OPEN ACCESS

IJABR

International Journal of Advanced Biotechnology and Research (IJABR)
ISSN 0976-2612, Online ISSN 2278–599X,
Vol-16, Issue3, 2025, p-01-19

DOI: 10.5281/zenodo.15867394

Review Article

Comprehensive SWOT analysis of cotton stalk compost

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Abstract

Cotton is one of the major crops of India and the country occupies first place among cotton growing countries of the world. Cotton stalk is one of the important byproducts of the cotton crop, cotton stalk agricultural waste is a serious environmental issue. The cotton stalk is either abandoned or burned, which results in the formation of toxic gases and ash content, thus contaminating the environment. Composting cotton stalks is an effective method to manage this waste and improve soil health. The management of agricultural and crop residues is an essential component of modern farming and sustainable development. Proper handling, processing, and utilization of waste generated from agricultural activities, including cotton stalks, play a crucial role in reducing environmental impact. Cotton stalks, a major byproduct of cotton cultivation. However, with effective management, they can be converted into valuable resources such as bio-compost for soil enrichment or biofuel for energy production. However, various factors influence the viability and effectiveness of cotton stalk composting. This review article provides a comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of cotton stalk compost, discussing its benefits, limitations, potential market opportunities, and challenges. Understanding these aspects can help stakeholders, including farmers, researchers, and policymakers, to make informed decisions about adopting cotton stalk composting as a sustainable agricultural practice.

Keywords Cotton stalk, Compost, Strength, Weakness, Opportunities, Threats.

Article Info

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Received: 05/06/2025
Accepted: 07/07/2025
Published: 10/07/2025

DOI: 10.5281/zenodo.15867394

Background

Cotton (*Gossypium hirsutum* L.) is a vital fiber-producing cash crop that plays a crucial role in the textile industry and the overall economy. In India, the cotton-based textile sector is the second-largest source of employment, accounting for approximately 5% of the country's GDP, 14% of industrial output, and 11% of total export revenue [74,75]. Cotton stalks are the leftover biomass from cotton harvesting. The amount of cotton stalk produced per hectare varies based on factors such as cotton variety, plant type, growing conditions (rainfed or irrigated), soil type, and climate. On average, about 3 tonnes of cotton stalks are produced per hectare in the country.

Major cotton-producing districts in Tamil Nadu include Coimbatore, Madurai, Ramanathapuram, Salem, and Tiruchirappalli. These regions have consistently contributed to the state's cotton output. There has been a notable increase in cotton cultivation across several districts in recent years. For instance, the area under cotton farming in the delta districts specifically Trichy, Tiruvarur, Nagapattinam and Thanjavur expanded from approximately 50,000 acres to about 84,000 acres, marking a 40% increase. Similarly, districts such as Perambalur, Salem, Dharmapuri, Ariyalur, Trichy, Virudhunagar, Madurai and Cuddalore have experienced a 10% rise in cotton cultivation. The increase in cotton cultivation directly correlates with a surge in cotton stalk biomass. The growing interest in sustainable agricultural practices suggests a potential uptick in utilizing cotton stalks for composting. This practice not only aids in waste management but also enhances soil fertility.

Cotton stalks, the residual biomass left after harvesting cotton, are directly proportional to cotton production. state-wise cotton production offers insights into the generation of cotton stalks across India. According to data from the Central Institute for Cotton Research (CICR).

In the Tamil Nadu Perambalur district area of cotton cultivation, around 35-40 million tonnes of cotton stalks are generated annually. However, most of this biomass is discarded as waste and burned in the fields, with only a small portion used as fuel by rural communities [38]. Cotton stalks are lignocellulosic, consisting of approximately 67.3 to 70.0% holocellulose, 24.3 to 28.2% lignin and 5.9 to 8.3% ash. Cotton is one of the most widely cultivated fiber crops, contributing significantly to the global textile industry. However, its cultivation generates vast amounts of agricultural residues, with cotton stalks being a major byproduct. These stalks are often burned or discarded, leading to environmental issues such as air pollution and soil degradation. Composting cotton stalks presents an eco-friendly alternative to waste management, promoting sustainability and enhancing soil health [23].

Cotton stalk composting presents a sustainable approach to managing agricultural residues while enhancing soil health and reducing environmental impact. A comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis provides insights into the viability and challenges associated with cotton stalk composting [85]. The strengths of cotton stalk compost include its nutrient enrichment properties, which enhance soil fertility, organic matter content, and microbial activity. It also supports environmental sustainability by reducing waste, minimizing greenhouse gas emissions, and improving soil structure [70]. Additionally, composting provides an effective waste management solution, diverting agricultural residues from landfills and preventing air pollution caused by burning [84]. However, weaknesses such as the slow decomposition rate of cotton stalks due to high lignocellulosic content and the risk of pest and disease carryover pose challenges to widespread adoption. High labor and processing costs, along with limited awareness among farmers, further hinder its large-scale implementation [51].

