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From Waste to Energy: A Critical Review of Crop Residue Management and Bioenergy Implicit in Pakistan

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Abstract

Agriculture plays a significant part in Pakistan's economy, contributing overall to its GDP, yet it's also a vital motorist of environmental declination due to practices like crop residue burning. This paper reviews the current state of crop residue handling in Pakistan, concentrating on the environmental and profitable charges of residue burning, which remains a pervasive practice despite its harmful effects. This review examines the potentiality for using crop residues as renewable energy sources, pressing both the challenges and chances for integrating bioenergy results into Pakistan's agrarian sector. The paper also analyzes the programs governing crop residue operation and their effectiveness in bridling burning practices, identifying gaps in enforcement and offering recommendations for policy reform. Through a comprehensive literature review and critical analysis, the paper underscores the need for sustainable residue handling practices, promoting a shift towards cleaner choices that could soothe environmental impacts, reduce air pollution, and contribute to addressing Pakistan's energy extremity. Mainly this paper presents recommendations for sustainable governance practices and discusses the integration of bioenergy as a feasible way.

Keywords: Agricultural byproducts • Renewable power generation • Environmental degradation • Sustainable farming practices • Waste-to-energy solutions

Introduction

Farming is the largest sector of Pakistan's economy, contributing 24 to the country's GDP in 2023-2024. Despite this, numerous rustic villages in Punjab face electricity dearth, with frequent power outages due to the country's energy extremity. One significant contributor to environmental declination is the wide practice of crop residue burning, which negatively impacts air quality and exacerbates climate change.

Despite the reality of a ban on crop residue burning, the practice persists, largely due to ineffective policy perpetration and limited access to alternate result the deficient combustion of biomass, including agrarian remainders, produces black carbon, which is the alternate-largest contributor to global warming after carbon dioxide [1]. In Pakistan it accounts for 20% of the country's air contaminant emissions (Table 1). In the downtime, an estimated 3.6–5 million tons of rice residue are burned to plant wheat [2].

Country	Rice/paddy	Wheat	Maize	Sugarcane	Total
Pakistan	1,521,057	3,657,239	1,334,000	735,033	7,247,329

Table 1. crop wise residue burnt in Pakistan in 2016 (Tons) (major crops only).

The deleterious gases released include CO_2, SO_2, NO_2, CH_4, and N_2O, which not only contribute to global warming but also result thick haze, particularly in the Indo-Gangetic plain (Table 2). The performing poor air quality is responsible for significant public health issues, with an average life expectation reduction of 4.3 times per citizen. In fact, metropolises in Pakistan, India, and Nepal rank among the most weakened in the world due to these emissions [3].

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Name of gas emission	Factors of crop residues (g/kg)
Carbon Dioxide (CO_2)	1,515
Methane (CH_4)	2.7
Nitrous Oxide (N_2O)	0.07

Table 2. The deleterious gases released include CO_2, SO_2, NO_2, CH_4, and N_2O.

One of the smart ways to use crop residues is through bioenergy product. By converting crop remainders into renewable energy, we can significantly reduce greenhouse gas emissions, creating a more sustainable energy source and mollifying environmental damage. People are n't apprehensive of smart application of crop use rice, wheat, sugarcane, cotton, and maize are among the five major harvested crops in Pakistan, producing waste in the form of rice husk and straw, wheat straw, bagasse, cotton straw, and corn stove which can be used for renewable energy [4].

Although crop remainders are atmosphere friendly, but it's energy generation is limited. The generation of energy from the biomass is limited by the collection effectiveness of biomass [5]. Simulation results revealed that indeed if production and transportation costs drop and biomass yields ameliorate, high collection costs could still limit its use for power generation. Still, Maung and McCarl stressed that rising coal prices and improved carbon duties could make biomass an appealing option for power generation companies.

