Life cycle assessment of agricultural waste recycling for sustainable environmental impact

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Agricultural waste recycling is crucial for sustainable farming operations and farming practices. Life cycle assessment has emerged as an innovative and comprehensive viewpoint that considers the entire recycling process to evaluate the potential and true implications of agricultural waste recycling. This study considered methods for recycling different agricultural waste streams, such as crop waste, animal manure, pruning materials, and by-products and subsequent uses. Furthermore, the life cycle assessment method was used to investigate the process of handling agricultural waste, from collection and recycling to final usage in the agricultural system. Environmental impact categories, including greenhouse gas emissions, energy usage, eutrophication, acidification, and land use, were evaluated to determine their potential effects on climate change, resource depletion, and ecosystem health. The results were compared with those of 31 studies that analyzed the potential environmental impacts of agricultural waste management. Various methods initially developed and implemented for agricultural waste landfilling methods have now changed to energy-generating sources, such as biochar, biogas, briquettes, and various energy production methods. Furthermore, composting, a popular method of recycling agricultural waste, significantly lowers greenhouse gas emissions and energy use compared to traditional waste disposal techniques. The study also examines cutting-edge technologies, such as anaerobic digestion and biomass-to-energy conversion, highlighting their potential to manage agricultural waste and being a sustainable energy source. These findings indicate potential environmental advantages in terms of decreased greenhouse gas emissions and fossil fuel consumption, leading to a circular economic approach for agriculture. When integrating agricultural waste, including composting, anaerobic digestion, and pyrolysis, biochar is highlighted as a waste recycling method that is promising for sustainable waste management. In addition to efficiently managing agricultural waste, these technologies help generate electricity and sequester carbon, thereby advancing the objectives of climate change mitigation and circular economy. Although life cycle assessment has been used to analyze several waste management strategies, including those specific to agricultural waste, certain significant gaps and discoveries still require attention for a more thorough analysis. It might be challenging to gather complete and accurate data to assess the entire lifecycle of agricultural waste management technology. The direct environmental effects of waste management are frequently the focus of life cycle assessment studies, but they may overlook secondary effects such as indirect land use change, habitat damage, and biodiversity effects. It is crucial to consider these secondary effects in a more comprehensive analysis.

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INTRODUCTION

Pursuing sustainable practices has become essential across industries due to escalating environmental problems. As a foundational element of civilization, agriculture significantly impacts the planet’s future fate. However, given that traditional agricultural methods adversely affect the environment, it is important to look for alternatives that balance agricultural output and environmental stewardship (Eyhorn et al., 2019). A paradigm shift in approaching agricultural operations is necessary in light of the world’s expanding population, climate change, and loss of natural resources. Conventional approaches caused detrimental environmental effects such as soil erosion, water pollution, and greenhouse gas (GHG) emissions, frequently accompanied by ineffective waste management (Sharma et al., 2023). Sustainable agriculture can potentially help create a more sustainable and resilient global future. There is a growing understanding that recycling and circular economy strategies may transform waste into valuable resources (Kurniawan et al., 2022). An innovative and comprehensive perspective that considers the complete life cycle of these recycling processes is required to evaluate the potential and implications of recycling agricultural waste. The method, known as “Life Cycle Thinking,” explains the extensive environmental effects of recycling agricultural waste and provides insights into sustainable practices (Dahiya et al., 2020; Zeug et al., 2023). The core idea of “sustainability” is life cycle thinking, an original and comprehensive strategy that goes beyond conventional linear evaluations. Life Cycle Thinking provides a thorough understanding of the environmental impact at every stage by considering the entire life cycle of agricultural waste from its origin through final recycling or disposal (Hauschild et al., 2020; Puspita et al., 2023), and it helps create transformational opportunities to reduce unfavorable effects and improve sustainable behaviors. Furthermore, Life Cycle Thinking gives a precise and comprehensive assessment by considering the entire life cycle of trash from its initial generation through its eventual reuse or disposal. Recycling techniques using this strategy are suitable for the environment but have uncovered potential trade-offs (Wahyono et al., 2023; Wu et al., 2021). Additionally, Life Cycle Thinking ensures that decision-makers are aware of the long-term effects of their decisions, promoting the development of intelligent policies and practices. Waste can be diverted from conventional disposal procedures and reused to reduce environmental harm and improve the circular flow of resources within agricultural systems. Recycling agricultural waste is a practical method that balances environmental protection with human advancement, paving the way for a resilient and regenerative planet. Life-cycle assessment (LCA) is a robust framework that directs research and has an ambitious purpose and clear objectives. The LCA technique analyzes the entire life cycle of agricultural waste recycling (Gilani et al., 2023). While various studies have analyzed the potential environmental impacts of various agricultural waste management methods, no studies have analyzed and compared each method completely in Asian nations. Therefore, this study’s results can help Asian countries consider adding agricultural waste management methods and assess the environmental effects of each stage, revealing vital information that guides sustainable decision-making. Furthermore, this study aims to enable readers to holistically analyze the implications of recycling agricultural waste, noting its broader environmental effects. Moreover, this study aims to uncover the potential for sustainable practices, promote circular economy principles, educate policy decisions, increase stakeholder engagement, and contribute to global sustainable development goals using LCA methodology. Finally, this study aims to promote and help implement sustainable agricultural waste recycling procedures to encourage a more peaceful coexistence between agriculture and the environment. This study was conducted in an Asian country in 2023.

