



REVIEW ARTICLE

Agro-waste management in India: A thematic review of practices, impacts and sustainable pathways

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Abstract

Recent evidence on agro-waste management in India is synthesised through a thematic review of 58 peer-reviewed studies published between 2020 and 2025. Using a preferred reporting items for systematic reviews and meta-analyses (PRISMA)-based systematic approach, the study analyses disposal practices, recycling pathways, soil health impacts, technological innovations, socio-economic drivers, environmental implications and governance mechanisms. The synthesis integrates evidence related to residue generation, disposal practices, recycling pathways, environmental impacts and policy interventions across diverse agricultural regions of India. The findings indicate that residue burning continues across many agricultural regions due to operational and institutional constraints. In contrast, recycling approaches including composting, mulching, biochar application and *in situ* incorporation significantly improve soil organic carbon, nutrient availability and microbial activity. However, adoption remains uneven due to economic, technical and institutional barriers. The study advances a systems-level perspective, highlighting that agro-waste management is shaped by interactions among technology, policy and farmer decision-making. It concludes that enabling governance frameworks, improved service delivery systems, functional machinery networks and viable residue-based value chains are essential for achieving sustainable and scalable agro-waste management in India.

Keywords: bioeconomy; circular economy; crop residue burning; crop residue management; resource recovery; soil health

Introduction

Agricultural systems generate substantial quantities of agro-waste globally, including crop residues such as straw, husks and stubble. Although animal-derived wastes form an important component of agricultural waste systems, the present review primarily focuses on crop residue management practices in Indian farming systems. These materials present a twin challenge when handled improperly. They contribute to environmental degradation through air pollution, greenhouse gas emissions and water contamination. When used well, they are valuable resources for bioenergy, composting, soil supplements and circular bioeconomy pathways. While other recycling methods like mulching, composting and biochar production have shown a lot of promise to improve soil organic carbon and nutrient cycling. Burning crop residue in particular has been found to be a substantial source of particle emissions and greenhouse gases (1–3).

Approximately 70–80 % of the 350–500 million tonnes of agricultural residues produced in India each year are concentrated in cereal-based systems, such as the rice-wheat cropping regions of northern India. Particularly in Punjab, Haryana and western Uttar Pradesh, a significant amount of these wastes is either underutilised or burned on open fields. Large amounts of loose straw are still in fields as a result of the widespread use of mechanised harvesting,

especially combine harvesters, which presents serious management issues for farmers. Changes in farming practices have reduced the traditional uses of leftovers, such as domestic fuel and fodder, increasing the amount of extra biomass that needs disposal (4, 5).

In many parts of India, open-field burning is still a common practice despite the availability of sustainable alternatives. Research shows that operational constraints, such as limited sowing windows, labour shortages and restricted access to machinery, have a significant impact on residue burning (6–8). Rapid residue clearing is crucial for adhering to cropping schedules since farmers frequently have limited operational durations between successive crops. Despite its acknowledged negative effects on the environment, burning appears to be a quick and economical remedy in such situations (9).

Burning residue has significant negative effects on the environment and public health. Studies show that during burning times, concentrations of carbon monoxide, black carbon and particulate matter (PM_{2.5} and PM₁₀) significantly increase, contributing to severe air pollution and related respiratory hazards (10, 11). Previous research has shown that burning agricultural residue considerably increases seasonal PM_{2.5} concentrations in northern India during post-harvest periods, particularly in October and

November. In addition to having negative effects on the atmosphere, repeated burning lowers soil organic carbon, disrupts microbial activity and inhibits nutrient cycle processes, all of which contribute to long-term soil deterioration (12–14). These consequences show that controlling agro-waste is not only a farm-level issue but also a broader environmental and public health concern.

On the other hand, an increasing number of studies highlights the advantages of resource recovery and recycling. In a variety of agroecosystems, techniques like composting, vermicomposting, residue inclusion and biochar application have been demonstrated to improve soil fertility, microbial biomass and crop yield (15–17). Further enabling effective residue utilisation while lowering reliance on burning are technological advancements, such as *in situ* residue management tools as Happy Seeder and straw choppers (18–20).

However, because of institutional, technical and socioeconomic obstacles, the implementation of these sustainable methods is still uneven. Large-scale adoption is nevertheless hampered by limited policy implementation, poor extension services, high operating expenses and restricted access to machinery (21–23). International experiences show that rather than relying just on regulatory actions, efficient residue management necessitates integrated policy support, technological accessibility and commercial incentives (24).

Studies on agro-waste management are still dispersed across agronomic, environmental, technological and socioeconomic aspects despite growing research interest. Few studies combine these elements to offer a thorough systems-level comprehension of the dynamics of residue management. Designing scalable and lasting solutions requires addressing this gap.

Therefore, the present study adopts a thematic analytical approach based on 58 peer-reviewed publications (2020–25). It aims to synthesise evidence on agro-waste management practices in India, including disposal and recycling pathways and their environmental and soil health impacts. The study further examines the socio-economic and technological factors influencing farmer decision-making and develop a systems-level understanding of how governance, technology and market conditions interact to shape sustainable residue management transitions.

The majority of the literature on crop residue management is still fragmented, concentrating only on agronomic, environmental, or technological aspects without incorporating socioeconomic and governance viewpoints, despite the increasing number of research and reviews on the subject. Furthermore, residue management as a systems-level problem influenced by interactions between technology, politics and farmer decision-making has received little attention. In order to create an integrated framework that connects ecological outcomes with socio-technical and institutional dynamics, this study offers a thorough thematic synthesis of recent literature (2020–25), providing a more comprehensive understanding of sustainable agro-waste management in India.

Materials and Methods

Literature search and study selection

A systematic literature analysis was conducted using the Scopus database in compliance with preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines in order to locate relevant peer-reviewed literature on agro-waste

management. The search period was restricted to 2020–25 in order to take into account recent developments, state-of-the-art technology and ongoing policy interventions in agro-waste management. This time span was selected to include the most recent scientific findings and sustainability-focused management strategies. Despite the extensive peer-reviewed coverage of Scopus, some unpublished or region-specific studies might not have been included due to the exclusion of other databases and grey literature.

