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Research paper

Addressing Stubble Burning in Punjab: A Comprehensive Review of Causes, Impacts, and Sustainable Alternatives Through AgriThermoSolution

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ABSTRACT

In Punjab's intense rice-wheat cropping system, stubble burning is a frequent practice. It releases a substantial amount of pollutants, such as PM2.5 (200–500 μg/m^3), PM10, CO, and CH4, which contributes to severe air pollution and greenhouse gas emissions. The reasons, including the 15–20 day gap between crops, the scarcity of reasonably priced residue management solutions, and financial limitations, are examined in this research. Significant dangers to public health, such as a 36% rise in respiratory infections, are associated with the environmental effects, which include a 30–40% reduction in soil organic carbon. Scalability and acceptance issues plague current mitigation initiatives, such as the Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) policy and Happy Seeder technology. Alternatives that are sustainable are investigated, including crop diversification, in-situ management, and using residues for bioenergy. Adoption depends on legislative initiatives such as financial subsidies and carbon credits. The evaluation emphasises the need for comprehensive, empirically supported solutions that strike a compromise between farmers' financial reality and environmental sustainability.

1. Introduction

Definition and Historical Context

Stubble burning is the process of lighting agricultural residue that remains after harvest, mainly rice and wheat stubble. During the Green Revolution of the 1960s and 1970s, which brought high-yielding crop types and increasing mechanisation, this practice spread throughout Punjab. Large amounts of agricultural residue accumulated as a result of the switch to intensive rice-wheat cropping cycles,

particularly during the short time between rice harvest and wheat sowing. Due to a lack of accessible options, time restraints, and the urgency of clearing fields for the u'coming crop season, farmers turned to burning the stubble (Kumar, Rohit & Kaur, Navneet 2024). [Fig. 1]

1.1 Importance of the Issue

Because it contributes significantly to air pollution, stubble burning has become a serious environmental concern in India, especially in the northern regions of Punjab and Haryana. Burning crop residue releases toxic pollutants like methane (CH4), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM2.5 and PM10). These pollutants have a negative impact on air quality and raise the risk of lung cancer by 36% (Shailly, Kedia et al., 2020). They also contribute to localised haze and smog (Ishita Chandana, et al., 2023). This practice has a significant role in the seasonal air pollution crisis, especially In the winter when the atmosphere is more likely to retain pollutants due to weather patterns (Muhammad Isa Abdurrahman, et al., 2020). Moreover, burning stubble reduces organic matter and depletes vital minerals from the soil over time, which has a detrimental effect on agricultural productivity (Pradhan, Pratistha 2024).

1.2 Objective of the Review

This review's goal is to present a thorough examination of Punjab's stubble burning practices, looking at the causes, effects on the environment and human health, and viable sustainable solutions. The review attempts to provide a comprehensive understanding of the problem and investigate novel solutions that can lessen the negative effects of stubble burning on the environment and human health while preserving agricultural output. It does this by addressing the underlying causes of the problem and assessing existing mitigation initiatives. [Fig. 2,3].

Fig. 1 The map shows major regions of Punjab where stubble burning is prevalent, these areas are vital in understanding the environmental impact and subsequent policy interventions required
[*Maps of India. Punjab, (IN) (2022)*]

Fig. 2 Leftover Stubble after Paddy Harvesting (Bhindi Saidan, Amritsar, Punjab, 15th October, 2024)

Fig. 3 Stubble Burning in Practice (Bhindi Saidan, Amritsar, Punjab, 25th October, 2024)

2. Literature Review

2.1 Overview of Crop Residue Burning in India

Crop waste burning has long been a problem for the environment in India, especially in Punjab and Haryana, according to research by Tianjia Liu et al. (2020). This page provides a thorough analysis of residue burning's current state, stressing both how common it is and the difficulties with using traditional farming methods. The severity of this practice and its role in air pollution and soil quality degradation in India are further emphasised by Singh G.K. et al. (2022). According to Deshpande et al. (2023), burning residue is a substantial contributor to greenhouse gas emissions, which have increased by 75% since 2011.

2.2 Environmental and Health Impacts of Stubble Burning

Burning crop residue has significant negative effects on the environment and human health. According to Huang, Tao, et al. (2022), there is a direct correlation between stubble burning and rising PM2.5 levels in northern India, which has a major effect on air quality. In a study evaluating the health burden of stubble burning, Chakrabarti et al. (2019) found that there is a higher risk of acute respiratory infections, which disproportionately affect poor individuals in rural areas. Similarly, Singh and Gurdev (2024) talked about how this activity affects the environment and how the greenhouse gas emissions it produces worsen climate change.

2.3 Policy and Management Strategies

Numerous studies have examined the difficulties in enacting policies and possible fixes for handling crop wastes. According to Bhuvaneshwari et al. (2019), there are new laws and creative ways to reduce stubble burning, like encouraging the manufacture of biofuel from crop leftovers in other ways and putting conservation agriculture into practice. Buttar et al.'s (2023) discussion of the adoption patterns of agricultural machinery-based solutions highlights the possibility for scalable interventions and provides useful insights into Punjab's in-situ management practices.

2.4 Alternative Uses of Crop Residues

Several substitutes for burning stubble have been suggested, such as the manufacture of bioethanol from rice straw, as researched by Singh, Renu, et al. (2016). These substitutes not only lessen harm to the environment but also present business prospects. The importance of conservation agriculture practices—which lessen the need for burning and improve soil health through sustainable agricultural methods—is covered by Sébastien Sauvé et al. (2016). Furthermore, as investigated by Khurana, Ananya, et al. (2024), attempts to incorporate these activities with carbon credit systems offer farmers a financial incentive to switch to environmentally beneficial practices.