In Pakistan, energy dearth has been a significant hedge to industrial growth, with numerous sectors experiencing reduced productivity and rising costs. One implicit solution is biomass-to-electricity power plants, which have shown to be economically competitive. Chaudhry et al., found that the cost of electricity from these biomass plants is similar to fossil energy-grounded plants and indeed more affordable than solar and wind energy plants. In Pakistan, bagasse and rice cocoon are being employed for process heating and power generation on small-scale to meet energy and brume demands of sugar and rice industry. Still, there's a critical need to increase electricity generation from crop residue on a commercial scale by making power plants at named favorable sites in pastoral areas.

Background

During the course of farming practices, it has been observed that the remains of crops like sugarcane, rice and cotton etc. are also left in the field without proper mounding or major part is burnt in the open field. Open field burning of agrarian remainders not only results in loss of organic matter in the soil but also hits useful insects, over all deteriorates the environmental condition of the surroundings due to emission of fatal gases, smoke and ash. At present large share of residue burning in farming sector is in result of post-harvest handling of rice crop because of difficult management ways, limited coffers of husbandry community and short window for sowing of coming crop. Rice straw burning is the most common practice in Punjab, a study revealed that rice straw burning constitutes 72% alone.

In Pakistan, amongst the other staple food grain crops, Rice ranks second, it's also an important cash crop of the country and has been a major source of foreign exchange earnings among cereal crops. Around 90 of rice is harvested using colorful models of Combine Harvesters, mainly old models from the 1990's imported from Japan and other countries. These machines are neither registered nor tested by any department, leading to significant losses for agronomists. A 2018-19 study by the field sect innovate that the use of these old combines results in losses of 5 to 10, causing substantial profitable damage. After harvesting, handling rice crop residue becomes a challenge due to the limited time for harvesting in Punjab. To snappily clear fields for wheat sowing, agriculturists frequently burn the residue, which damages the atmosphere and leads to smog. Burning releases dangerous air impurities that affect air quality, public health, and climate. Introducing rice straw handling practices is pivotal to reduce open burning and cover the terrain.

Rice straw can be managed by two ways:

In-field rice straw management: Rice straw handling in the field is generally done either through open field burning or by incorporating it into the soil using recently developed agrarian instrument. But it leads to varied disadvantages including discharges of smog, and farming sector contributes around 20% in smog (Figure 1).

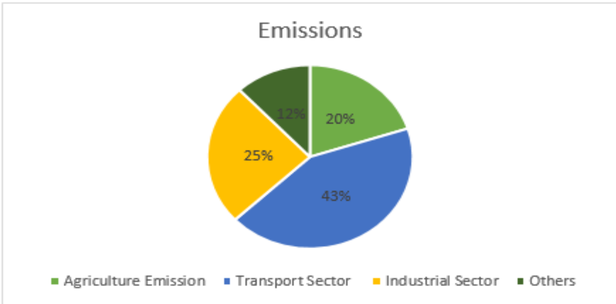

Figure 1. In-field rice straw management.

Off-field rice straw management: Off-field handling involves removing the rice straw from the field for varied uses, similar asbio-energy output, mushroom cultivation, animal feed, mulching for other crops, or silica manufacturing [6].

Materials and Methods

The use of crop remainders for renewable energy production has been explored in multiple countries. Studies have demonstrated that remainders similar as wheat straw, rice cocoons, and sugarcane bagasse can be converted into biofuels through thermochemical processes. These remainders have the eventuality to replace fossil powers in energy generation, therefore reducing greenhouse gas emissions and mollifying climate change. Still, despite the accessibility of these remainders, their use for energy generation remains underutilized, especially in developing countries like Pakistan.