A set of structured search strings was developed by combining keywords related to agro-waste (e.g., “crop residue”, “agricultural waste”, “residue management”), soil parameters (e.g., “soil fertility”, “soil organic carbon”, “nutrient status”), recycling approaches (e.g., “composting”, “biochar”, “mulching”, “organic amendments”) and socio-economic aspects (e.g., “farmer behaviour”, “adoption”, “smallholder farmers”). The detailed search strategy is provided in Supplementary Table 1.

A total of 2542 records were identified in the initial search. After the removal of 284 duplicate records arising from repeated database indexing and overlapping search outputs, 2258 records were screened based on titles and abstracts. Of these, 1265 records were excluded as they were not relevant to agricultural waste management. Full-text assessment was conducted for the remaining 993 records, of which 141 articles were retrieved for eligibility evaluation. Subsequently, 83 studies were excluded due to unclear methodology, insufficient findings, or thematic inconsistency. Ultimately, 58 studies were included in the qualitative synthesis, as they met all inclusion criteria. The study selection process is illustrated using a PRISMA flow diagram (Fig. 1) and the inclusion and exclusion criteria applied during screening are summarised in Table 1. The PRISMA framework enhanced transparency and reproducibility throughout the screening and selection process.

Inclusion and exclusion criteria

The influences of soil fertility, farmer adoption in agricultural systems, recycling or resource recovery measures and agricultural residue management techniques were all taken into account. Only research carried out in actual farming environments was taken into account. Studies that focused on non-agricultural waste streams (such industrial or biomedical waste), lacked empirical results, or were purely theoretical with no practical use were excluded. Review articles, conference abstracts, non-English publications and research with inadequate methodological transparency were also excluded in order to maintain analytical consistency and reliability.

Thematic analysis and data extraction

To methodically find, classify and evaluate themes throughout the chosen works, a thematic analysis approach was used. Each article's study site, research focus, residue management strategy, methodological methodology and major findings pertaining to environmental, soil and socioeconomic consequences were extracted.

Iterative reading and labelling of the chosen studies led to the inductive development of themes. Finding recurrent trends in disposal methods, recycling routes, soil health implications, environmental effects, technical advancements, socioeconomic limitations and governance systems was the main goal of the coding procedure. A systematic thematic framework was created by grouping these codes into more general conceptual groups. The thematic synthesis allowed for the identification of recurrent links between residue management strategies, environmental impacts, technological uptake and socioeconomic constraints across different agricultural areas.

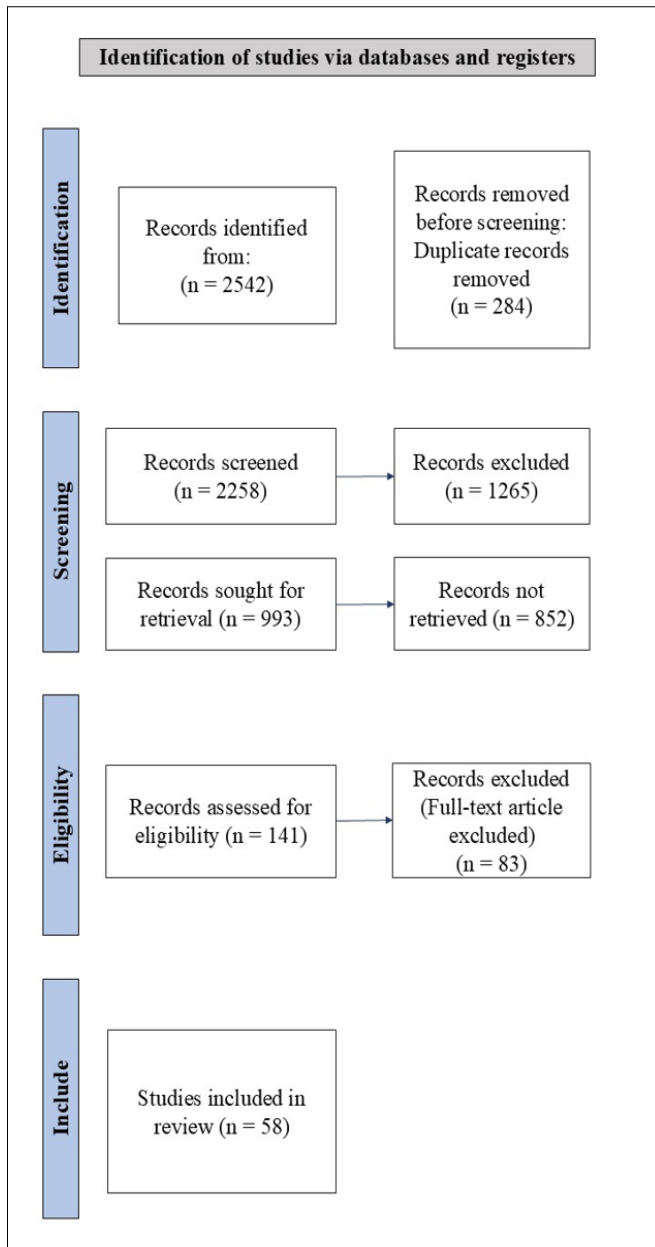


Fig. 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram illustrating the identification, screening, eligibility assessment and final inclusion of studies for thematic analysis.

Seven major themes emerged from the analysis. They are (i) conventional disposal methods; (ii) recycling and resource recovery pathways; (iii) soil health and fertility enhancement; (iv) technological innovations; (v) socio-economic and technical factors; (vi) implications for public health and the environment; and (vii) institutional and policy support. The thematic framework is shown in Fig. 2.

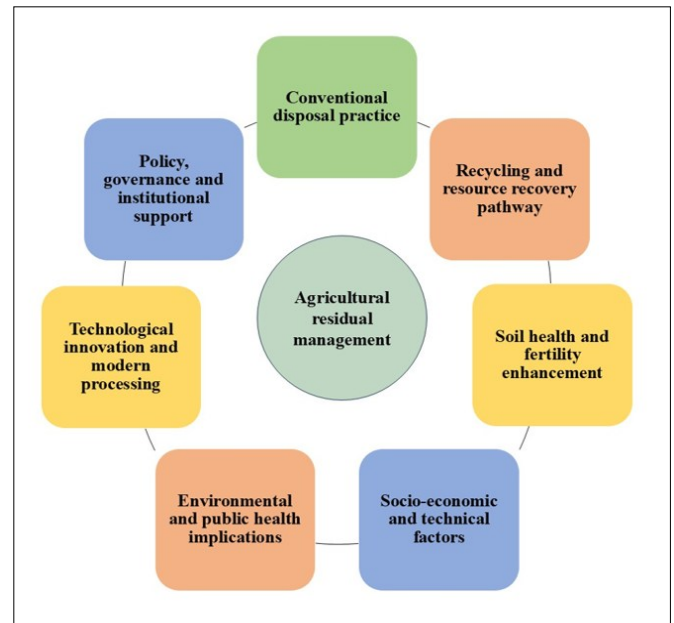


Fig. 2. Thematic framework illustrating the seven key dimensions of agro-waste management identified through the review.