2.5 Sociotechnical Transitions in Agriculture

In order to solve the issue, farmer attitudes on residue management—particularly their reluctance to change—are crucial. The sociotechnical changes required to convince farmers to switch from burning to more sustainable techniques were investigated by James Erbaugh et al. in 2024. Gaining an understanding of different viewpoints is essential to creating interventions that work and encouraging widespread adoption of sustainable alternatives.

3. Material and Methodology

3.1 Research Design

Using a systematic review methodology, this review paper focusses on the material that already exists on crop residue burning, its effects on the environment and human health, and the available management approaches. The goal of the research design was to compile, assess, and integrate pertinent papers that tackle important issues about the extent, causes, and remedies of the burning of agricultural residue, especially in northern India.

3.2 Data Sources

Reputable databases, such as ScienceDirect, Springer Link, PubMed, Google Scholar, and many more, provided the material for this study's review. Keywords like "crop residue burning," "stubble burning in India with special account of North Indian," "alternative residue management strategies," and "environmental impact of agricultural residues" were used in search searches. To offer a thorough grasp of the subject, both original research pieces and reviews from peer-reviewed journals were included.

3.3 Inclusion and Exclusion Criteria

The following were the inclusion criteria for the studies included in this review:
Published in the years 2015–2024. Peer-reviewed publications that concentrate on sustainable agriculture, environmental science, public health, or burning of agricultural residue. Studies that talk about new technology, legislative changes, or creative uses for crop leftovers. Research that makes substantial theoretical or empirical contributions to the field.
Among the exclusion standards were:
Non-English articles. Studies that don't address residue management and instead concentrate on other agricultural techniques. Studies that lack peer review or have inadequate methodological rigour.

3.4 Data Collection and Synthesis

In the beginning, 35 studies were found. Following the application of the inclusion and exclusion criteria, 25 studies were chosen for a thorough examination. Important details were gleaned about the extent of crop residue burning and the areas most impacted. Effects on the environment and human health, such as air quality and the prevalence of respiratory diseases. Technological advancements for different approaches to managing residue. Frameworks for policies and government programs. The results were divided into various categories, including the effects on the environment, public health, farmer viewpoints, and technology initiatives, using a thematic analysis approach.

3.5 Limitations of the Review

The availability of data from specific Indian locales and the review's dependence on secondary data from published studies are its main limitations. Furthermore, the paper's primary focus is on the provinces of Punjab and Haryana, which would restrict the applicability of its findings to other areas of India. The absence of primary data gathering and actual fieldwork places further limitations on the methodology.

3.6 Ethical Considerations

This is a review paper, thus ethical approval is not required because no human or animal subjects were used. To prevent plagiarism, all mentioned materials were formatted according to academic standards, and where appropriate, permits for the use of public data were obtained. [Fig. 4]

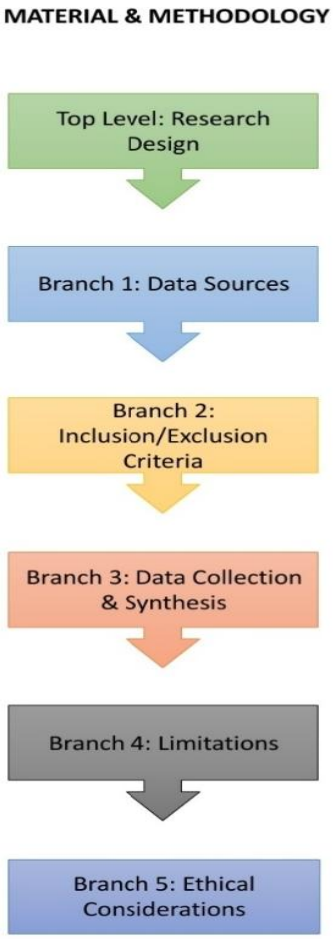

Fig. 4 Flow Chart Shows the Material & Methodology Employed for Review Article in Journal "Addressing Stubble Burning in Punjab: A Comprehensive Review of Causes, Impacts, and Sustainable Alternatives"

4. Agricultural Practices in Punjab

4.1 Overview of Crop Cycles

Punjab has an extensive rice-wheat cropping system that has long been essential to the country's agrarian economy. October is usually when rice is harvested, and November is when wheat is sown (Andrea S. Downing et al., 2022). Farmers are forced to clear fields rapidly in order to be ready for the next sowing cycle because of this brief, overlapping cropping window. Crop leftovers were managed manually prior to mechanisation. But when combine harvesters and other mechanised harvesting methods were introduced, a large amount of stubble—particularly rice straw—was left behind. Because rice stubble is difficult to break down and cannot be used as fodder, farmers must burn it to quickly and economically

clear the fields. In contrast, wheat stubble is easier to handle (Bhuvaneshwari, S. et al., 2019).

4.2 Role of Mechanization and Green Revolution

The 1960s and 1970s Green Revolution was a major factor in changing Punjab's agricultural environment. Crop productivity was greatly increased by the advent of chemical fertilisers, high-yielding crop varieties, and contemporary irrigation methods. But the revolution also had an unanticipated consequence: a problem with disposing of the vast amounts of crop leftovers, particularly from rice (Singh, R.B. 2000). With the widespread adoption of combine harvesters and other forms of mechanisation, harvesting got faster but unmanageable amounts of straw were left behind. Farmers found it convenient to burn the stubble because of their busy schedules between the rice harvest and the wheat sowing. The absence of financially feasible alternatives caused this practice to become more and more common over time (Singh, Vikas, et al., 2019).