Several studies have emphasized the potentiality of crop remainders, similar as cereals and corn, to be used for producing liquid or gassy biofuels through thermo-chemical or biological processes. Nguyen et al., proposed using wheat straw for electricity generation rather of depending on coal and natural gas. Their study emphasized that using straw for energy could help alleviate global warming and reduce dependence on renewable energy sources. These studies emphasize the growing recognition of the need to more understand the connections between farming, biomass production, bioenergy, and climate change to directly estimate bioenergy eventuality emphasized the biomass energy potentiality of rice remainders, showing that energy yields could be significantly increased through more effective collection and processing ways. Still, in Pakistan, logistical challenges similar as the lack of structure for residue collection and transportation have hindered the wide relinquishment of biomass energy. There's a need for a comprehensive strategy to manage crop residues and harness their energy implicit efficiently.

Global perspective on biomass and crop leftovers

Countries like the USA, China, and Brazil have made notable advancements in using crop remainders for energy. For instance, in Brazil, the use of sugarcane bagasse for bioelectricity generation is well-established, contributing significantly to the country's energy grid (FRONTIERS, IRENA). Also, China and the USA have developed technologies to convert agrarian by-products into electricity through combustion and gasification processes (borders). These countries have established biomass energy manufactories and have formulated procedures that incentivize biomass application, therefore driving the growth of this sector (Figure 2).

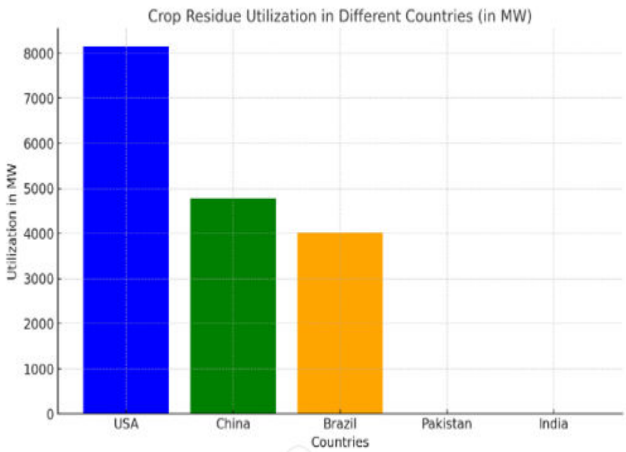

Figure 2. World Energy Statistics 2016. IEA.

Biomass in Pakistan

Pakistan, with its rich agrarian sector, produces significant quantities of crop remainders annually, yet much of this biomass is either burnt in the fields or left unused (IRENA). Studies show that Pakistan generates roughly 40 million tons of crop remainders each year, which has the implicit to produce around 11,000 MW of electricity. Despite this vast eventuality, biomass-grounded energy generation in Pakistan remains limited due to varied profitable, technological, and logistical challenges (IRENA). The lack of structure for collection, transportation, and storehouse of crop remainders is a major interference to the wide adoption of biomass energy (borders) (OSTI).

Hedges to crop residue use in Pakistan: The profitable and logistical hedges to the application of crop residues for renewable energy generation in Pakistan are significant and need to be addressed to unlock the full eventuality of biomass energy. These challenges stem from a combination of high collection and transportation costs, seasonal accessibility of remainders, and inefficiencies in the structure needed to handle large volumes of biomass.

High collection and transportation costs: The cost of collecting and transporting crop leftovers in Pakistan is vastly high when compared to traditional fossil energies, primarily due to the lack of developed structure, inefficiencies in collection ways, and the seasonal nature of crop residue production.

- Collection costs: The process of collecting crop leftovers is frequently inefficient and labor-intense. In Pakistan, numerous agriculturists still depend on manual labor or small-scale mechanical equipment to gather crop leftovers like wheat straw, rice covers, and sugarcane bagasse. These ways are n't only time-consuming but also need significant human resources, which drives up the overall cost. According to studies, labor costs for residue collection can be as high as$ 10 to$ 15 per ton in pastoral areas, depending on the crop and site can be as high as $10 to $15 per ton in rural areas, depending on the crop and location.

