing pyrolysis units were a significant hurdle for small-scale farmers. The study suggested that financial subsidies or government incentives could help reduce these upfront costs and make the venture more profitable for farmers.

Sirin and Atalay [15] also assessed the profitability of Biochar production in East Africa, including Kenya. Their analysis revealed that Biochar production could be profitable, especially if operations were scaled up. They pointed out the opportunity for increased revenue from selling Biochar as a soil amendment, as well as the possibility of generating carbon credits from the carbon sequestration capabilities of Biochar. However, the study highlighted the challenges posed by the lack of infrastructure and market development for Biochar in Kenya.

Kizito and Muwanga [24] focused on the economic analysis of Biochar production from sugarcane bagasse in Uganda, a country with similar agricultural and economic conditions to Kenya. They found that Biochar production from sugarcane bagasse was economically viable, with the potential for significant returns on investment. The study emphasized the need for cost-effective feedstock collection, the right pyrolysis technology, and efficient distribution systems to ensure profitability.

Van der Werf and Weststrate [23] conducted an analysis of the economic feasibility of Biochar production in developing countries, including Kenya. Their study underscored the importance of economies of scale for making Biochar production financially viable. They concluded that while Biochar production is technically feasible, it requires substantial capital investment and government support to become a commercially sustainable industry.
Financial analyses of Biochar production in Kenya indicate that while the initial capital costs for setting up pyrolysis units are high, the profitability of Biochar production increases as operations grow in scale. According to Sirin and Atalay [15],Biochar production from agricultural residues can be economically viable when large-scale production is implemented. Additionally, carbon credit opportunities add a valuable revenue stream, which enhances the financial appeal of Biochar production [1].

The financial feasibility of Biochar production in Kenya is heavily influenced by feedstock availability and costs. Agricultural residues like maize cobs, sugarcane bagasse, and crop residues are abundant across Kenya, making them an attractive resource for Biochar production. However, while these materials are readily available, there are significant challenges related to their collection, transportation, and storage. These costs are particularly high in rural areas, where transportation infrastructure is lacking, and moving bulky agricultural waste can be prohibitively expensive [13].The seasonal nature of agricultural waste availability also poses a challenge, as feedstock supplies fluctuate with harvest periods, causing inconsistencies and price volatility. This seasonality can complicate financial planning and affect the profitability of Biochar production.

The capital costs for establishing a Biochar production facility are another significant factor impacting the financial viability of Biochar in Kenya. Costs vary depending on the scale of production and technology used. Small-scale producers may opt for low-tech kilns, which are more affordable initially but less efficient, leading to higher operational costs in the long term. Larger-scale gasification systems, which offer higher efficiency and better economies of scale, require a much larger upfront investment. For smallholder farmers or entrepreneurs, this can be a major barrier to entry [23]. Therefore, the choice of production technology is critical, as it directly influences both initial investment costs and long-term operational expenses.

Revenue generation is another key factor in determining the financial feasibility of Biochar production. The demand for Biochar is closely tied to the growing interest in organic farming and sustainable agricultural practices. Biochar has been recognized for its benefits, such as improving soil fertility, water retention, and crop yields, making it an attractive option for farmers seeking alternatives to synthetic fertilizers[15]. However, despite these advantages, the market for Biochar in Kenya remains underdeveloped. One of the primary challenges is the relatively high cost of Biochar compared to conventional fertilizers, which makes it difficult for smallholder farmers to justify the expense. Additionally, there is limited awareness among farmers about the long-term benefits of Biochar, which further hampers its adoption. Without a strong market demand, Biochar producers may struggle to sell enough products to sustain their operations, making it challenging for the industry to become financially viable in Kenya.

Carbon credits represent another potential revenue stream for Biochar producers in Kenya. Since Biochar production contributes to carbon sequestration, producers can potentially sell carbon credits as part of global efforts to mitigate climate change. However, the process of obtaining carbon credits is complex, costly, and time-consuming. It involves meeting rigorous verification and certification requirements, which can be a barrier for smaller producers. Furthermore, the carbon credit market in Kenya is still developing, and it remains uncertain whether Biochar producers will consistently generate significant revenue from this source in the short term. While carbon credits offer a promising financial incentive, they are unlikely to provide a major revenue stream without substantial investment in the necessary infrastructure and regulatory support.

Transportation costs play a crucial role in determining the economic feasibility of Biochar production. Palma et al. [25] found that Biochar's net present value increases when mobile pyrolysis units are relocated less frequently. Studies by Harsono et al. [26] and Shabangu et al. [27] showed that Biochar production can be economically viable if feedstock costs are controlled and if pyrolysis technologies are cost-efficient.