Validation and analytical rigour

Through several rounds of evaluation, the theme coding procedure was cross-verified to guarantee analytical consistency and robustness. Every study was reassessed to ensure that the themes were assigned consistently. To increase the credibility of the results, triangulation among research covering comparable agro-ecological and socio-economic environments was carried out. This procedure reduced interpretational bias and increased the thematic synthesis's dependability. This strategy made sure that the final themes represented both recurrent trends and context-specific differences in agro-waste management techniques.

A thorough systems-level understanding of agro-waste management in India is made possible by the integration of agronomic, environmental, technological and governance aspects through the use of a theme analytical framework.

Quality assessment of included studies

A simplified critical appraisal skills programme (CASP)-based methodology tailored for thematic synthesis studies was used to assess the quality of included research in order to improve the review's methodological rigour. The evaluation took into account the objectives' clarity, the methodology's transparency, the results' adequacy, the conclusions' dependability and their relevance to the management of agricultural waste. During the eligibility screening phase, studies with ambiguous methodology or insufficient analytical detail were excluded. This quality appraisal process enhanced the reliability and consistency of the final thematic synthesis.

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Studies that look at waste management techniques, treatment approaches, or agricultural residues	Research on waste streams other than agriculture, such as municipal, industrial and biomedical
Documents detailing results pertaining to resource recovery, recycling effectiveness, disposal practices, or environmental advantages	Articles that do not provide results that can be analysed or have unclear outcome measurements
Research assessing anaerobic digestion, biochar systems, vermicomposting, composting and wastewater treatment in an agricultural setting	Research that merely provides theoretical descriptions of technology without applying them to agricultural waste
Studies carried out in rural production settings, farming systems, or agricultural communities	Research conducted solely in industrial laboratories with no connection to wastes produced on farms

Results and Discussion

Conventional disposal practices

Cereal straw leftovers in northwest India, horticulture biomass and pruning residues in Himalayan regions and mixed organic residues in northeastern states are only a few examples of the diverse types of agro-waste found in India's agroecosystems. For example, horticultural pruning leftovers are more prevalent in Himalayan regions, rice and wheat straw dominate residue streams in Punjab and Haryana and mixed biomass residues and shifting cultivation residues are commonly found in northeastern agroecosystems. Across the reviewed studies, conventional residue disposal practices primarily include open-field burning, boundary dumping, the removal of residue for fodder or fuel and unmanaged natural decomposition. Among these, open-field burning is consistently reported as one of the dominant disposal methods in rice-wheat systems, with several studies indicating high seasonal prevalence in northwestern India following mechanised harvesting (25). In such systems, large quantities of loose straw remain after harvesting, necessitating rapid clearance for subsequent crop establishment.

Residue removal and complete stubble extraction are also commonly practiced, especially where mechanised sowing requires a clean seedbed (1, 26). In some cases, residues are transported off-field for alternative uses or disposal, while in others they are left unmanaged to decompose naturally. However, these practices often result in inefficient nutrient utilisation and loss of potential biomass value (27).

The persistence of these disposal methods reflects farmers' response to immediate operational constraints, including narrow sowing windows, labour shortages and limited access to residue management machinery. Burning and removal provide rapid and low-cost solutions for field clearance, enabling timely crop establishment despite their adverse long-term effects (16, 27, 28).

Several studies highlight that these practices negatively affect soil health by reducing soil organic carbon, weakening soil structure and disrupting biological activity (27, 29). Additionally, the continued reliance on conventional disposal methods is reinforced by underdeveloped mechanisation services, limited access to custom hiring centres and inconsistent institutional support (30). The characteristics, advantages and limitations associated with each method is summarised in Table 2.

Recycling and resource recovery pathways

The research reviewed indicates a clear shift from viewing agricultural residues as waste to recognising them as valuable biological resources. Composting, vermicomposting, mulching, biochar generation, microbial decomposition and biomass valorisation are some of the recycling and treatment processes that have been identified.

Composting and residue recycling practices, particularly when combined with organic amendments and improved cropping systems, have been reported to enhance soil organic carbon accumulation, improve nutrient cycling efficiency and promote favourable biological and chemical changes in soil properties, thereby contributing to long-term soil health and sustainability (31). Compared to traditional composting, vermicomposting creates nutrient-rich organic additions with increased microbial activity and speeds up decomposition even further (32).

It has been repeatedly demonstrated that residue retention through mulching and *in situ* integration under reduced or zero-tillage regimes improves microbial biomass, soil aggregation and moisture retention (16, 33). Particularly in intensive agricultural systems, these techniques improve long-term soil fertility and nutrient cycling.

The manufacture of biochar from agricultural waste has drawn interest as a sustainable method of managing carbon emissions. Applying biochar to soil improves its physicochemical characteristics, increases nutrient retention and lessens reliance on artificial fertilisers (34). Similarly, leftovers are transformed into energy-rich products by torrefaction and biomass densification methods, providing prospects for both soil amendment and the production of renewable energy (27). However, some research suggests that early application of biochar may temporarily immobilise nutrients in particular types of soil, which could have an impact on crop response and short-term nutrient availability.

Furthermore, it has been shown that microbially assisted decomposition methods, like the use of better organic formulations and residue-degrading consortia, increase soil enzymatic activity and breakdown rates (16, 10). These biological methods enable efficient soil regeneration and nutrient recycling.