Transportation costs: The lack of centralized collection systems means that farmers are responsible for transporting crop residues to biomass power plants or storage facilities. The transportation costs are exacerbated by poor road infrastructure in rural regions, which increases the fuel costs and transportation time. For example, in Punjab, where a significant portion of crop residues is produced, farmers must often transport residues over long distances to centralized biomass plants. Given the poor road conditions and lack of specialized vehicles, transportation costs can range from $20 to $30 per ton. In comparison, fossil fuels (such as coal and natural gas) are often much cheaper to transport, with average transportation costs being much lower due to established supply chains and infrastructure.

Seasonal availability of crop residues

The seasonal nature of crop residue production adds another layer of complexity to biomass energy generation. Crop residues are mainly produced after harvests of major crops, such as rice, wheat, and sugarcane, with the bulk of residues being generated during the harvest season (typically in the autumn and spring). This creates challenges for power plants that require a consistent year-round supply of biomass fuel.

- Seasonal surges: During the peak harvest periods, a large amount of crop residue is generated in a short time frame. This surge in biomass production can overwhelm existing collection and transportation systems, leading to inefficiencies and high costs. Power plants and biomass energy projects that rely on these seasonal spikes may face supply disruptions or be forced to pay higher prices for transport during peak periods.
- Storage issues: Since crop residues are produced seasonally, storing large quantities for year-round use becomes a challenge. Residues must be stored properly to avoid spoilage and degradation, which adds further costs. Without adequate storage infrastructure, residues that cannot be immediately processed may lose their value as a viable energy source, particularly in areas where storage facilities are insufficient or poorly maintained.

Economic viability and fossil fuel comparison

When comparing biomass to traditional fossil fuels, biomass derived from crop residues is often more expensive due to the high collection, transportation, and storage costs associated with it.

- Cost of biomass *vs.* fossil fuels: The cost of producing electricity from biomass is typically higher than that of fossil fuels, particularly coal and natural gas. In Pakistan, the cost of generating electricity from biomass can range from $0.10 to $0.15 per kWh, whereas the cost of generating electricity from coal can be as low as $0.05 per kWh. This price difference is largely driven by the high collection and transportation costs of crop residues, compared to the relatively established supply chains for coal and natural gas.
- Subsidy requirements: To make biomass energy more competitive, government incentives, such as subsidies or tax rebates, are needed to offset the higher operational costs. Without these incentives, biomass energy remains less economically attractive to investors and energy companies, making it harder to scale up.

Logistical inefficiencies

The logistical challenges associated with crop residue utilization are compounded by the fragmented nature of the agriculture sector in Pakistan. Most farmers, especially smallholders, are not equipped to handle large quantities of crop residues, leading to inefficiencies in the collection process.

- Lack of centralized collection systems: Unlike countries with well-established biomass energy industries, Pakistan does not have a centralized system for collecting, processing, and transporting crop residues. This lack of coordination results in inefficiencies, as residues are often collected and transported over long distances in small batches, raising overall costs.
- Limited mechanization: The limited mechanization of crop residue collection and processing further drives up costs. In regions like Punjab, the use of old combine harvesters and outdated machinery results in crop residue loss during harvest, making it difficult to gather and transport the full amount of available biomass. Modern mechanized systems, such as balers and biomass harvesters, could significantly reduce the cost of collection and improve efficiency, but these technologies are not widely available or affordable to many farmers.

Technological innovations

Technological advancements in combustion technologies such as fluidized bed combustion and gasification have improved the efficiency and environmental impact of biomass energy production. Studies have shown that modern biomass plants can achieve high combustion efficiency and low emissions, making them viable for large-scale electricity generation. The co-firing of biomass with coal is another technology being explored in many countries, which helps reduce CO_2 emissions from traditional power plants

To unlock the full potential of biomass energy from crop residues in Pakistan, several measures are recommended:

Improving infrastructure: Developing efficient supply chains for biomass collection and transportation will reduce costs and enhance the feasibility of biomass energy plants.

Incentivizing investment: Government policies, such as tax rebates and subsidies, could stimulate investment in biomass energy infrastructure

Regional studies: More localized studies in Pakistan, focusing on Punjab and Sindh, which have higher crop residues, could help identify optimal locations for biomass power plants.