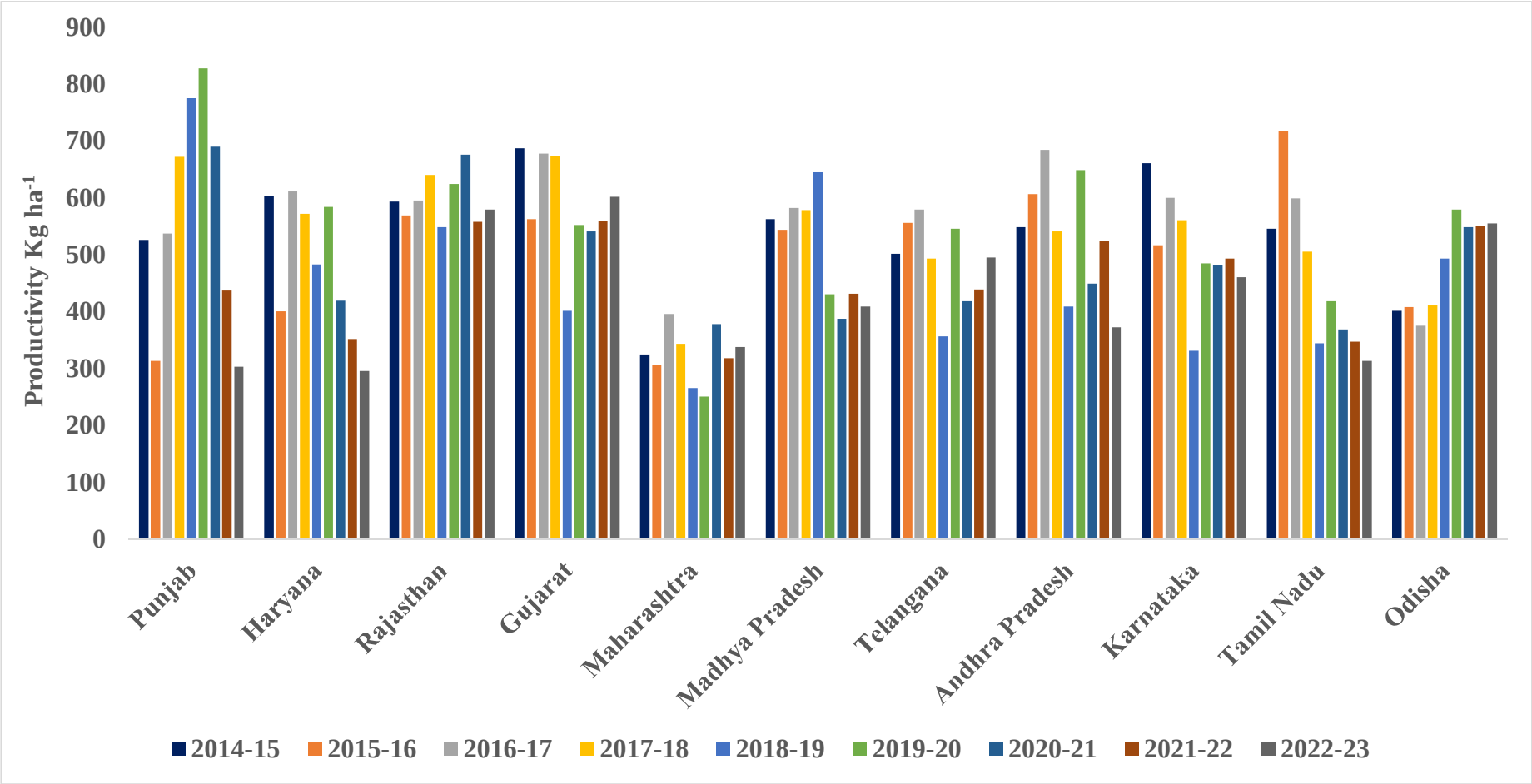

Fig 1: State wise cotton productivity (kg ha^{-1}) from 2014-15 to 2023-24

(Note: One lakh bale equals 100,000 bales; 'P' denotes provisional

Cotton stalk composting arise from the rising demand for organic farming, government policies promoting sustainable agriculture, and the potential for commercialization. The increasing global focus on climate change mitigation and soil restoration further supports the adoption of composting practices as an eco-friendly alternative to synthetic fertilizers [35].

Despite its benefits, threats such as competition from chemical fertilizers, fluctuating market demand for compost, and the presence of alternative biomass utilization methods could limit its growth. Additionally, regulatory constraints and inadequate composting infrastructure in certain regions may pose challenges to scaling up production [88].