Table 2. Conventional residue disposal practices: Characteristics, advantages and limitations

Disposal practices	Characteristics	Advantages	Disadvantages	Reference
Residue removal from field	Farmers remove crop residues completely as part of the conventional system	Helps in faster land preparation for next crop	Leads to decline in soil organic matter and weak soil structure	(12)
Residues left unmanaged after harvest	Biomass often remains unattended, allowed to dry and degrade naturally	No labour or cost required for management	Unmanaged residues cause nutrient loss and slow natural decomposition	(27)
Open-field burning of rice straw	Rice straw placed in the field after harvest with minimal handling	Quick clearance of fields without machinery	Leads to residue accumulation and reduced soil microbial activity	(10)
Uncontrolled biomass decomposition	Agricultural residues left to decompose under uncontrolled environmental conditions	Fully natural degradation with zero input	Inefficient decomposition and loss of potential biomass value	(27)
Complete stubble removal after combine harvest	Combine-harvested fields are cleared of stubble for uniform seedbed	Smooth preparation of seedbed and compatible with available machinery	Reduces residue recycling and affects fertility improvement	(16)
Residue extraction for off-field disposal	Farmers transport residues outside the plot for disposal as per convenience	Helps keep fields clean for mechanical sowing	Off-field disposal causes waste accumulation in dumps and environmental stress	(8)

Overall, these recycling methods convert agricultural waste into valuable inputs that enhance soil health, increase productivity and reduce environmental impacts. These methods are regenerative procedures that incorporate residue management into sustainable agriculture systems rather than merely being disposal solutions. A comparative summary of the techniques, resulting products, applications and related benefits and drawbacks is given in Table 3.

The reviewed research collectively show that sustainable residue recycling pathways support broader ecosystem functions such as nutrient cycling, carbon stabilisation and climate-resilient soil management, in addition to waste reduction.

Soil health and fertility enhancement

The reviewed literature clearly demonstrates that recycling agricultural residues is essential for improving soil fertility and overall soil health. Recycling channels can restore soil organic matter and biological functioning, in contrast to traditional disposal techniques like burning or removal (35, 36). Numerous field-based studies have demonstrated that composting, vermicomposting, mulching, biochar application and residue retention under reduced or zero-tillage systems improve soil organic carbon (SOC), microbial biomass, nutrient availability and moisture retention (37). When compared to traditional tillage techniques, field-based research in rice-wheat and maize cropping systems shows that residue absorption enhances microbial biomass, enzymatic activity and carbon stability (38, 39).

Organic additions generated from leftovers, like compost and biochar, help with soil aggregation and pH regulation in addition to increasing the availability of essential nutrients including nitrogen (N), phosphorus (P) and potassium (K) (40). These improvements increase the soil's capacity to support microbial communities, retain moisture and sustain agricultural productivity over time. Several studies demonstrate how continuous recycling of residues improves soil structure and function over time. Higher SOC levels improve soil aggregation, water-holding capacity and climate stress resilience. Increased microbial and enzymatic activity support soil regeneration and efficient nitrogen cycling (37).

Overall, the results show that recycling residues turns soil from a passive medium into a dynamic biological system that can maintain ecological balance and production. Sustaining soil organic matter through residue management is therefore critical for long-term soil sustainability, as evidenced by consistent improvements

reported across studies.

Technological innovations and modern processing

Technological advancements play a crucial role in enabling sustainable agro-waste management by reducing labour constraints and improving operational feasibility. Across the reviewed studies, mechanised *in situ* residue management tools have emerged as key interventions for minimising open-field burning and promoting residue incorporation (41). Equipment such as Happy Seeder, Super Seeder, straw choppers and rotavators allow farmers to manage dense crop residues while simultaneously preparing seedbeds for subsequent crops. These technologies facilitate zero-tillage or reduced-tillage systems, conserving soil moisture and reducing labour requirements (20, 42, 43). Such equipment greatly lessens reliance on burning by allowing direct sowing without first removing residue. Despite its benefits, systems like the Happy Seeder may encounter operational difficulties in situations with high soil moisture, large residue load, low technical expertise and smallholder farmers limited financial resources.

Opportunities for resource recovery have increased due to developments in residue processing technology as well as field-level mechanisation. Crop scraps are transformed into stable carbon-rich materials that improve soil quality and lower fertiliser requirements using biochar production facilities, such as inexpensive pyrolysis systems (34, 44, 45). Similar to this, energy-dense products that can be used in both industrial and agricultural settings are produced using torrefaction and biomass densification methods (27). Organic residue recycling is now more efficient and scalable due to recent advancements in composting technologies, such as mechanical shredders and quick composting systems (46). These approaches improve the quality of produced organic amendments and shorten the breakdown time.

Improved residue control is also facilitated by digital and monitoring systems. In order to identify fire incidents, track residue spread and assist with intervention planning decision-making, remote sensing and geographic information system (GIS) technologies are being utilised more and more (47). Environmental monitoring and more focused policy execution are made possible by these technologies.

The advances in technology typically bridge the gap between the real-world implementation of sustainable residue management strategies. By reducing labour intensity, increasing operational efficiency, resulting in value-added products, these

Table 3. Agro-waste recycling and resource recovery pathways: Products, applications, advantages and limitations

Recycling / treatment method	Product derived	Application	Advantages	Disadvantages	Reference
Composting of residues (aerobic decomposition of residues using turning and moisture management)	Straw-decomposition boosting mix	Applied to soil to speed up residue breakdown	Improves soil carbon and nutrient supply	Needs time, labour, proper Carbon: Nitrogen (C:N) ratio	(10)
Torrefaction of rice straw (heating biomass under low oxygen to create stable bio-material)	Carbon-rich torrefied straw granules	Used as carbon enhancing soil amendment	Produces energy-dense carbon product	Requires controlled equipment	(27)
Biomass valorisation (residues processed for industrial energy/biofuel outputs)	Densified straw bioenergy pellets	Used as soil carbon additive or energy-linked soil input	Adds economic value, reduces waste load	Requires logistics and industrial demand	(27)
Microbial-enriched soil inputs	Zinc-enhanced organic soil booster	Incorporated into calcareous soils	Faster breakdown, improved soil enzymes	Inoculant efficiency varies with environment	(10, 16)
Biological residue enhancement	Multi-residue field compost blend	Applied before sowing as soil amendment	Increases nutrient availability	Dependent on microbial efficiency	(16)

technologies make recycling systems more viable and scalable. Their effectiveness is still influenced by institutional support structures, cost and accessibility. The long-term sustainability of these technologies depends on their affordability, ease of upkeep, compatibility with local agricultural service systems and regional adaptation.