By addressing these barriers and leveraging technological advancements, Pakistan could significantly reduce its reliance on fossil fuels and develop a sustainable, renewable energy sector base d on crop residues.

Identifying gaps

While substantial research has been conducted on crop residue burning and its environmental consequences, particularly in relation to air pollution, there remain several gaps in the literature that need to be addressed to fully understand the potential of crop residues as a renewable energy source in Pakistan. These gaps fall under various domains, including methodological limitations, regional specificity, and economic feasibility.

Limited focus on the socioeconomic and policy context of Pakistan: Although global studies on biomass burning and energy generation from agricultural residues are abundant, there is a significant lack of research focused on the Pakistani context. The existing literature often overlooks critical socioeconomic factors that influence the decision-making process of farmers in Pakistan, such as land tenure systems, economic constraints, and the lack of infrastructure for energy conversion.

Studies that explore the financial and policy barriers to implementing biomass energy technologies in Pakistan are rare. Furthermore, while some studies note the environmental impact of residue burning, there is little analysis of how government policies, subsidies, and technological adoption influence farmers' choices regarding crop residue management. More research is needed to understand these factors and how they can be addressed to promote sustainable energy production from agricultural waste.

Inadequate consideration of alternative biomass energy technologies: Most of the studies reviewed focus on the environmental benefits of burning crop residues and the potential for energy recovery. However, the technological aspects of converting these residues into usable energy are often not explored in depth. For example, while some research mentions the use of biomass gasification or biogas production, there is limited analysis of the technical feasibility of these technologies at a large scale in rural Pakistan. There is also a lack of studies evaluating the cost-effectiveness and efficiency of these technologies in the specific conditions found in Pakistan, such as seasonal variations in residue availability and the dispersed nature of agricultural land. To fully understand the potential of crop residues as a renewable energy source, further research is needed on the practical application and economic viability of biomass conversion technologies in the Pakistani context.

Absence of long-term impact studies on crop residue utilization: Another gap in the literature is the lack of longitudinal studies examining the long-term impacts of using crop residues for energy generation in Pakistan. While many studies assess the immediate benefits of using biomass for energy or mitigating air pollution, there is little research on the sustainability of this practice in the long term. For instance, how does the conversion of crop residues to energy affect soil health and agricultural productivity over multiple seasons? Are farmers likely to reduce residue burning if they can rely on biomass energy, or will other challenges arise in managing residues sustainably? Understanding the long-term economic and ecological effects of biomass energy utilization is crucial for developing comprehensive policies that promote sustainable practices.

Limited integration of social and behavioral factors in farmers' decision-making: A key gap in the literature is the lack of consideration of social and behavioral factors that influence farmers' decisions to burn crop residues or utilize them for energy. While several studies have explored the economic and environmental drivers of crop residue burning, few have delved into the cultural, psychological, and community-level factors that may play a role in these decisions. Factors such as community norms, access to information, and the level of education among farmers may significantly affect their willingness to adopt alternative residue management practices. More research on these behavioral aspects could provide valuable insights into how farmers can be encouraged to shift toward more sustainable practices, beyond just offering financial incentives or technological solutions (Figure 3).

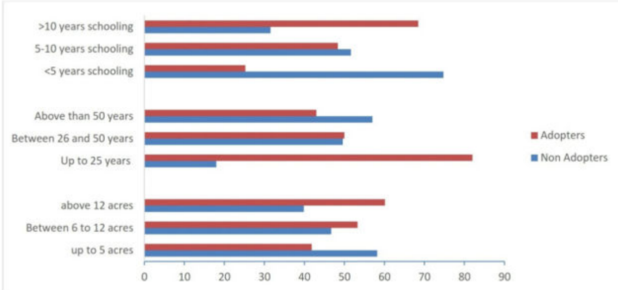

Figure 3. Limited integration of social and behavioral factors in farmers' decision-making.