4.3 Farmer Perspectives

From the viewpoint of a farmer, financial, scheduling, and resource limitations are important reasons why stubble burning is still done.

Economic constraints: For smallholder farmers, the expense of alternative residue management methods, such employing balers or Happy Seeders, is frequently prohibitive. Furthermore, logistical difficulties and the small market for such goods in rural regions make it impractical to sell rice straw for biofuel or other uses (Md. Kamrul Hassan, et al., 2021).

Time Pressure: Farmers who use the rice-wheat system have a limited amount of time—usually 10 to 20 days—to prepare the field for the following crop. The time required to remove stubble by hand or with machinery is greater, which might cause a delay in sowing and ultimately lower wheat yields. Consequently, burning stubble is thought to be the quickest fix (Asik Dutta, et al., 2022).

Restrictions on Resources: Compounding the problem is the fact that marginal farmers, in particular, have limited access to machinery like Happy Seeders, mulchers, and balers. Burning residue is the simplest way to deal with it rapidly because, even with subsidies, not all farmers have the financial or logistical means to purchase such equipment (Andrea S. Downing et al., 2022). [Table 1]

Table 1 Summary of Punjab's agricultural practices, including crop cycles, the effects of mechanisation and the Green Revolution, and farmer opinions

Start	Mechanization in Agriculture	Impact of Green Revolution	Farmer Perspective	End
Agricultural Cycle in Punjab: *Rice-wheat System* 1. Rice Harvest: October 2. Wheat Sowing: November 3. Short Time Gap (10-20 days) for field preparation (Bhuvaneshwari S, et al., 2019).	**Pre-Mechanization**: Manual Handling of crop residues.	**Introduction of:** 1. High yield crop varieties 2. Chemical Fertilizers 3. Modern irrigation techniques (Singh, R.B. 2000).	**Economic Constraints:** 1. High cost of Happy Seeders, Balers, and other machines 2. Selling straw for biofuel impractical due to low market demand in rural areas (Md. Kamrul Hassan, et al., 2021).	**Stubble Burning as a Common Practice:** Quick, cheap, and easy solution for field preparation.
	Post Mechanization: 1. Introduction of combine harvesters. 2. Results in large amount of leftover stubble (mainly rice). 3. Difficult in managing rice straw (can't be used as fodder) (Singh, Vikas, et al., 2019).	**Result:** 1. Higher crop productivity = Increased crop to manage residue (mainly rice straw) 2. Mechanization of farming with little time to manage residues (Singh, R.B. 2000)	**Time Pressure:** 1. 10-20 days to clear fields between rice harvest and wheat sowing 2. Delays in field preparation = Lower wheat yield (Asik Dutta, et al., 2022).	
			Resources Constraints: 1. Limited access to machinery 2. Marginal farmers often don't have financial means to buy machines (Andrea S. Downing et al., 2022).	

5. Causes of Stubble Burning

5.1 Lack of Residue Management Infrastructure

In Punjab, one of the main causes of stubble burning is the absence of infrastructure for economical and effective residue management. The use of devices like Happy Seeders, mulchers, and balers—which can assist farmers in managing crop leftovers without burning—is restricted. Small and marginal farmers frequently find these solutions to be either too costly or logistically difficult to apply, despite government efforts to give subsidies for such machinery (James Erbaugh, et al., 2024). Consequently, burning stubble continues to be the most practical way to quickly clear fields.

5.2 Short Window Between Crops

Another important element contributing to stubble burning is the short time span between the sowing of wheat and the harvesting of rice. It usually takes farmers only 15 to 20 days to get their fields ready for the following crop, which leaves little time for alternate methods or manual residue management. Farmers are under more pressure to clear the ground as soon as possible since delayed wheat sowing can result in lower yields. Farmers can fulfil the strict agricultural schedule by using burning stubble as a labor-saving, quick fix (Carlo Montes, et al., 2022).

5.3 Economic and Policy Gaps

Many farmers feel that the government's policies and subsidy programs to support sustainable farming practices are either poorly executed or insufficient (Khundrakpam, P., & Sarmah, J. K. 2023). Furthermore, farmers are not given enough incentives to switch to environmentally appropriate substitutes for stubble. For instance, there are frequently distribution delays and the subsidies offered for devices such as Happy Seeders do not always cover the entire cost. Furthermore, there aren't enough incentives for farmers to switch from stubble burning to more environmentally friendly practices like organic composting or using agricultural wastes for bioenergy. Farmers still burn stubble since it's the least expensive and fastest alternative, but without adequate financial support and policy enforcement (Bhuvaneshwari, S. et al., 2019).