A conceptual mapping of technological innovations and modern processing solutions identified across the reviewed studies is presented in Fig. 3.

Socio-economic and technical factors

The examined research consistently shows that practical and economic factors, rather than ignorance, play a major role in farmers' decisions about residue management. Labour availability, time limits, access to machinery and quick financial benefits are important factors that affect these choices (17, 48, 49). The viability of labour-intensive recycling techniques is severely limited by labour shortages during periods of high harvest. In these situations, farmers typically choose burning or removal as the quickest way to remove residue. Similarly, the adoption of *in situ* recycling technologies is hindered, especially among smallholders, by restricted access to equipment including seeders, mulchers and residue integration tools (22).

Decision-making is also influenced by economic factors. Because these choices offer quick financial rewards, residues are frequently redirected for alternate applications including fuel, livestock feed, or sale. On the other hand, recycling methods like composting or producing biochar can be more expensive, time-consuming and have unclear advantages, which would make them less appealing to farmers (17). Extension-related and institutional factors are also quite important. Numerous studies show that the adoption of better residue management techniques is hampered by poor extension services, few training opportunities and insufficient technical assistance (21, 50). Farmers' trust in implementing new technologies is further diminished by inadequate knowledge of operating procedures and advantages.

These results show that decisions for residue management are context-dependent and entail trade-offs between immediate operational requirements and long-term sustainability advantages. When immediate restrictions are severe, farmers put quick crop establishment, labour efficiency and economic viability ahead of ecological considerations.

When sustainable residue management techniques are in line with farmers' operating circumstances, lower labour costs and offer observable financial advantages, their adoption generally improves dramatically. This emphasises how crucial it is to combine technology solutions with financial incentives, service delivery methods and extension support in order to guarantee practical viability at the farm level. These results demonstrate that adoption hurdles are complex and require more than just technology solutions.

Environmental and public-health implications

Residue burning is consistently found to be the most environmentally harmful disposal method in all of the examined studies. According to empirical data, burning contributes significantly to seasonal air pollution episodes in a number of northern Indian states by releasing large amounts of particulate matter and greenhouse gases (51). In addition to decreasing visibility and raising the risk of respiratory and cardiovascular illnesses in those who are exposed, these emissions also contribute to the creation of smog (52). Burning residue has long-term ecological effects in addition to acute effects on the atmosphere. Soil deterioration occurs gradually as a result of repeated burning's reduction of soil organic carbon, disruption of microbial biomass and impairment of nutrient cycle activities (27, 53). These consequences increase reliance on outside inputs like chemical fertilisers and reduce soil production.

Improper residue disposal practices, including dumping in field boundaries or water channels, also contribute to localised environmental pollution. Such practices lead to nutrient leaching, water contamination and unpleasant odours, further highlighting that environmental impacts extend beyond burning alone (54).

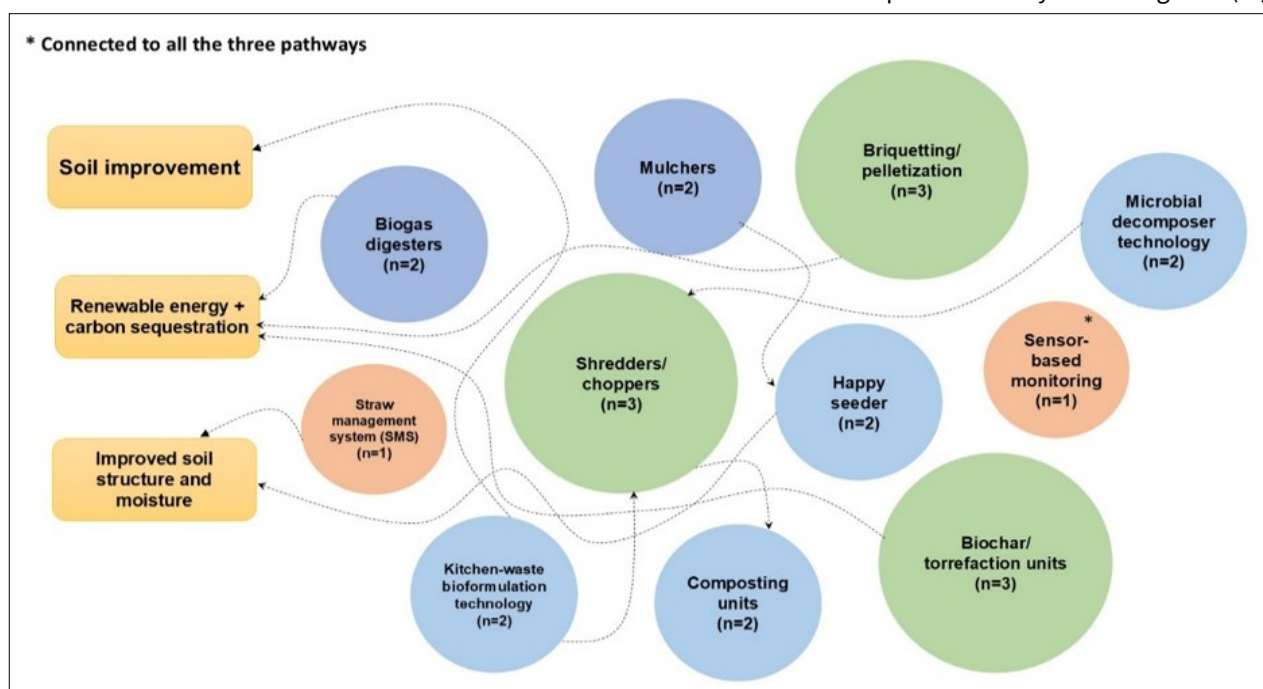


Fig. 3. Conceptual mapping of technological innovations in agro-waste management, including mechanised *in situ* tools, residue processing technologies and digital monitoring systems.

One of its primary features is the unequal distribution of residue burning's effects. Farmers may use fire as a temporary fix for operational issues, but the ensuing air pollution has an impact on a larger population, including urban dwellers, rural communities and vulnerable populations like children and the elderly. This spatial distance between the source of pollution and its effects highlights the broader implications of residue management strategies for public health.