The lack of infrastructure and market development remains a major challenge for the commercialization of Biochar in Kenya. Effective infrastructure is essential to ensure a reliable and efficient supply chain, from collecting feedstock to distributing finished products. In many rural areas, poor road conditions, limited transportation options, and inadequate storage facilities contribute to high costs and delays. Moreover, the Biochar market in Kenya is still emerging, with a lack of awareness among both consumers and producers. To overcome these barriers, investments in infrastructure and efforts to raise awareness about the benefits of Biochar are critical. Developing a reliable market and distribution network will be essential for ensuring the long-term success and profitability of Biochar production in Kenya [24].

Financial Feasibility of ICOF Production

The production of Insect-Composted Organic Fertilizer (ICOF) in Kenya presents a promising yet complex economic opportunity, particularly for addressing waste management challenges and enhancing sustainable agricultural practices. ICOF production utilizes organic waste, such as food scraps and agricultural residues, which are processed by insects typically Black Soldier Fly larvae into nutrient-rich compost. This process not only manages waste but also provides a valuable, eco-friendly alternative to chemical fertilizers. However, several factors influence the financial feasibility of ICOF production, including the availability and cost of feedstock, technological investments, market demand, and regulatory hurdles.

Kenya's agricultural sector generates a significant amount of organic waste, including residues like maize stalks, sugarcane bagasse, and food scraps from urban areas [3].The availability of these feedstocks creates a substantial opportunity for ICOF production. However, the cost of acquiring and transporting organic waste can be high, especially in rural areas with underdeveloped infrastructure. Seasonal fluctuations in the availability of certain organic materials further complicate feedstock procurement. Despite these challenges, Kenya's abundant organic waste represents a low-cost resource for ICOF producers if transportation and logistics issues can be addressed. Establishing ICOF production facilities requires significant investment in insect farming infrastructure, including systems for rearing insects, processing waste, and ensuring proper composting conditions. While the Black Soldier Fly is highly efficient at converting organic waste into protein-rich larvae and compost, the initial costs for setting up such operations can be a barrier for small-scale farmers and entrepreneurs [2]. Smaller operations may mitigate some of the costs by using simpler, low-tech systems, though these may not be as efficient or scalable as more advanced technologies. Operational costs, such as labor, energy, and maintenance, also vary depending on the scale and type of technology used. Therefore, small-scale producers may face financial challenges in accessing the most efficient systems, which could affect profitability.

The demand for organic fertilizers is on the rise globally, driven by the negative environmental effects of synthetic fertilizers and growing interest in sustainable farming [19].In Kenya, the increasing adoption of organic farming practices suggests a potential market for ICOF. However, ICOF products are often more expensive than traditional fertilizers, posing a challenge for widespread adoption, particularly among smallholder farmers who may have limited financial resources. Additionally, there is a lack of awareness about the long-term benefits of organic fertilizers, which could hinder market development. A key factor in increasing demand will be raising awareness and educating farmers on the advantages of ICOF for soil health, crop yields, and overall sustainability.

Another potential source of income for ICOF producers is carbon credits. The recycling of organic waste through ICOF production helps reduce methane emissions from landfills and sequesters carbon in the compost, which could qualify producers for carbon credits[1]. However, the process for registering ICOF projects and selling carbon credits is complex, time-consuming, and costly, which may deter smaller producers from participating. While the carbon credit market in Kenya is still emerging, it holds potential as a long-term financial incentive for ICOF producers, though it is unlikely to provide immediate returns.

Inadequate infrastructure, particularly in rural areas, presents a significant challenge for ICOF producers. Poor roads, limited transportation options, and inadequate storage facilities can increase logistics costs and hinder efficient feedstock collection and distribution [24]. Additionally, Kenya's regulatory framework for organic waste management and fertilizer production is still developing, and producers may struggle to navigate the necessary permits and certifications. A lack of clear policies and government support further complicates the situation. Investment in infrastructure and clearer regulations would help reduce these barriers and improve the financial viability of ICOF production.

ICOF production offers several economic and environmental benefits, such as increasing farm income, improving soil health, reducing reliance on synthetic fertilizers, and recycling organic waste. Insects like the Black Soldier Fly are efficient at converting waste into high-quality compost.However, for ICOF production to reach its full potential, more research is needed on quality control, the development of value-added products, and the integration of ICOF into existing agricultural systems. Proper scaling, along with government support and regulatory improvements, could enable ICOF to become a sustainable and profitable industry in Kenya.