5.4 Social and Cultural Factors

Beard burning customs are also influenced by social norms and cultural traditions. Punjabi farmers have been using fire as a tried-and-true technique to clear fields for decades, and many of them are ignorant of the risks it poses to the environment and their health. Furthermore, not many people are aware of the long-term advantages of sustainable residue management techniques. It is difficult to interrupt the cycle of stubble burning without successful farmer education programs or community-led initiatives, especially with older generations who may be resistant to change (Lopes, Adrian et al., 2020). [Fig. 5,6,7]

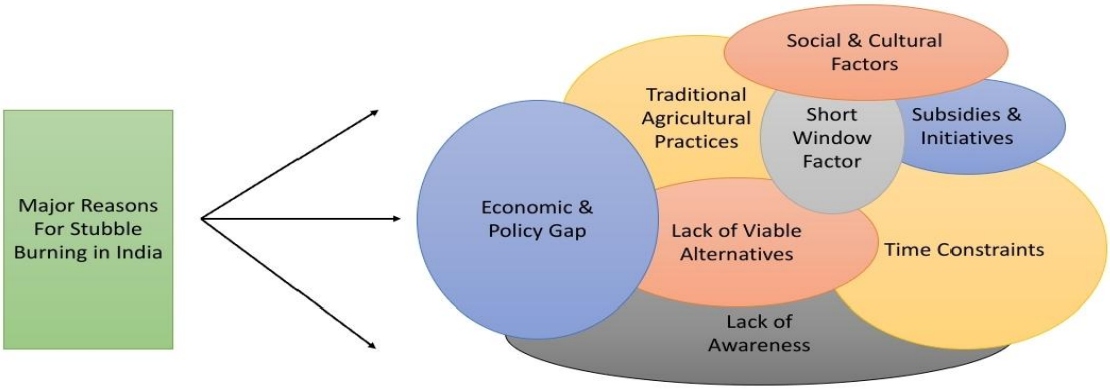

Fig. 5 Major Reasons for Stubble Burning in India

This table provides an extensive statistical summary of fire incidents that were reported in different Punjabi districts between 2016 and 2022, emphasising notable variations in the amount of stubble that was burned. The information comes from the Punjab Remote Sensing Centre in Ludhiana and shows that some districts—Barnala, Bathinda, Sangrur, and Fazilka, (Table. 1) for example—report more fire incidents than others. In 2020, there were 76,590 incidents reported. These patterns highlight the difficulties in controlling stubble and the harm that residue burning does to the environment in Punjabi agriculture. Even though there were fewer accidents in 2022 (49,922 fires), the continued high numbers suggest that policy changes and more advanced technical interventions are required. The information is crucial for directing future studies on viable substitutes and regulations to reduce stubble burning and enhance air quality, especially during harvest seasons when the problem is most severe in northern India (Kumar, Rohit & Kaur, Navneet. 2024).

Table 2 Table Showing Statistical Data of Fire Events Recorded From the Year 2016-2022

District	2016	2017	2018	2019	2020	2021	2022
Amritsar	1788	999	1151	1510	2413	2175	1542
Barnala	4585	2481	2735	3257	4519	4326	2910
Bathinda	7047	3693	5402	6036	7806	4481	4592
Faridkot	3550	2277	2570	2545	3845	3953	2693
Fatehgarh Sahib	1862	1229	828	896	1362	1724	1149
Fazilka	3063	1359	2181	1886	3125	2388	2856
Firozpur	6036	3496	4924	5313	6947	6288	4295
Gurdaspur	1769	1185	1036	1497	1938	1396	854
Hoshiarpur	709	378	175	316	407	331	259
Jalandhar	3679	1543	1198	1627	1794	2548	1388
Kapurthala	2369	1155	684	1422	1631	1797	1279
Ludhiana	7697	3239	2481	2532	4330	5817	2682
Mansa	4405	3293	3596	3924	4961	3217	2815
Moga	7150	2200	3280	3267	5843	6515	3609
Muktsar	5250	3003	4792	3961	5458	4600	3884
Pathankot	28	13	9	4	11	6	1
Patiala	4986	3829	3784	4212	5204	5368	3336
Rupnagar	554	244	82	131	209	307	246
Sangrur	9556	6968	6862	7021	9705	8006	5239
SAS Nagar	240	168	144	201	262	206	246
SBS Nagar	1100	547	256	279	192	355	5239
Tarn Taran	3619	2085	2420	3373	4528	4117	162
Malerkotla	-	-	-	-	-	1383	270
Total	81042	46384	50590	55210	76590	71304	49922

Punjab Remote Sensing Centre, Ludhiana, Punjab (India)

Fig. 6 Stumble Burning in Daylight in Different Districts of Punjab. (1) Tarn Taran, (2) Jalandhar, (3) Kapurthala, (4) Gurdaspur, (5) Amritsar, (6) Ropar, (7) Sangrur

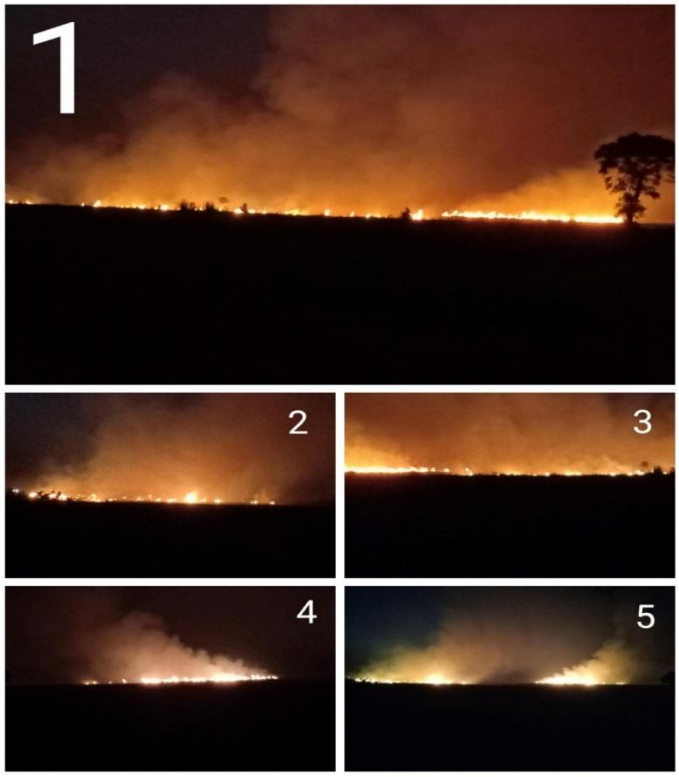

Fig. 7 Stumble Burning in Late Night in Different Districts of Punjab. (1) Barnala, (2) Faridkot, (3) Mansa, (4) Rupnagar, (5) Patiala