Overall, the findings indicate that agro-waste management is not solely an agronomic issue but a critical environmental and public-health concern. The cumulative effects of air pollution, greenhouse gas emissions and soil degradation emphasise the need for integrated management strategies that address both ecological sustainability and human well-being. These findings demonstrate that sustainable agro-waste management is closely linked with broader climate mitigation, environmental protection and public health objectives.

Policy, governance and institutional support

Across agricultural systems, residue management techniques are heavily influenced by institutional and policy frameworks. The evaluated studies consistently show that field-level implementation of residue control policies is just as important to their efficacy as their design (55, 56). The National Policy for Management of Crop Residues (2014), regulatory bans, subsidy-based programs and regulations put in place by the Commission for Air Quality Management (CAQM) have all been implemented with the goal of reducing residue burning, but their effectiveness has been limited when they are not backed by sufficient service delivery mechanisms. Numerous studies point out that farmers' access to workable alternatives is hampered by enforcement gaps, unequal machinery distribution and custom hiring centres' limited operating capacity (21, 57). As a result, farmers operating under time and labour constraints often find it difficult to comply with regulatory measures in the absence of practical options.

The execution of policies is made more difficult by institutional fragmentation. The engagement of several ministries, such as rural development, agriculture and the environment, frequently results in poor coordination and uneven support service delivery (58). The overall efficacy of residue management programs is diminished by this lack of synergy. Research from the evaluated studies indicates that policies are more successful when they take into account the operational challenges that farmers confront. Adoption of sustainable practices is greatly enhanced by timely machinery availability, efficient rental and servicing networks and focused financial incentives. However, in the absence of supporting infrastructure, enforcement-driven tactics usually create compliance challenges without promoting behavioural change (10). Recent Indian policy measures have focused more on *ex situ* residue utilisation, custom hiring centres and mechanisation support. However, implementation gaps and uneven regional accessibility continue to hinder their effectiveness. Experiences from throughout the globe demonstrate that residue burning may be considerably reduced by comprehensive policy frameworks that incorporate financial incentives, technological assistance and regulatory measures (24). These approaches highlight how important it is to align policy instruments with institutional capacity and technological accessibility.

All things considered, the results show that effective residue management requires a change from regulatory control to enabling governance. To effectively implement policy objectives at the farm level, institutional coordination must be strengthened, service delivery mechanisms must be improved and access to reasonably priced technology must be guaranteed.

The integrated theme framework of agro-waste management is shown in Fig. 4, which shows how disposal methods, recycling routes, technological advancements, socioeconomic factors, environmental effects and governance structures interact.

Discussion

The review's conclusions show that agro-waste management in India functions as a socio-technical system, with residue management techniques influenced by the interplay of institutional support, agronomic needs, technology accessibility and socioeconomic limitations. Current methods are logical reactions to structural constraints in production systems rather than representing the desires of individual farmers.

One important realisation is the continued use of conventional disposal techniques, particularly residue burning, despite the availability of sustainable alternatives. Larger structural and logistical limitations are reflected in the frequency of residue burning in intensive agricultural production systems. Residue burning is a workable operational solution rather than a solitary behavioural issue because farmers emphasise rapid field clearing and crop planting in these circumstances.

On the other hand, there is significant potential to improve soil organic carbon, nutrient availability and microbial activity through recycling and resource recovery methods such as composting, mulching, residue integration and biochar application. In circular agricultural systems, these methods reframe agro-waste as a useful biological resource. However, due to limitations with regard to cost, labour, time and technological viability, especially in smallholder farming situations, their adoption is still unequal.

In order to close the gap between sustainability and practicality, technological advancements are essential. The viability of sustainable practices is increased by mechanised *in situ* residue management tools and residue processing technology, which lower labour intensity and boost operational efficiency. However, accessibility, cost and the availability of auxiliary service delivery systems like custom hiring centres are prerequisites for their efficacy. This suggests that without complementary institutional support, technical solutions by itself cannot propel widespread acceptance. These results imply that price, institutional accessibility and region-specific operational realities must be taken into consideration in addition to technology availability for sustainable agro-waste management.

The unequal distribution of these consequences highlights the need for coordinated interventions and the public-goods component of agricultural waste management.

Governance and policy frameworks are found to have a major impact on the adoption of sustainable practices. Research indicates that enforcement-driven tactics alone are inadequate in the absence of enabling infrastructure. However, integrated approaches that include financial incentives, institutional coordination and technical availability are more successful in