Table 1 Specific characteristics of cotton stalk for composting

Category	Characteristics
Physical Properties	Woody, fibrous and branched structure
Height	0.8 - 2 meters
Diameter	1 - 3 cm
Color	Brownish
Moisture Content	Fresh: 50-60%, Dry: 10-15%
Density	0.3 – 0.5 g cm^{-3} (varies with moisture content)
Chemical Composition	Cellulose: 40-50% Hemicellulose: 15-25% Lignin: 20-30%
Ash Content	1 - 3% (Contains minerals like silica, calcium and magnesium)
Calorific Value	3,500 - 4,500 kcal kg^{-1}
Nutrient Composition (For Composting)	C: N Ratio: 50:1 Nitrogen: 0.3-0.6% Phosphorus: 0.02-0.1% Potassium: 0.4-0.8%
Decomposition Rate	Slow due to high lignin content; requires shredding and microbial inoculation for faster composting
Mechanical Properties	Brittle when dry High bulk density Moderate tensile strength
Composting Suitability	Acts as a carbon-rich (brown) material in composting - Requires nitrogen-rich sources (e.g., animal manure, green leaves) for balanced decomposition - Shredding increases surface area and speeds up microbial activity - Effective microorganisms (EM), Trichoderma, or fungal cultures can enhance breakdown
Time Required for Composting	4-6 months (Can be reduced with proper aeration, moisture control, and microbial additives)
Alternative Uses	Biofuel: Used in making briquettes, pellets and biochar Pulp & Paper Industry: An alternative to wood pulp Fiber board & Particle Board: Eco-friendly construction material Mushroom Cultivation: A good substrate for growing oyster mushrooms

The management of agricultural and crop residues is an essential component of modern farming and sustainable development. Proper handling, processing, and utilization of waste generated from agricultural activities, including cotton stalks, play a crucial role in reducing environmental impact. Cotton stalks, a major byproduct of cotton cultivation, are often discarded or burned, leading to pollution [49]. However, with effective management, they can

be converted into valuable resources such as bio-compost for soil enrichment or biofuel for energy production. A SWOT analysis helps evaluate the practicality of using cotton stalk compost in agriculture by identifying its internal strengths and weaknesses, along with external opportunities and threats.

Strengths of cotton stalk compost

1. Nutrient enrichment

Cotton stalk compost improves soil fertility by providing essential nutrients such as nitrogen, phosphorus, and potassium. It also enhances the availability of micronutrients, improving crop yield and quality. Nutrient enrichment in cotton stalk compost involves enhancing the nutrient content of compost made from cotton stalks, which are typically rich in organic material but may require additional nutrients to create a balanced, nutrient-dense compost. Cotton stalks, as plant residues, are high in cellulose but can be low in nitrogen and other essential nutrients for plant growth. To improve the nutrient profile, you can add various materials and organic amendments during the composting process [16].

Cotton stalk compost is a valuable organic amendment due to its nutrient enrichment properties, which enhance soil fertility and crop productivity. During the composting process, microbial activity breaks down the lignocellulosic structure of cotton stalks [78], releasing essential nutrients such as nitrogen, phosphorus, potassium and micronutrients like calcium and magnesium. These nutrients improve soil health and provide a slow-release fertilizer effect, reducing the need for synthetic inputs. The balanced nutrient composition of cotton stalk compost contributes to improved soil structure, water retention, and microbial diversity, which are essential for sustainable agriculture [67]. Additionally, composting enhances the bioavailability of nutrients by reducing C: N ratios, making them more accessible for plant uptake [48]. Co-composting with other organic materials or biofertilizers can further increase nutrient density and efficiency [83].

Research supports the role of cotton stalk compost in soil nutrient management. According to Hyde et al. [24], applying cotton stalk compost significantly improved soil organic carbon and increased nitrogen and phosphorus availability. Similarly, Composting cotton stalks with manure enhanced nutrient content and microbial activity, leading to better crop yields and soil fertility restoration Tomczyk et al. [77]. As a sustainable alternative to chemical fertilizers, nutrient-enriched cotton stalk compost provides a cost-effective and environmentally friendly solution for long-term agricultural productivity [9].

2. Environmental sustainability

Environmental sustainability plays a critical role in cotton stalk composting, as it promotes eco-friendly practices that benefit both the environment and agricultural systems. It protecting the environment for future generations. Environmentally sustainable organizations take steps to enhance efficiencies, reduce resource consumption and waste, and measure and monitor carbon emissions across the entire supply chain. Today, many organizations are amping up their environmental efforts by adopting sophisticated technology, which allows them to track and reduce their environmental impact [13].

Cotton stalk composting contributes to environmental sustainability by reducing agricultural waste, minimizing greenhouse gas emissions, and enhancing soil health. Instead of burning cotton stalks, which releases carbon dioxide, methane and other pollutants into the atmosphere, composting offers an eco-friendly alternative that converts waste into a valuable soil amendment [12]. This process helps mitigate climate change by promoting carbon sequestration and reducing air pollution. Furthermore, cotton stalk compost improves soil structure, increases organic matter content and enhances microbial biodiversity, improving soil fertility and water retention [61]. By reducing dependency on chemical fertilizers, composting lowers the risk of soil degradation, water contamination, and ecological imbalances caused by excessive synthetic

inputs. Furthermore, using compost as an organic amendment aligns with sustainable farming practices that promote long-term agricultural productivity and environmental conservation [42].