6. Impacts of Stubble Burning

6.1 Environmental Impacts

1. ***The contamination of air*** By releasing dangerous particulate matter (PM2.5 and PM10), carbon monoxide, methane, and other pollutants into the sky, stubble burning greatly contributes to air pollution. Long-distance transport of smoke from burning stubble affects not only Punjab's air quality but also that of nearby states and cities. Hazardous air quality conditions might result from a sharp increase in particulate matter concentrations in the air during harvest season (Pratika Chawala, H.A.S. Sandhu, 2020).
2. ***Second, Greenhouse Gas Emissions*** In order to combat global warming and climate change, stubble burning is a practice that increases greenhouse gas emissions. Airborne greenhouse gases, including carbon dioxide, are released during the burning of biomass. Local climates and weather patterns are also impacted, in addition to contributing to global warming. Broad effects on global climate systems may result from the cumulative effect of these emissions from stubble burning (Monish Vijay Deshpande, et al., 2023).
3. ***Degradation of Soils*** Burning stubble can cause soil degradation by removing organic matter and vital nutrients. By burning the remains, valuable biomass that may otherwise improve soil fertility is eliminated. Over time, this technique may cause a deterioration in soil health by upsetting the normal soil structure. In the long run, continuous stubble burning might have a detrimental effect on agricultural output by reducing soil microbial activity (Singh, G. et al., 2021).

6.2 Health Impacts

4. ***Issues with Public Health*** Burning stubble produces smoke and other pollutants that are extremely harmful to the public's health. Numerous health concerns, including respiratory disorders and cardiovascular ailments, are associated with exposure to air pollution, especially particulate matter. Because vulnerable people are more susceptible to changes in air quality, such as children and the elderly, they are particularly at risk. Research indicates that during the stubble burning season, hospital admissions for respiratory conditions rise (Chakrabarti, S. et al., 2019).
5. ***Burden of Healthcare*** The burden of stubble burning on healthcare systems affects public health services and results in significant financial consequences. Poor air quality can cause an increase in health-related problems, which can raise hospitalisation rates, raise healthcare costs, and reduce productivity in those who are impacted. The overall financial impact on society increases when peak pollution seasons place additional strain on healthcare systems (Devesh Singh et al., 2022).

6.3 Economic Impacts

6. ***Productivity in Agriculture*** The productivity of agriculture may be greatly impacted in the long run by the soil deterioration brought on by stubble burning. Reduced crop yields, decreased farmer profitability, and increasing food poverty are all caused by depleted soil health. Farmers may need to use more chemical fertilisers when soil fertility decreases, which would exacerbate environmental problems (Pradhan, Pratistha 2024).
7. ***Economic Costs*** The financial cost of the negative effects stubble burning has on the environment and human health is significant. The costs of healthcare, environmental cleanup, and decreased agricultural productivity fall on governments and society. This financial burden might impede economic growth and take funds away from other vital sectors like infrastructure and education (Devesh Singh et al., 2022). [Fig. 8,9]