Insufficient regional comparisons within Pakistan: Although the research on crop residue burning in Pakistan highlights the broader environmental and economic issues, there is limited regional comparison within the country. Pakistan is a vast and diverse country with varying agricultural practices, climates, and socioeconomic conditions across regions. Studies tend to generalize the findings from one region to the entire country, which may overlook the regional disparities that could affect crop residue management and energy generation. Research that takes into account regional variations in crop types, farming systems, and energy needs is necessary to develop region-specific strategies for utilizing crop residues.

Methods

This narrative review synthesizes the research methodologies utilized in studies on crop residue management and its potential for bioenergy production in Pakistan. The studies reviewed employed a variety of methods, which are summarized as follows:

Literature review and data collection:

- A comprehensive literature review was conducted to identify key studies on crop residue management and bioenergy potential in Pakistan. Relevant articles were sourced from academic databases such as Google Scholar, PubMed, and Scopus, focusing on peer-reviewed research published within the last two decades.
- The studies reviewed included both theoretical and experimental research on the conversion of crop residues into biofuels, such as biogas, bioethanol, and electricity, with an emphasis on practices in Pakistan.

Field surveys and interviews:

- Several studies used field surveys to collect primary data from farmers and agricultural stakeholders in Pakistan. These surveys focused on understanding factors influencing crop residue management, such as socio-economic factors, access to technology, and environmental conditions.

- In particular, studies in rice-wheat cropping systems gathered data to evaluate variables like farm size, socio-economic status, and regional differences in crop residue management practices.

Experimental and laboratory research:

- A number of experimental studies utilized laboratory-scale tests to assess the bioenergy potential of various crop residues. Methods such as anaerobic digestion, pyrolysis, and fermentation were applied to test the energy yield of residues like wheat straw, rice husks, and sugarcane bagasse.
- Data from these experiments were used to determine the efficiency of conversion technologies and to identify optimal conditions for large-scale bioenergy production.

Modeling and simulation:

- Studies also employed modeling tools to simulate the potential of crop residues for bioenergy production at larger scales. These models incorporated variables such as crop yield, residue availability, climate conditions, and conversion efficiencies.
- Simulations were used to predict the economic feasibility and environmental impact of integrating bioenergy technologies into Pakistan's agricultural sector.

Data analysis:

- The studies utilized statistical techniques such as regression models and econometric analyses to evaluate the relationship between crop residue management practices and bioenergy yields. These methods helped identify the key factors influencing the viability of bioenergy production, such as crop type, soil conditions, and geographic location.
- Cost-benefit analysis and other econometric tools were used to assess the economic viability of bioenergy technologies compared to conventional energy sources.

Synthesis and comparative analysis:

- Finally, a comparative analysis of the methodologies and findings of the reviewed studies was conducted to identify trends, challenges, and opportunities for improving crop residue management and bioenergy production. Both qualitative and quantitative data were synthesized to offer a comprehensive understanding of the current research landscape.

Critical analysis of findings

A study by M. Kashif et al., have shown that biomass power plants can enhance energy security by using locally sourced crop residue, reducing reliance on imported fossil fuels. Currently, excess residue is used for burning, animal feed, and manufacturing, with the rest burned in fields, causing pollution. Using biomass can reduce these emissions and improve air quality. Offering lower electricity tariffs in rural biomass collection areas can increase collection, benefiting the rural economy, creating jobs, and boosting local industries. It also provides electricity to remote areas, supporting small-scale manufacturing. But, there is still a gap of cost of transportation and literacy rate of farmers in Pakistan, which can hinder this method for renewable energy.

Despite technological potential, biomass power faces economic, logistical, regulatory, and political challenges. A 100-150 MW co-fired plant can be viable if located near biomass sources with good transport, but high generation costs, competition for biomass, and infrastructure issues complicate implementation. A simpler analysis has been used here, but a more detailed study could include other local biomass sources. Addressing collection and storage costs, and reducing biomass competition, can improve feasibility. Biomass plant ash can also be used as fertilizer or in cement production. Although theoretically this method works but it is still difficult to apply in developing countries like Pakistan.