Research highlights the role of cotton stalk compost in sustainable agriculture. According to Li et al. [41], composting agricultural residues, including cotton stalks, significantly reduces carbon emissions and enhances soil carbon storage. Similarly, a study by Patel and Mehta [54] found that applying compost improved soil health indicators while reducing reliance on chemical fertilizers, leading to more sustainable land use. As global agricultural practices shift towards sustainability, cotton stalk composting emerges as an effective strategy to support environmental conservation and resource-efficient farming [3].

3. Waste management and reduction

Cotton stalk composting plays a crucial role in waste management and reduction by converting agricultural residues into a valuable organic amendment. Cotton production generates a significant amount of biomass waste, and improper disposal methods, such as open-field burning, contribute to air pollution and greenhouse gas emissions. Composting offers an environmentally friendly alternative, reducing agricultural waste accumulation while improving soil health [21].

By recycling cotton stalks through composting, farmers can minimize waste disposal challenges and enhance resource efficiency. The decomposition process transforms lignocellulosic material into nutrient-rich compost, reducing the need for synthetic fertilizers and lowering agricultural input costs [60]. Additionally, composting helps in managing landfills by diverting biodegradable waste, contributing to a circular economy in agriculture [18].

According to Singh et al. [73], the benefits of composting in agricultural waste management, composting cotton stalks significantly reduces biomass waste and provides an eco-friendly alternative to residue burning. Similarly, integrating composting techniques in cotton farming enhances sustainability by reducing environmental pollution and improving soil fertility and sustainable farming practices gain importance, cotton stalk composting emerges as an effective solution for waste management and agricultural sustainability [52].

4. Soil health and fertility

Cotton stalk compost offers significant benefits for soil health and fertility, making it a valuable organic amendment in sustainable agriculture. It enhances soil structure by increasing organic matter content, improving aeration, water retention and microbial activity. The gradual decomposition of cotton stalks releases essential nutrients, including nitrogen, phosphorus and potassium, which contribute to long-term soil fertility [50]. Additionally, composted cotton stalks support beneficial microbial communities that aid in nutrient cycling and suppress soil borne pathogens, reducing the need for chemical fertilizers and pesticides [62].

The lignocellulosic nature of cotton stalks, when properly composted, contributes to soil humus formation, improving cation exchange capacity and nutrient retention [63]. Furthermore, cotton stalk compost mitigates soil erosion and enhances soil carbon sequestration, supporting climate-resilient farming practices [36]. Despite these benefits, proper composting techniques, including sufficient aeration, microbial inoculation, and nitrogen supplementation, are crucial for optimizing decomposition and nutrient release. Cotton stalk composting thus represents an eco-friendly and sustainable approach to maintaining soil productivity while minimizing agricultural waste.

5. Carbon sequestration

Organic compost, including cotton stalk compost, helps sequester carbon in the soil. The breakdown of carbon-rich materials like cotton stalks releases stable forms of carbon (humus), which are stored in the soil, preventing carbon from entering the atmosphere as CO_2 [6].

Carbon sequestration is a crucial process in mitigating climate change by capturing atmospheric carbon dioxide and storing it in

organic and inorganic forms. One effective method of carbon sequestration is through composting agricultural residues such as cotton stalks [90]. Cotton stalks, a by-product of cotton cultivation, are rich in lignocellulosic materials, making them a valuable organic resource for composting. Composting cotton stalks enhances soil organic carbon content by converting plant residues into stable humic substances. The degradation of cotton stalks during composting is facilitated by microbial activity, which breaks down complex organic compounds into simpler forms, enriching the soil with nutrients and increasing its carbon retention capacity [2]. Additionally, the application of cotton stalk compost improves soil structure, water retention, and microbial diversity, further promoting soil carbon sequestration.

Studies have shown that the composting of cotton stalks leads to a significant reduction in carbon loss through CO_2 emissions compared to direct burning, which is a common disposal method in many agricultural regions. For example, research by Zhang et al. [91] highlighted that composting agricultural residues like cotton stalks results in higher soil organic matter content and enhances long-term carbon storage. Similarly, Singh et al. [72] demonstrated that compost derived from cotton stalks improves soil fertility and contributes to sustainable carbon management in agricultural systems.

Incorporating cotton stalk compost into soil management practices provides a dual benefit of waste reduction and climate change mitigation. As agricultural waste continues to be a concern, adopting composting as a strategy for carbon sequestration offers an environmentally friendly alternative to conventional residue disposal methods.

6. Reduction of chemical inputs

Cotton stalk compost plays a significant role in reducing chemical inputs in agriculture by improving soil fertility and providing essential nutrients in an organic form. The decomposition of cotton stalks during composting releases macronutrients such as nitrogen, phosphorus, and potassium, along with micronutrients essential for plant growth. This natural nutrient supply reduces the dependence on synthetic fertilizers, thereby lowering input costs and minimizing the environmental risks associated with excessive chemical use [7].