The financial feasibility of ICOF production in Kenya hinges on overcoming several obstacles, including high initial investment costs, logistical challenges related to feedstock collection and transportation, and the underdeveloped market for organic fertilizers. Despite these challenges, the availability of organic waste, increasing interest in organic farming, and the potential for carbon credits provide significant opportunities for growth. With proper investments in technology, infrastructure, and market development, ICOF production could become a financially viable and sustainable industry, offering both economic and environmental benefits for Kenya's agricultural sector. Further research into cost-reduction strategies, market expansion, and regulatory frameworks will be essential to ensure the long-term success of ICOF production in Kenya.

Comparison of Profitability of ICOF and Biochar

In recent years, both Biochar and Insect-Composted Organic Fertilizer (ICOF) have emerged as sustainable alternatives to conventional chemical fertilizers in Kenya, offering benefits like improved soil health, waste management, and carbon sequestration. While both products show promise, their profitability depends on various factors such as feedstock availability, technology costs, market demand, and infrastructure. A key factor affecting the profitability of both Biochar and ICOF is the cost and availability of feedstock. For Biochar, raw materials like agricultural residues (maize cobs, sugarcane bagasse, and other crop residues) are abundant in Kenya, making it relatively inexpensive to source feedstocks [13].However, costs can increase when factoring in collection, transportation, and storage. Furthermore, since agricultural residues are seasonal, prices can fluctuate, leading to inconsistent feedstock supply. ICOF production, on the other hand, relies on organic waste, such as food scraps, vegetable peels, and manure, which are readily available in urban areas. However, the cost of collecting and transporting this waste can be significant, and maintaining a steady supply of Black Soldier Fly larvae adds further costs. Both Biochar and ICOF face challenges related to feedstock consistency and logistics, which can impact their overall profitability [2].

The technology required for both Biochar and ICOF production plays a major role in determining profitability. Biochar production involves pyrolysis or gasification systems. Small-scale producers may use basic kilns or traditional methods, but larger operations use advanced and more efficient pyrolysis systems, which require a significant initial investment [1].These larger systems, while more efficient, also have higher energy and maintenance costs, which can reduce profitability. The supply of feedstock for Biochar may also be inconsistent, which affects large-scale production. In contrast, ICOF production depends on insect farming, specifically Black Soldier Fly larvae, and requires specialized infrastructure such as rearing units, processing plants, and drying systems [3]. Though ICOF production also demands high initial investment, it can have lower operational costs due to the high efficiency of the insect larvae in converting organic waste. Nevertheless, scaling up ICOF production may require investment in automation and advanced technologies, raising operational costs. Both Biochar and ICOF face high capital investment requirements, but ICOF's lower operational costs could offer a financial advantage in the long run due to the efficiency of the insect larvae.

Market demand is a critical factor in the profitability of Biochar and ICOF in Kenya. Biochar has gained recognition as a soil amendment that enhances soil fertility, improves water retention, and reduces dependency on chemical fertilizers. As organic farming practices gain popularity, the demand for Biochar as a more sustainable alternative to chemical fertilizers has grown [15].However, Biochar is typically more expensive than chemical fertilizers, making it less accessible to smallholder farmers, which limits its market penetration. Despite this, Biochar's potential benefits for soil health and the increasing focus on sustainable agriculture support its long-term profitability in Kenya. ICOF, meanwhile, is also growing in popularity as an organic fertilizer, particularly with the rise of organic farming. ICOF is marketed as a sustainable, nutrient-rich option for enhancing soil health and boosting crop yields. Yet, like Biochar, ICOF's higher cost compared to synthetic fertilizers and a general lack of awareness about its benefits pose challenges. Building awareness and educating farmers will be key to increasing ICOF's market share in Kenya [15].As the market for organic farming grows, ICOF could see significant revenue potential in the coming years.

Both Biochar and ICOF offer the potential for generating revenue through carbon credits. Biochar is known for its ability to act as a carbon sink, storing carbon in the soil and mitigating climate change. As a result, Biochar producers in Kenya can register their projects for carbon credits, which could be sold on international markets. However, obtaining carbon credit certification is costly and time-consuming, and the carbon credit market in Kenya is still developing, so the revenue potential is uncertain [1]. ICOF production also has carbon credit potential through waste diversion and methane emission reductions. However, the carbon credit potential for ICOF remains less explored compared to Biochar, and the certification process for ICOF producers could be challenging [2]. Although both Biochar and ICOF offer carbon credit opportunities, Biochar's established position in the carbon market provides a more predictable revenue stream in the short term.