A study from Tanvir Ahmed and Bashir Ahmad (©The Pakistan Development Review) have found:

Biomass potential and technological advancements: The capacity to generate at least 6000 MW from crop residue is indeed a promising prospect, especially when considering the technological advancements in combustion efficiency (65-70%) and future improvements with advanced boilers like fluidized bed and pulverized fuel technologies. However, while these projections are optimistic, the estimates rely heavily on technological progress and the assumption that biomass collection and crop yields will continually improve. This future growth hinges not just on technological adoption but also on consistent policy support, infrastructure development, and farmer participation. It is important to note that the feasibility of this potential is tied to regional crop yields, seasonal variations, and collection efficiencies, which can vary from year to year.

Energy security and reduction in fossil fuel dependence: The use of locally sourced biomass for energy generation presents a crucial advantage in terms of enhancing energy security. By tapping into crop residue, Pakistan can reduce its reliance on imported fossil fuels, thus fostering a more sustainable energy system. This aligns with the global trend towards promoting energy independence through renewable sources. However, this transition could face resistance from industries and stakeholders with vested interests in traditional fossil fuel systems, such as coal and natural gas, which could hinder rapid adoption.

Environmental impact: The environmental benefits of using biomass are significant, particularly in reducing the harmful effects of crop residue burning, which is a major contributor to air pollution in Punjab. The findings corroborate earlier studies suggesting that transitioning to biomass utilization could mitigate these environmental harms. However, while biomass use reduces pollution, the scale of its environmental impact depends on several factors, including the energy efficiency of the plants, transportation emissions, and the sustainability of crop residue collection. A detailed Life-Cycle Assessment (LCA) could provide further insights into the net environmental benefits of biomass over its entire production and consumption cycle.

Economic implications and rural development: Offering preferential electricity tariffs in rural biomass collection areas is a sound economic strategy to incentivize collection efforts, boost local economies, and create jobs. This approach not only stimulates local agricultural economies but also provides a dual benefit of rural energy access and income generation. However, it raises the question of financial sustainability. Offering subsidies or incentives may place a burden on the government or utilities unless a clear long-term economic model, possibly through public-private partnerships, is in place. A more detailed cost-benefit analysis would help quantify the impact on local economies and ensure that these projects remain viable over time.

Challenges in biomass utilization: Despite the clear technological potential of biomass as a renewable energy source, several barriers need to be addressed for large-scale adoption. Economic challenges, such as high generation costs and competition for biomass, along with logistical hurdles like the lack of transport infrastructure, are key concerns. Regulatory and political barriers could also slow the implementation of biomass projects, especially given the complex nature of energy policy in Pakistan. Addressing these challenges requires coordinated efforts from multiple stakeholders, including government, private sector players, and local communities. Furthermore, while co-firing with existing plants (100-150 MW) is mentioned as a viable option, the long-term sustainability of such mixed energy solutions must be carefully assessed, particularly in the context of future fuel price volatility and demand for biomass.

Collection, storage, and infrastructure: The high costs associated with the collection and storage of crop residue remain a critical challenge. The analysis suggests that plant location optimization could alleviate some of these costs, but more targeted solutions need to be explored. Additionally, infrastructure development will play a crucial role in scaling up biomass power plants. These projects should include investment in local transport and storage facilities to ensure a stable and reliable feedstock supply. Incentivizing local communities to collect biomass at scale would also require educational campaigns and training to improve collection efficiency.

Use of biomass ash in circular economy: The proposal to use biomass ash as fertilizer or in cement production is an excellent example of promoting a circular economy. This approach not only provides a potential revenue stream but also addresses the environmental concern of waste disposal from biomass power plants. The inclusion of biomass ash in agricultural and construction industries could reduce costs for farmers and manufacturers, while promoting sustainable practices. However, the scale at which this could be implemented requires further research into the chemical properties of the ash, its long-term effects on soil health, and its compatibility with cement production processes.