The addition of cotton stalk compost enhances soil microbial activity, which improves nutrient cycling and bioavailability. Beneficial microorganisms in compost contribute to the suppression of soil-borne pathogens, reducing the need for chemical pesticides and fungicides [31]. Furthermore, the organic matter in compost improves soil structure, water retention, and aeration, leading to healthier plant growth and reduced reliance on synthetic soil amendments.

Studies have demonstrated that the application of cotton stalk compost can significantly reduce the need for chemical fertilizers while maintaining or even improving crop yields. For example, research by Patel et al. [51] indicated that integrating cotton stalk compost with reduced fertilizer application resulted in comparable yields to conventional chemical fertilizer use while enhancing soil health. Similarly, a study by Kumar et al. [34] found that composting cotton stalks not only provided a sustainable alternative to chemical fertilizers but also improved soil microbial diversity, which plays a crucial role in long-term soil fertility management.

By incorporating cotton stalk compost into agricultural practices, farmers can reduce their reliance on synthetic inputs while promoting a more sustainable and eco-friendly farming system. This approach not only supports soil health but also helps mitigate the adverse effects of excessive chemical use on the environment.

Weaknesses of cotton stalk compost

1. Slow decomposition rate

One of the main weaknesses of cotton stalk compost is its slow decomposition rate due to its high lignocellulosic content. Cotton stalks are rich in lignin, cellulose and hemicellulose,

which are resistant to microbial degradation, leading to prolonged composting periods [17]. This slow breakdown delays the release of nutrients, making it less immediately available for crops compared to other organic amendments. The slow decomposition rate can be a limiting factor in large-scale composting operations, requiring additional treatments such as shredding, microbial inoculation, or co-composting with nitrogen-rich materials to accelerate the process. Without such interventions, the extended composting time can increase labour and operational costs, making it less attractive for rapid soil amendment needs [46].

Research has shown that the decomposition of cotton stalks can take several months if not properly managed. According to Li et al. [39], the high lignin content in cotton stalks significantly slows microbial activity, necessitating the addition of microbial consortia or nitrogen sources to enhance breakdown. Similarly, a study by Zhang et al. [89] found that composting cotton stalks with manure or green waste improved decomposition efficiency and nutrient availability but required careful monitoring of the carbon-to-nitrogen ratio. Despite its benefits, the slow decomposition rate of cotton stalk compost remains a challenge, requiring proper management techniques to optimize its effectiveness as a soil amendment.

2. High labour and processing costs

The high labour and processing costs associated with cotton stalk composting are significant challenges that can limit its widespread adoption. Cotton stalks require collection, transportation, shredding, and proper composting management, all of which demand labour and financial investment. Unlocking value [79] Unlike easily degradable organic materials, cotton stalks have a high lignin content, necessitating additional processing steps such as mechanical grinding or microbial inoculation to accelerate decomposition.

The composting process also requires consistent monitoring of factors like temperature, moisture and aeration to ensure efficient microbial activity. Without proper management, the decomposition process can be prolonged, leading to increased labour costs and resource consumption [5]. In addition, large-scale composting operations need infrastructure such as composting pits, turning machines, and water sources, further increasing capital investment. Studies indicate that the cost-effectiveness of cotton stalk composting depends on efficient processing techniques. According to Singh et al. [73], the mechanical shredding of cotton stalks before composting significantly reduces decomposition time but increases initial processing costs. Similarly, a study by [68] highlighted that integrating bio augmentation techniques can enhance decomposition but requires additional expenditures on microbial inoculants and expertise in compost management. Despite its environmental benefits, the high labour and processing costs associated with cotton stalk composting remain a barrier to its large-scale implementation, necessitating cost-effective innovations to improve its feasibility.

3. Disease and pest hazards

Cotton stalk composting poses a risk of harbouring diseases and pests if not properly managed. Cotton plants are susceptible to various fungal, bacterial, and viral pathogens, some of which can persist in plant residues. If the composting process does not reach sufficiently high temperatures, these pathogens may survive and reintroduce diseases into the soil, affecting subsequent crops [15]. Furthermore, insect pests such as bollworms can use cotton stalk residues as breeding sites, increasing infestation risks in agricultural fields [4].

Proper composting conditions, including maintaining temperatures above 55°C for an extended period, are essential to eliminate harmful pathogens and pests [80]. However, achieving and sustaining these conditions in large-scale composting operations requires careful monitoring and regular turning of compost piles, which can add to labour and operational costs. Improperly managed

compost may also attract secondary pests, further complicating pest control efforts.

Research indicates that inadequate composting of cotton stalks can contribute to disease carryover. According to Li et al. [40], cotton stalk residues can harbour *Verticillium dahliae*, a soil-borne fungus responsible for cotton wilt, if not composted under optimal conditions. Similarly, a study by Boshoven [10] found that incomplete decomposition of cotton stalks increased the risk of insect infestations in stored compost, leading to potential re-infestation of crop fields. While cotton stalk composting offers soil fertility benefits, disease and pest risks highlight the need for stringent composting management practices to ensure its safe use in agriculture.