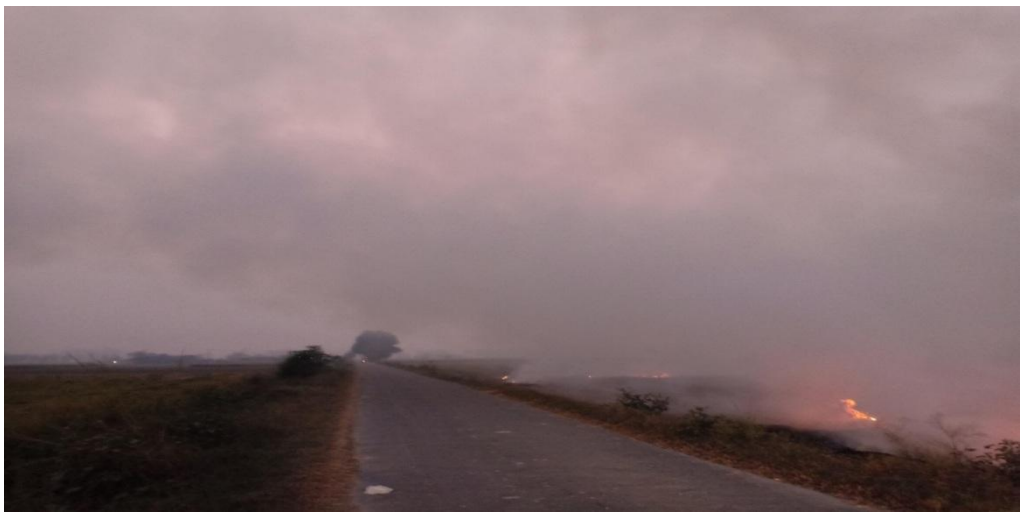

Fig. 8 Post Stubble Burning Air Pollution

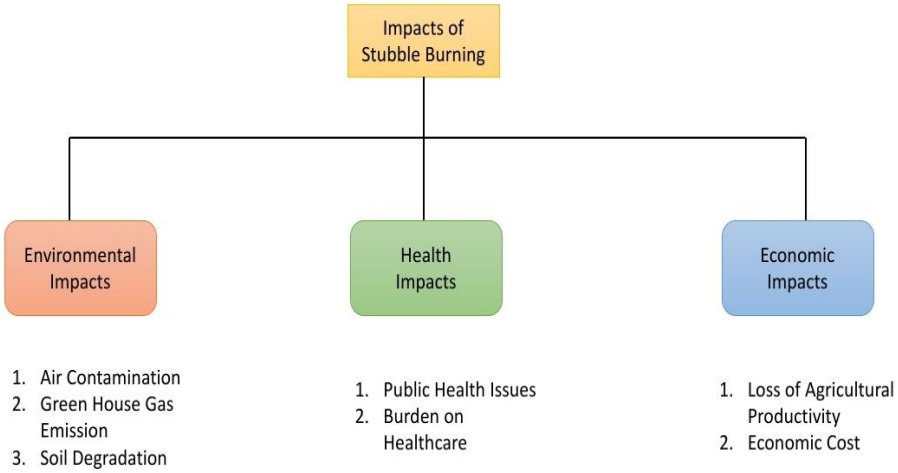

Fig. 9 Post Stubble Burning Potential Impacts

7. Current Mitigation Efforts and Challenges

7.1 Government Policies and Initiatives

The Indian government has taken a number of measures to alleviate the problem of Punjabi stubble burning, including policies and initiatives. One of the most important of them is the Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) program, which gives farmers direct financial support so they can spend money on sustainable farming methods. (Ramit Gottipati and others, 2021). Initiatives that support in-situ residue management also push farmers to employ crop residues on their fields as an alternative to burning them. To enable improved crop residue management, subsidies for equipment like the Happy Seeder and Super Straw Management System have been implemented. Nevertheless, despite these initiatives, there are still obstacles to overcome before these policies can be widely embraced and complied with (Abdurrahman, Muhammad, et al., 2021).

7.2 Technological Solutions

There have been various technical methods created to address the problem of stubble burning. These include sophisticated stubble-managing equipment like Happy Seeders, which enable simultaneous crop sowing while leaving crop leftovers on the field. Other technologies, including balers and mulchers, assist in gathering and shredding crop waste for later applications. By offering farmers effective and practical techniques for managing residue, these technologies hope to lessen their dependency on burning. The field is still undergoing research and development, which could lead to better stubble management techniques (Saini, Dinesh, et al., 2018).

7.3 Limitations

Notwithstanding advancements in technology and policy, a number of constraints reduce the efficacy of mitigation techniques. Problems with policy enforcement frequently result from insufficient oversight and responsibility, which causes farmers to disobey the law. Furthermore, there is a dearth of widespread adoption of existing technology, mostly because smallholder farmers may find the high expenses of buying and maintaining gear to be unaffordable. It is difficult for many smallholders, who account for a sizable share of Punjab's agricultural population, to invest in these technologies without sizable financial support or incentives. To promote wider adoption, it is also necessary to communicate the advantages and perceived efficacy of alternative approaches more effectively (Khanna, Richa 2021). [Fig. 10]

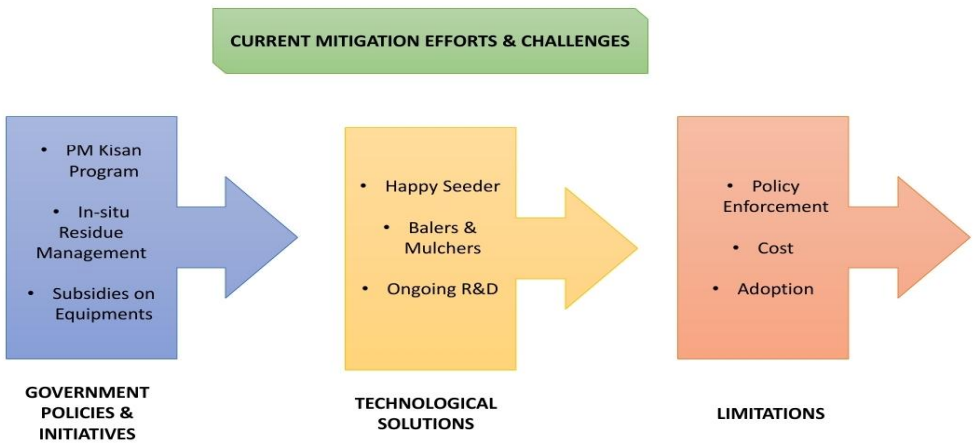

Fig. 10 Current Mitigation Efforts and Challenges Against Stubble Burning

Following data analysis, it was discovered that, generally, patterns of stubble burning from 2016 to 2022 showed a downward trend. (Fig.11) displays the patterns of burning stubble. The issue of stubble burning, particularly the burning of paddy-straw, is gaining attention from farmers, and the fall in the geographical patterns of stubble burning can be attributed mostly to government regulations, incentives, and interventions. Therefore, we can categorise each year into three groups based on the overall number of severe occurrences that occurred: low, medium, and high. A thorough explanation of each category is provided below (Kumar, Rohit & Kaur, Navneet. 2024).