Results and Discussion

The exploration of crop residue burning in Pakistan reveals critical intersections between agriculture, environmental sustainability, and energy production. Despite the substantial economic contribution of agriculture, particularly the rice-wheat cropping system in Punjab, the continued practice of residue burning poses significant challenges for both the environment and public health. The burning of agricultural residues has long been recognized as a major contributor to air pollution, emitting harmful gases such as CO_2, SO_2, and CH_4, which exacerbate global warming. In Pakistan, this practice contributes approximately 20% of the nation's air pollutant emissions, underscoring the urgency of addressing this issue.

Existing policies have been insufficient in curbing residue burning, largely due to the lack of access to viable alternative solutions and the high costs associated with transitioning to more sustainable practices. Moreover, the incomplete combustion process results in the release of black carbon, which has a disproportionately high impact on global warming. While efforts have been made to promote alternative uses for crop residues, such as their conversion to renewable energy sources, challenges remain regarding both the infrastructure and economic incentives needed to facilitate this transition.

Notably, this review highlights the significant potential of utilizing crop residues for electricity generation. Several studies have demonstrated the feasibility of converting rice and wheat straw into bioenergy, which could help mitigate the country's ongoing energy crisis. However, despite this potential, the implementation of large-scale renewable energy projects remains constrained by various factors, including limited investment, outdated technology, and inadequate governmental support. Furthermore, while crop residues are an abundant and renewable resource, competing priorities for their use, such as fodder for livestock and soil enrichment, complicate the situation.

Conclusion

In conclusion, crop residue burning in Pakistan is a major environmental and public health concern that requires immediate action. While bioenergy offers a promising alternative to mitigate the negative impacts of burning, several challenges must be overcome, including the development of infrastructure, policy enforcement, and financial support for farmers. The government plays a crucial role in facilitating this transition by implementing stronger regulations, increasing awareness, and promoting sustainable residue management practices. By adopting these measures, Pakistan can reduce its environmental footprint, contribute to global climate goals, and address its energy crisis through cleaner, renewable sources.

Recommendations

In light of the challenges identified, several strategic recommendations can be made to promote sustainable practices in the handling of crop residues in Pakistan:

Policy reforms and enforcement: Strengthening the enforcement of existing bans on residue burning and introducing stricter regulations are necessary to reduce the environmental and health impacts. However, enforcement must be complemented by incentives to facilitate the transition to alternative practices. Policymakers should consider providing subsidies or tax incentives for farmers to adopt sustainable residue management techniques, such as composting, mulching, or using residues for bioenergy production.

Investing in bioenergy infrastructure: There is significant potential for utilizing crop residues as a feedstock for renewable energy generation. The government and private sector should invest in modern biomass conversion technologies, such as biomass power plants, that can efficiently convert crop residues into electricity. Partnerships with international organizations and investors could help improve the technical and financial viability of such initiatives.

Public awareness and education: Farmers need to be educated about the environmental and economic benefits of alternative uses for crop residues. Extension services could provide training on how to process and use residues as bioenergy or in other productive ways, helping farmers to overcome logistical and financial barriers. Additionally, local communities should be made aware of the long-term health and economic benefits of reducing air pollution and improving energy access.

Research and development: Further research is required to identify more efficient and cost-effective methods for converting crop residues into bioenergy. Additionally, studies should explore the potential for integrating crop residue-based bioenergy into Pakistan's broader energy mix, including the feasibility of small-scale, decentralized energy generation systems that can serve rural communities.

Multi-stakeholder collaboration: Collaboration between farmers, energy producers, and the government is essential to create an integrated approach to residue management. Local governments should work closely with agricultural associations, energy companies, and environmental groups to design and implement sustainable solutions that can reduce residue burning while enhancing the country's energy security.

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