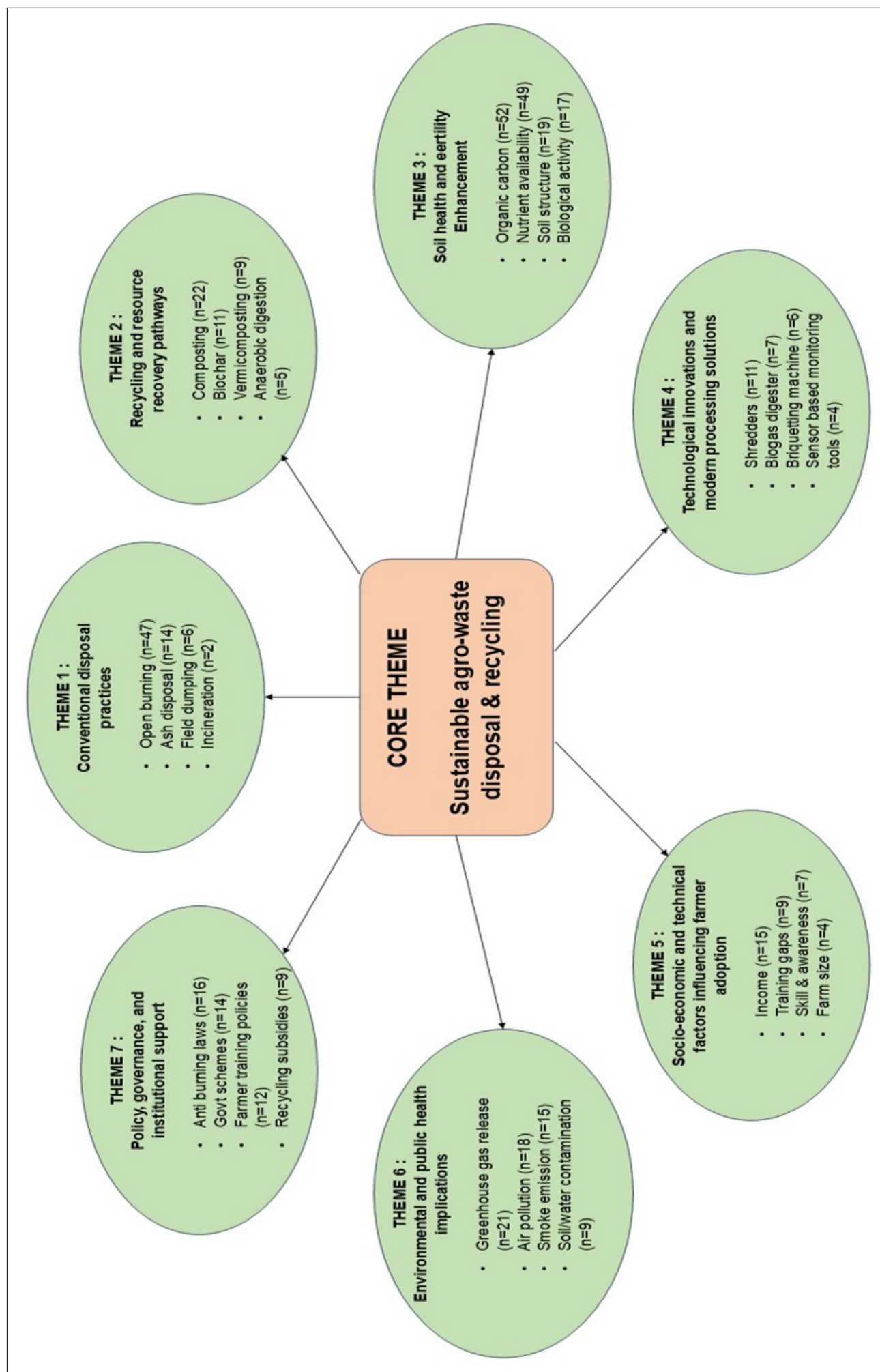


Fig. 4. Thematic framework of sustainable agro-waste disposal and recycling derived from the reviewed 58 studies.

promoting adoption. Ensuring timely machinery availability, strengthening service delivery infrastructure and developing sustainable residue-based value chains are all necessary for achieving scaled solutions.

In general, the transition to sustainable agro-waste management requires striking a balance between the environmental benefits and farmers' pragmatic requirements. A systems-based approach that combines socioeconomic incentives, political assistance and technological innovation is necessary for long-term sustainability. Without such congruence, even technically good solutions are difficult to be widely adopted. When considered collectively, the findings emphasise the importance of integrated and context-sensitive approaches for addressing the operational, financial and environmental issues surrounding agro-waste management in India.

Research gaps and future directions

There are still a number of important gaps in the growing body of research on agro-waste management. First, most studies focus on immediate results rather than long-term effects of residue management techniques on microbial activities, nitrogen cycling and soil organic carbon dynamics. This makes it more challenging for humans to comprehend how long-lasting ecological advantages are.

Second, there is still a lack of integration across the agronomic, environmental, technological and socioeconomic domains in the corpus of existing work. The development of comprehensive, systems-level solutions is hampered by the lack of transdisciplinary frameworks.

Third, little is known about the behavioural components of farmer decision-making. Constraints including labour shortages and access to machinery are well-documented, but risk perception, adoption behaviour and reactions to policy incentives especially in smallholder contexts have received less attention.

Fourth, economic evaluations of value chains and residue management techniques are inadequate. Robust cost-benefit analyses that look into recycling methods' market integration, scalability and financial viability are lacking.

Lastly, research pertaining to policy frequently emphasise design over execution. Understanding how policies work in practice is hampered by a lack of focus on institutional coordination, service delivery systems and governance efficacy.

In order to create scalable and context-specific solutions, future research should take long-term, interdisciplinary, systems-oriented approaches that incorporate ecological, economic, behavioural and institutional factors.

Policy implications

The results show that residue burning cannot be addressed by regulations alone because they do not alleviate farmers' operational challenges. Therefore, policy strategies must change to support frameworks that make sustainable alternatives feasible.

It is crucial to increase access to residue management equipment. Long-term adoption of sustainable residue management techniques may be enhanced by an integrated policy framework that connects mechanisation support, biomass usage networks, financial incentives, extension programmes and environmental monitoring. Enhancing decentralised service delivery

mechanisms, such as private rental networks and bespoke hiring centres, can guarantee timely machinery availability during periods of high agricultural demand, especially for smallholders.

Building value chains based on residues is just as crucial for generating financial incentives. Encouraging markets for biomass-based energy, compost and biochar may turn agricultural waste into a resource with added value and promote recycling.

Instead, then just encouraging equipment ownership, targeted financial incentives should concentrate on lowering operating costs and rewarding sustainable practices. Adoption can be further improved by mechanisms like ecosystem service fees or performance-based subsidies.

To increase awareness, technical expertise and farmer confidence, extension systems must be strengthened. The practical application of technologies can be improved via location-specific training, demonstrations and advisory help.

Lastly, to guarantee successful policy implementation, more institutional coordination between the agriculture, environmental and energy sectors is required. Sustainable agro-waste management at scale requires integrated governance frameworks that coordinate economic, environmental and technological goals. A conceptual foundation for creating integrated and scalable agro-waste management solutions in many agricultural contexts is provided by this systems-oriented viewpoint.

A conceptual policy integration framework for sustainable agro-waste management is shown in Fig. 5, emphasising the relationship between residue-based value chains, technology access, governance systems, farmer support mechanisms and environmental sustainability.

Limitations

When interpreting the results, it is important to take into account the many limitations of this review. First, the study is based on 58 studies that differ in terms of measuring indicators, regional focus and methodological techniques, which may have an impact on comparability in various circumstances.

Second, the majority of the reviewed research focus on the immediate effects of residue management techniques, which restricts our knowledge of the long-term effects on microbial processes, soil carbon dynamics and ecosystem sustainability.