4. Limited awareness and adoption

The limited awareness and adoption of cotton stalk composting remain significant challenges, particularly among smallholder farmers. Many farmers lack knowledge about the benefits of composting cotton stalks and continue to rely on traditional disposal methods such as burning, which is faster but environmentally harmful. The absence of widespread extension programs and training further hinders the adoption of composting techniques. Additionally, misconceptions about the effectiveness of compost compared to chemical fertilizers contribute to its low utilization [14].

Economic and logistical barriers also play a role in the slow adoption of cotton stalk composting. In regions where composting infrastructure is lacking, farmers may find it difficult to implement large-scale composting operations [82]. The initial investment required for shredding equipment, composting pits, and labour can discourage farmers, especially in resource-constrained areas. Furthermore, the absence of well-established market linkages for compost products reduces incentives for commercial-scale composting.

Studies highlight the need for improved awareness and policy support to promote cotton stalk composting. According to Kumar et al. [33], farmer training programs and government incentives have been effective in increasing the adoption of organic waste composting in some agricultural sectors. Similarly, Patel and Singh [56] found that integrating composting into sustainable farming initiatives enhances adoption rates, particularly when coupled with financial support and technical guidance. Addressing the limited awareness and adoption of cotton stalk composting requires targeted extension services, demonstration projects and policy measures that encourage farmers to embrace this sustainable agricultural practice.

Opportunities for cotton stalk compost

1. Rising demand for organic farming

The rising demand for organic farming presents a significant opportunity for cotton stalk compost as a sustainable soil amendment. Organic farming relies on natural inputs to maintain soil fertility and plant health, reducing the dependence on synthetic fertilizers and pesticides. Cotton stalk compost, rich in organic matter and essential nutrients, aligns well with these principles, making it a valuable resource for organic agriculture [50]

Cotton stalk compost enhances soil structure, increases microbial diversity, and improves nutrient availability, all of which contribute to higher crop productivity in organic farming systems. Additionally, its application helps in carbon sequestration, reducing greenhouse gas emissions compared to conventional residue disposal methods like burning, Similar studies reported by Omer [47]. With growing consumer preference for chemical-free food products, farmers are increasingly seeking organic alternatives, further boosting the demand for compost-based fertilizers.

Studies suggest that the use of compost, including cotton stalk compost, can significantly improve soil health and crop yields in organic farming. According to Sharma et al. [69], applying cotton stalk compost in organic vegetable farming increased soil organic carbon content and enhanced nutrient retention. Similarly, a study by Patel and Mehta [57,58] found that composting cotton stalks with other organic residues improved the quality of organic fertilizers, making them

more effective for sustainable agriculture. As organic farming continues to expand globally, cotton stalk compost presents an eco-friendly and economically viable opportunity for farmers and composting industries to meet the increasing demand for organic soil amendments.

2. Government policies and incentives

Government policies and incentives provide significant opportunities for promoting cotton stalk composting as a sustainable agricultural practice. Many governments are implementing policies to encourage organic farming, reduce agricultural waste, and promote environmentally friendly alternatives to chemical fertilizers. Similar finding was studied by [20]. Subsidies, grants, and tax incentives for composting infrastructure, equipment, and organic inputs make it easier for farmers and businesses to adopt cotton stalk composting.

Regulations aimed at reducing crop residue burning further drive interest in composting as an alternative disposal method. Many countries have introduced strict environmental laws and financial penalties for open-field burning, [66] pushing farmers toward sustainable solutions like composting. Additionally, government-backed training programs and extension services play a crucial role in educating farmers about the benefits of cotton stalk compost, increasing its adoption.

Research highlights the positive impact of policy support on compost adoption. According to Kumar et al. [37], subsidy programs for composting equipment in India led to a significant increase in agricultural waste recycling. Similarly, a study by Zhang and Li [86] found that financial incentives and awareness campaigns in China helped farmers transition from residue burning to composting, reducing environmental pollution and improving soil health. With continued policy support and financial incentives, cotton stalk composting has the potential to become a mainstream agricultural practice, benefiting both farmers and the environment.

3. Climate change mitigation

Cotton stalk composting presents a valuable opportunity for climate change mitigation by reducing greenhouse gas emissions and enhancing carbon sequestration in agricultural soils. Traditional disposal methods. According to [22] open-field burning of cotton stalks releases significant amounts of CO_2, methane and nitrous oxide, contributing to global warming. In contrast, composting converts cotton stalks into stable organic matter, reducing emissions while enriching soil health.

The application of cotton stalk compost improves soil organic carbon content, which enhances carbon storage and reduces atmospheric CO_2 levels. Additionally, composting promotes microbial activity, which plays a crucial role in nitrogen cycling, potentially lowering N_2O emissions from synthetic fertilizers. [28] By adopting composting practices, farmers can contribute to climate change mitigation while improving soil fertility and crop productivity.