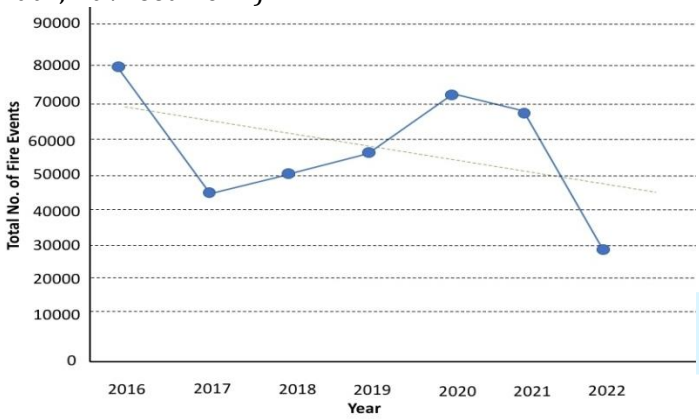

Fig. 11 Graph Shows the Recorded Trends in the Fire Events from 2016-2022 (It is evident from the graphical representation that by the year 2022 dramatic decrease in fire events across Punjab has been witnessed with minor fluctuation between 2017-2021)
[*Punjab Remote Sensing Centre, Ludhiana, Punjab*]

8. Sustainable Alternatives to Stubble Burning

8.1 Technological Interventions

1. In-situ administration to lessen the dependency on stubble burning, a number of in-situ management strategies have been developed. With the help of technologies like the Happy Seeder, farmers can plant fresh crops without having to clear away or burn crop residue. By covering the soil with crop wastes or other organic materials, a process known as mulching, weeds are inhibited and soil health is enhanced by improving moisture retention and nutrient cycling. Furthermore, farmers can plant seeds straight into the soil with direct seeding technologies, retaining soil fertility and structure while making use of crop leftovers (Buttar, Gurmeet et al., 2023; Muzamil, M. et al., 2023).
2. Ex-situ solutions concentrate on finding productive uses for agricultural leftovers. This involves turning wastes into biofuels, which can lessen reliance on fossil fuels and act as an alternate energy source. An further practical technique that improves soil fertility and health by turning agricultural waste into nutrient-rich organic matter is composting. Remainders can also be converted into biogas, which offers a sustainable waste management solution in addition to renewable energy. A circular economy can be facilitated by the use of crop leftovers as raw materials in sectors like the paper industry (Muzamil, M. et al., 2023).

8.2 Agro-Ecological Practices

3. ***Diversification of crops*** Because crop diversification encourages alternate cropping practices, it is essential in lowering stubble burning. Traditional rice-wheat systems can benefit from the addition of pulses, maize, and horticulture crops, which can enhance soil health and lessen the need to burn leftovers. Crop diversification promotes biodiversity, disrupts pest cycles, and maximises resource use—all of which contribute to more sustainable agricultural methods (Singh, G. K. 2022).
4. ***Ecological Farming*** Sustainable agriculture requires the use of techniques like integrated nutrient management, organic farming, and reduced tillage. Minimising soil disturbance through less tillage preserves soil biodiversity and structure. By using less chemical pesticides and fertilisers, organic farming promotes healthier ecosystems. By combining organic and inorganic fertiliser sources, integrated nutrient management maximises plant development while reducing its negative effects on the environment (Saliu, Fluturim et al., 2023).

8.3 Policy and Financial Incentives

5. ***Assistance and Encouragement for Substitutes*** In order to encourage farmers to embrace sustainable options, government subsidies and financial support are essential for residue management measures. Financial aid for the purchase of tools, such Happy Seeders or composting units, can greatly lessen farmers' financial burden and encourage them to stop burning stubble (Bhuvaneshwari S, et al., 2019).
6. ***Market Mechanisms and Carbon Credits*** Putting in place carbon credit programs can encourage farmers to cut back on emissions related to burning stubble. Farmers can obtain carbon credits by implementing sustainable practices that reduce greenhouse gas emissions. These credits can then be exchanged on carbon markets. This helps with national and international efforts to mitigate climate change in addition to giving farmers another source of income (Cariappa, A.A.G. et al., 2024).

7. Programs for Farmer Education and Awareness Programs for raising awareness and educating farmers are crucial to encouraging sustainable farming methods. Farmers can be empowered to make educated decisions via programs that educate them about the advantages of alternative techniques, the financial benefits of sustainable agriculture, and the environmental effects of stubble burning. The promotion of a sustainable culture can be greatly aided by community seminars, extension services, and partnerships with nearby agricultural institutions (Kumar, P. et al., 2015). [Fig. 12]