Third, rainfed areas, horticultural systems and a variety of agroecosystems are comparatively underrepresented in the geographic distribution of studies, which is tilted toward rice-wheat systems in northern India. This limits the findings' applicability to all Indian agricultural environments.

Fourth, a thorough evaluation of financial viability and market dynamics is hampered by the paucity of economic evaluations of residue management technologies and value chains in the body of current work. Lastly, because the review is based on published literature, it might not adequately represent developing, localised, or informal farmer-led innovations that are not recorded in scholarly sources.

Furthermore, there is currently little information on the long-term function of biological decomposition agents and advantageous microbial consortia under various field circumstances. The efficiency of residue recycling methods and biological treatments may also be impacted by regional farming

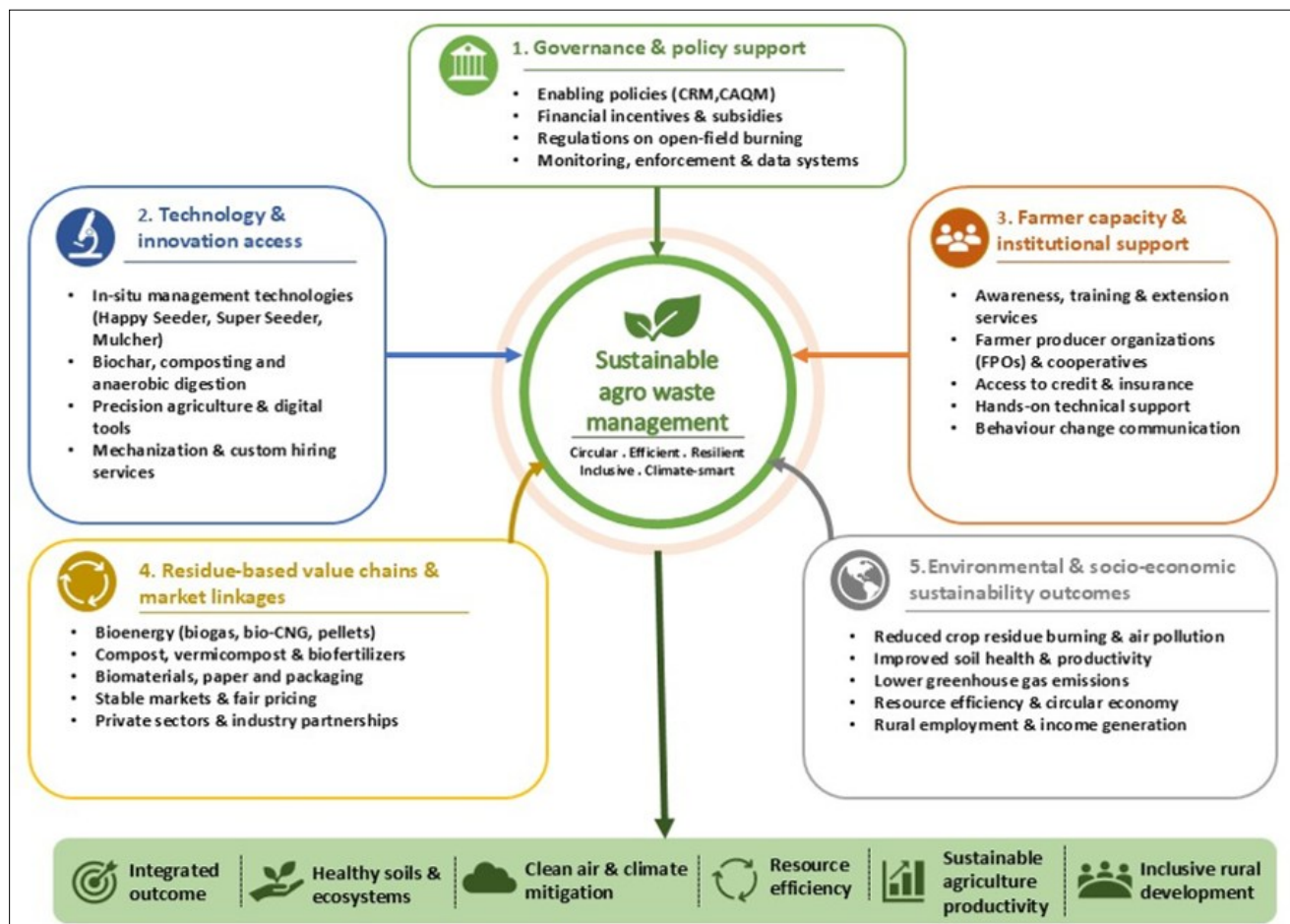


Fig. 5. Conceptual framework for sustainable agro-waste management in India.

CRM: Crop residue management; CAQM: Commission for air quality management

practices, climatic variations and residue composition. Thus, long-term field validation, region-specific adaptation techniques and integrated evaluation of ecological and economic consequences should be the focus of future research.

Notwithstanding these drawbacks, the paper presents a solid summary of recent research and insightful information about the institutional, socioeconomic and environmental aspects of agro-waste management in India.

Conclusion

This study shows that farmer preferences, which favour techniques like residue burning, have less impact on agro-waste management in India than structural and operational restrictions. However, institutional and financial obstacles prevent the adoption of sustainable methods like composting, mulching and using biochar, which greatly improve soil health and environmental consequences. The results show that a successful transformation necessitates a change from enforcement-driven strategies to enabling governance structures that guarantee prompt equipment access, effective service delivery and the creation of long-term residue-based value chains. This study highlights the need of considering agro-waste management as a socio-technical system in which the interplay of institutional, technological and economic elements influences farmer behaviour. Long-term climate-resilient agricultural systems require a systems-based approach that integrates institutional coordination, environmental sustainability, socioeconomic incentives and technology innovation. To enhance scalability,

affordability and environmental performance throughout India's various agricultural regions, future advancements should concentrate on region-specific residue management technologies, biological decomposition methods, decentralised biomass value chains and digital monitoring systems. The review's findings might help academics, policymakers and agricultural stakeholders create evidence-based, region-specific agro-waste management plans for India's sustainable agricultural transitions.

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Authors' contributions

SN conceived the study and drafted the manuscript. JR supervised and provided conceptual guidance. MP contributed to the study design and interpretation of results. SB and GS performed data analysis and contributed to critical revision of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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