Research supports the role of composting in reducing agricultural emissions. According to Velmourougane et al. [81], composting cotton stalks instead of burning them significantly reduces CO_2 and CH_4 emissions, making it an effective strategy for carbon management. Similarly, a study by Patel and Singh [53] found that the use of compost in farming systems lowered overall greenhouse gas emissions by improving soil structure and reducing reliance on chemical fertilizers. Climate change policies increasingly focus on sustainable agricultural practices, cotton stalk composting offers a practical and scalable solution for reducing carbon footprints in farming while promoting long-term soil health.

4. Soil restoration and land reclamation

Cotton stalk composting presents a significant opportunity for soil restoration and land reclamation by improving soil health, enhancing nutrient availability and rebuilding degraded lands. Continuous agricultural activities, deforestation, and industrial practices contribute to soil degradation, leading to nutrient depletion, loss of organic matter and

reduced fertility. [11] Cotton stalk compost, rich in organic carbon and essential nutrients, helps restore soil structure, increase microbial activity and improve water retention, making it a valuable amendment for degraded soils.

The application of cotton stalk compost enhances the biological and physical properties of the soil, promoting better root penetration and plant growth. It also plays a key role in reclaiming saline and alkaline soils by improving soil buffering capacity and increasing organic matter content, which facilitates microbial-driven nutrient cycling. [44] Additionally, composting provides a sustainable way to manage agricultural waste while simultaneously rehabilitating marginal lands.

Research supports the role of compost in soil restoration and land reclamation. According to Kacprzak, et al. [27], applying cotton stalk compost to degraded soils significantly improved organic carbon levels and enhanced soil microbial diversity. Similarly, a study by Zhang and Li [87] found that compost-amended soils exhibited better moisture retention and nutrient availability, making them more suitable for crop cultivation and afforestation efforts. With increasing concerns over land degradation and food security, cotton stalk composting offers an eco-friendly and cost-effective solution for restoring soil fertility and reclaiming unproductive lands.

5. Commercialization potential

The commercialization potential of cotton stalk compost presents a promising opportunity for sustainable agriculture and waste management. With increasing demand for organic fertilizers and eco-friendly soil amendments, cotton stalk compost can be developed into a marketable product for farmers, agribusinesses, and landscaping industries. The shift toward organic farming and sustainable land management practices further boosts the market potential for compost-based fertilizers [19].

Commercial-scale production of cotton stalk compost can generate economic benefits by creating value-added products from agricultural waste. Properly processed and packaged compost can be sold to organic farmers, horticulturalists, and urban gardening sectors, providing an alternative to chemical fertilizers. [32] Additionally, government policies promoting composting and offering subsidies for organic inputs further enhance the feasibility of commercializing cotton stalk compost.

Studies suggest that successful commercialization depends on efficient processing, quality control, and market linkages. According to Patel et al. [55], investment in composting infrastructure and branding can significantly increase the profitability of compost products. Similarly, Kizito et al. [29] found that compost enriched with beneficial microbes and biofertilizers had higher commercial value and greater adoption among farmers. The global agricultural sector moves toward sustainability, cotton stalk compost presents a viable commercial opportunity that aligns with environmental and economic goals, making it an attractive option for businesses and policymakers.

Threats to cotton stalk compost

1. Competition with chemical fertilizers

The adoption of cotton stalk compost faces significant competition from chemical fertilizers, which are widely used due to their immediate nutrient availability, convenience and established market presence. Farmers often prefer chemical fertilizers because they provide rapid plant nutrition, [43] whereas compost releases nutrients slowly over time and also, chemical fertilizers are easily accessible, heavily subsidized in many regions, and supported by extensive distribution networks, making them more attractive compared to organic alternatives like cotton stalk compost.

Despite its long-term benefits, cotton stalk compost struggles to compete due to longer decomposition times, inconsistent nutrient composition, and the higher labour costs associated with production and application. Many farmers also lack awareness of composting benefits or perceive it as less effective than synthetic fertilizers. Moreover,

the immediate yield-boosting effects of chemical fertilizers often outweigh the soil health advantages of compost in the short term, discouraging its widespread use [65].

Furthermore, the large-scale production and aggressive marketing strategies of chemical fertilizer companies create additional barriers to the adoption of compost. According to Patel and Kumar [52], financial incentives and subsidies for chemical fertilizers further reduce the economic competitiveness of organic alternatives. Additionally, Zhang and Li [88] highlight that policy gaps and a lack of infrastructure for compost production contribute to its lower adoption rates. To overcome these challenges, increased policy support, farmer education, and incentives for compost use are needed to create a more balanced competition between organic and synthetic soil amendments.

2. Seasonal availability of raw material

The seasonal availability of raw materials poses a significant challenge to the consistent production of cotton stalk compost. Cotton stalks are only available after the harvesting season, leading to limited supply periods and potential shortages for composting operations. This irregular availability disrupts the continuous production of compost and affects its market stability. [25,26]. Unlike chemical fertilizers, which are produced year-round, cotton stalk compost production is constrained by the seasonal nature of cotton cultivation. Furthermore, the storage and preservation of cotton stalks between harvest cycles present logistical and financial challenges.