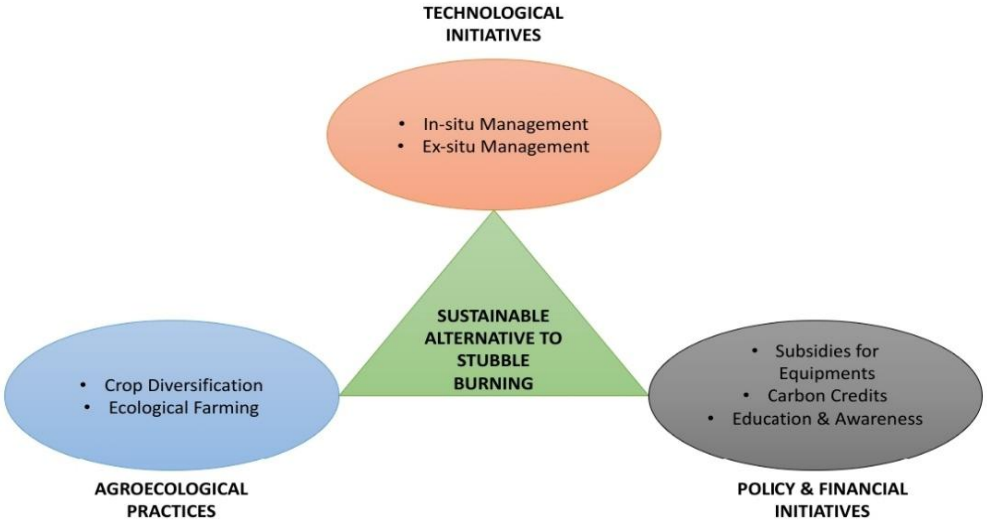

Fig. 12 Sustainable Alternatives to Stubble Burning

9. Future Directions and Research Opportunities

The use of crop residues In the future offers fascinating chances for creativity. Putting a strong focus on the development of technology for the generation of bioenergy can greatly improve the sustainability of agricultural activities. This includes investigating cutting-edge biogas systems and efficient methods for converting crop leftovers into biofuel. Furthermore, the ability to produce biochar from agricultural waste is drawing interest due to its potential to enhance soil fertility and absorb carbon, thereby aiding in attempts to mitigate the effects of climate change. Additional research on organic composting methods is also necessary, with an emphasis on optimising compost production efficiency and applying it to enhance soil health. These fields of study have the potential to yield profitable solutions for farmers in the form of sustainable techniques for handling agricultural waste (Prasad, Shiv et al., 2020).

9.1 Policy Integration and Governance

Addressing the issues associated with stubble burning and advancing sustainable practices requires the integration of governance and regulatory frameworks. Future research should focus on building comprehensive policies that facilitate multi-stakeholder collaboration between the government, commercial sector, and research institutions. Coordination of efforts to establish incentives for sustainable behaviours, guarantee the enforcement of laws, and encourage information exchange among stakeholders can all be facilitated by effective governance structures. In Punjab's agriculture sector, such cooperative methods are necessary to successfully execute residue management plans and attain environmental sustainability (Parihar, D. et al., 2023).

9.2 Regional Adaptations

It Is important to customise techniques to the distinct requirements of Punjab's agrarian sector in order to guarantee the viability of farming methods. Subsequent investigations ought to concentrate on recognising and customising efficacious approaches from other areas to suit the indigenous milieu, taking into account variables like temperature fluctuations, financial circumstances, and customary customs. It will be essential to include farmers in the study process to comprehend their viewpoints and challenges in order to develop practical solutions that enhance farmer livelihoods while addressing environmental issues. Furthermore, evaluating how different cropping systems and practices affect regional ecosystems might shed light on how to expand agriculture sustainably while meeting local requirements (Elena Grigorieva, et al., 2023). [Fig. 13]

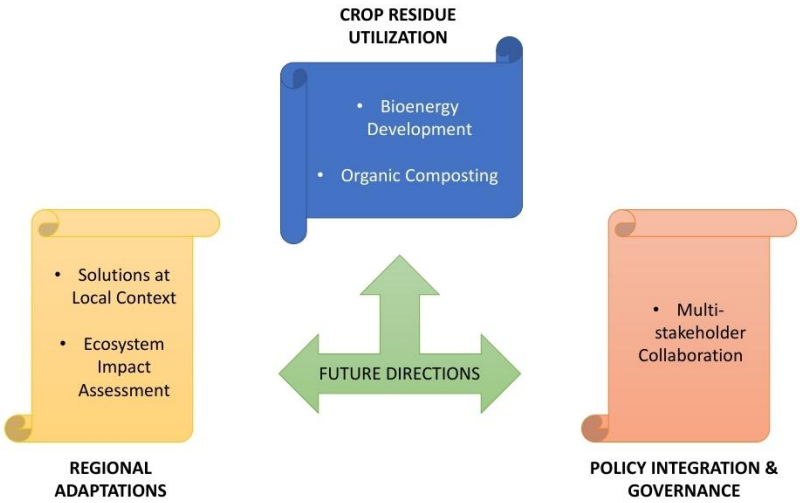

Fig. 13 Future Directions & Research Opportunities in Stubble Burning

10. Conclusion

10.1 Summary of Key Findings

The significant problem of stubble burning in Punjab has been brought to light by this review, which also outlines its root reasons, which include a lack of infrastructure for residue management, financial limitations, and cultural considerations. This practice has major negative effects on air pollution, greenhouse gas emissions, and public health issues in addition to degrading the environment. In addition to endangering agricultural productivity, the economic fallout places a heavy financial burden on public health systems. Agro-ecological techniques like crop diversification, technology interventions like in-situ management, and the introduction of laws and financial incentives targeted at curbing stubble burning have all been investigated as viable solutions in light of these difficulties.

10.2 The Way Forward

Adopting integrated strategies that incorporate policy, technology, and farmer participation is imperative going ahead. It will be crucial to fund research and development for cutting-edge technology that facilitate efficient management of crop residues. Policies also need to be created to support sustainable farming methods while making sure that farmers can profit from them. Including farmers in the process of making decisions and educating them about sustainable practices can increase the rate of adoption and produce better results.

10.3 Final Thoughts

In the end, it is impossible to exaggerate the significance of implementing sustainable practices. The long-term survival of Punjab's agrarian economy depends on striking a balance between environmental preservation and agricultural productivity. In addition to addressing current health and environmental issues, adopting sustainable alternatives to stubble burning will help build a more resilient agricultural system that will sustain farmer livelihoods while safeguarding our natural resources for coming generations. All parties involved in the agriculture industry must be committed to the road towards sustainability, highlighting the necessity of group effort to promote a more sustainable and healthful future.

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