The profitability of Biochar and ICOF production in Kenya is shaped by several factors, including feedstock availability, technological and capital investments, market demand, and carbon credit opportunities. Biochar is well-recognized for its soil and environmental benefits but faces challenges related to high production costs and limited market adoption. ICOF, though still growing in recognition, offers lower operational costs and presents significant market opportunities as organic farming expands. Both products require substantial initial investment and face similar challenges around feedstock availability and market penetration. However, ICOF production could potentially be a more cost-effective long-term solution due to its operational efficiency, offering a quicker return on investment compared to Biochar's higher capital investment and long-term profitability through carbon sequestration.

Sanergy's 2024 feasibility study assessed the practicality of transforming food and beverage waste into biochar within Kenya, highlighting both the opportunities and challenges of commercialization. The study proposed a modular, scalable facility capable of producing over 800 tonnes of biochar annually. The evaluation combined iterative design processes, vendor assessments, and detailed financial modeling that included financing costs, offering evidence of a pathway toward long-term operational viability. In addition, it emphasized that issues of equipment reliability and biochar quality must be resolved before large-scale deployment can be considered feasible [28].

Ageconsearch [29] looked at the economic costs and benefits of Black Soldier Fly (BSF) farming in Kenya indicated that insect farming for protein and fertilizer production is economically viable. The study found that small-scale BSF farming could generate significant revenue, even in scenarios with varying input costs and output prices. Sensitivity analysis revealed that BSF farming remains profitable despite fluctuations in market conditions. The use of BSF larvae for ICOF production further enhances profitability by reducing waste management costs and offering a sustainable, organic alternative to chemical fertilizers. Some studies have touched on the role of policy and focussed less on commercialisation for example, Ackerman & Smith, [30]. Additional research would also be needed to explore how potential incentives such as subsidies, tax breaks, and carbon credits could affect the growth and commercialization of Biochar and ICOF industries in Kenya. There is limited research on how Biochar and ICOF production might benefit smallholder farmers in Kenya with regard to improving their income generation and employment as well as improving productivity in agriculture.

Zeng and Xu [31] looked into how practical it is to produce biochar and pointed out Biochar both a soil enhancer and a way of locking carbon in the ground. They noted, however, that turning this potential into widespread use is not straightforward, since the process is still weighed down by high production costs, technical hurdles, and limited policy support. Their work suggests that for biochar to become commercially viable, efforts need to focus on lowering costs, making pyrolysis technologies more efficient, and building stronger regulatory and market structures that can support adoption.

LIMITATIONS OF THE STUDY

The research leaned heavily on existing literature and secondary reports, with very little data gathered directly from the field. While this approach helped in pulling together what is already known, it may not fully capture the day-to-day realities of smallholder farmers or reflect the subtle trade-offs they face when adopting new practices. The scope of the study is quite specific. It focuses mainly on the Kenyan agricultural landscape and therefore the conclusions may not translate perfectly to other regions that operate under different social, economic, or policy conditions. In addition, the technologies being studied Biochar and insect-composted organic fertilizer (ICOF) are still relatively new and evolving. As innovations continue to refine the production process, both the costs and the environmental outcomes may shift, which could alter some of the insights presented here. Economic projections made in this study should also be read with caution. Markets are rarely stable, and issues such as fluctuating input prices, changes in consumer demand, and shifts in government policy can all influence profitability and adoption levels in ways that are difficult to predict. Furthermore, some of the recommendations assume improvements in infrastructure and policy support, which in practice may take much longer to come into effect. Elements such as local beliefs, cultural attitudes, and personal motivations for either embracing or resisting innovation were outside the scope of this analysis. These human perspectives are crucial, and future studies could benefit from exploring them more deeply to build a clearer, people-centred understanding.

CONCLUSION

The commercialization of Biochar and insect-composted organic fertilizer (ICOF) in Kenya presents a promising avenue for sustainable agricultural development, offering environmental, economic, and agricultural benefits. While both technologies can be profitable, their widespread adoption is constrained by challenges such as high production costs, inadequate infrastructure, and limited market access. Financial analyses suggest that economies of scale, along with sufficient market demand, can make both Biochar and ICOF production viable. However, substantial investments are needed to overcome these barriers, including funding for research, infrastructure improvements, and the establishment of supportive policies. Policymakers should consider incentivizing the industry through subsidies, tax breaks, and carbon credit systems to enhance the profitability and long-term viability of these technologies. Future research should focus on addressing key challenges, including optimizing production methods, developing quality control standards, and exploring synergies with other sustainable agricultural practices. Enhanced support for the commercialization of Biochar and ICOF could significantly contribute to Kenya's agricultural and environmental sustainability goals.

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