Large quantities of stalks require proper storage facilities to prevent decomposition, pest infestations, and moisture-related damage. [64]. Without efficient collection and storage mechanisms, a significant portion of cotton stalks may be wasted or used for alternative purposes, such as fodder, fuel, or bioenergy production, [30] further reducing their availability for composting. Furthermore, fluctuations in cotton production due to climate variations, pest infestations, and market dynamics can impact the availability of cotton stalks for composting. In years of low cotton yield, the supply of stalks decreases, making compost production inconsistent and limiting its large-scale commercialization [88].

To address this threat, improved supply chain management, better storage infrastructure, and farmer incentives for composting raw materials are essential. Policy interventions promoting the sustainable use of cotton stalks can help mitigate these challenges and ensure a stable compost supply.

3. Resistance to change

Resistance to change is a significant threat to the adoption of cotton stalk compost, as many farmers remain hesitant to shift from conventional practices to organic composting. The long-established reliance on chemical fertilizers, coupled with their immediate yield benefits, makes it difficult for farmers to accept compost as a viable alternative. Additionally, limited awareness and knowledge about the benefits of cotton stalk compost further hinder its widespread adoption [59].

Traditional farming practices and ingrained habits also contribute to this resistance. Many farmers prefer familiar methods and are reluctant to invest time and effort into learning new composting techniques. Furthermore, the slow-release nature of composted nutrients, compared to the rapid effects of synthetic fertilizers, discourages farmers who prioritize short-term productivity over long-term soil health. [71].

Economic factors further reinforce this resistance. Government subsidies and financial incentives often favour chemical fertilizers, making them more affordable and accessible than compost. Additionally, a lack of proper infrastructure and market linkages for compost distribution reduces its attractiveness as a reliable input for farmers [45]. To overcome these barriers, extensive farmer education, demonstration projects, and policy interventions promoting organic composting are necessary. Incentivizing compost adoption through financial support and training programs can help shift farmer perceptions and encourage

a gradual transition toward sustainable soil management practices.

4. Climate dependency

Climate dependency poses a significant threat to the consistent production and effectiveness of cotton stalk compost. Cotton cultivation is highly influenced by climatic conditions such as temperature, rainfall, and drought, which directly impact cotton stalk availability for composting. Unfavorable weather, cotton yields may decline, leading to reduced biomass production and limiting the supply of raw materials for composting [1]. Moreover, the composting process itself is sensitive to climatic conditions. Optimal decomposition requires controlled moisture levels and temperature, which can be challenging in extreme weather conditions.

In arid regions, insufficient moisture slows down microbial activity, delaying compost maturity, while excessive rainfall can lead to nutrient leaching and anaerobic conditions that hinder decomposition efficiency [52]. Also, unpredictable climate events such as heavy storms, prolonged droughts, and heatwaves can disrupt composting operations and storage. Variability in seasonal conditions also affects the demand for compost, as farmers may prioritize other soil amendments or inputs based on changing climatic patterns and crop needs [88].

To mitigate these climate-related threats, adaptive composting techniques, improved water management strategies, and climate-resilient agricultural policies are essential. Implementing protective composting methods, such as covered composting systems and moisture control technologies, can help maintain production efficiency under varying climatic conditions [76].

Future perspectives

- In future, improved composting techniques can make the process faster and more efficient, reducing waste effectively.
- Using cotton stalk compost promotes eco-friendly farming and helps in sustainable soil management.
- Government policies and financial support can encourage farmers to adopt composting practices.
- Research on compost benefits can help farmers enhance soil fertility and improve crop yields.

Conclusions

Cotton stalk compost provides a sustainable and eco-friendly solution for managing agricultural waste while enhancing soil fertility. It enriches the soil with essential nutrients, supports microbial activity, and reduces the environmental impact of burning crop residues. Additionally, it offers a cost-effective alternative to synthetic fertilizers, promoting long-term soil health. However, several challenges hinder its widespread use. The slow decomposition of cotton stalks requires efficient composting techniques, while processing and transportation costs may discourage farmers. Moreover, synthetic fertilizers, which deliver quicker results, dominate the market, making it difficult for compost-based alternatives to compete.

To promote adoption, government incentives such as subsidies and training programs can encourage farmers to use composting. Technological advancements like microbial treatments can speed up decomposition and improve compost quality. Raising awareness about its long-term benefits through educational campaigns can further drive its use. Addressing these challenges can help integrate cotton stalk compost into sustainable agriculture, improving soil health and reducing environmental impact.

Acknowledgements: Not applicable.

Authors' contributions: Bharathiraja S wrote the manuscript draft, and Somasundaram S revised it. Kishorekumar A, Dinakar S, Rani T, Kumaresan G and Manibharathi S contributed

to discussion. All authors read, edited and approved the final manuscript.

Funding: Not applicable.

Availability of data and materials: Not applicable.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: The authors and co-authors have given their consent for publication.

Competing interests: The authors declare no competing interests.

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