METHODOLOGY

State of the art and challenges for agricultural waste management LCA in answering sustainable concept

Agricultural land use produces significant agricultural waste, such as crop leftovers, animal manure, and trash from food processing (Rani et al., 2023). Improper agricultural waste management can have adverse environmental effects, including soil, water, and air pollution, as well as land degradation; therefore, effective agricultural waste management is crucial (Koul et al., 2022). Regarding agricultural waste management, sustainability refers to balancing human needs and preserving and protecting the
environment. This entails techniques that enhance the social and economic well-being of farmers and communities around them and reduce harmful environmental effects (Nigussie et al., 2021). The LCA method is crucial for determining the environmental impact of a process or product from the perspective of production to final disposal. Regarding managing agricultural waste, LCA makes it possible to thoroughly assess the environmental effects of alternative waste treatment choices, including creating new treatment techniques and discovering potential enhancements in environmental performance (Llorach-Massana et al., 2023). A life-cycle thinking strategy is related to LCA and is advocated for managing agricultural waste. Life cycle gas emissions conserve natural resources such as land and water and boost soil fertility (Adekomaya and Majozi, 2022; Mondal and Palit, 2022). It is possible to develop efficient and sustainable policies and activities to address sustainability in managing agricultural waste by incorporating life-cycle thinking and LCA.

**Selection criteria of research LCA review**

This study focuses on LCA studies on the management of agricultural waste produced from each agricultural process in Fig. 1. This study utilizes SCOPUS and Google
## Agricultural waste management

### Table 1: Traditional agricultural waste management

<table>
<thead>
<tr>
<th>Research Study</th>
<th>Functional unit (FU), method, model &amp; Waste type</th>
<th>Agriculture waste management</th>
<th>Impact assessment result of parameter</th>
<th>Critical findings</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qatar</td>
<td>FU: 1 ton Method: CML 2 baseline 2000 Model: Simapro Waste type: agriculture general waste</td>
<td>S1: WC S2: AD S3: WC, AD</td>
<td>1. AD p 2. G 3. OD 4. HT 5. PO 6. AP 7. EP</td>
<td>In terms of overall impact, the use of fossil fuels for transportation accounts for around 60 percent (%) of the emissions produced. Composting follows with 40% of the emissions produced, particularly in terms of possible global warming.</td>
<td>Al-Rumaihi et al., 2020</td>
</tr>
<tr>
<td>China</td>
<td>FU: 1 Mt Method: Ecoinvent 3.2 Model: OpenLCA Waste type: Dairy manure</td>
<td>S1: AD S2: COMP S3: SS-AD, COMP</td>
<td>1. AD p 2. G 3. EP 4. RD</td>
<td>The combined GWP of solid-state AD and composting, which is 2900 kg CO2 eq/t of dairy manure, was the lowest. This figure is almost 14.8 times lower than that of the current status, which is liquid AD of dairy manure.</td>
<td>Li et al., 2018</td>
</tr>
<tr>
<td>Turkey</td>
<td>FU: 1 ton Method: Edip 2003 Model: Gabi 5 Waste type: Agriculture and organic fertilizer</td>
<td>S1: AD S2: GS S3: LF</td>
<td>1. AP 2. AE 3. G 4. PO F 5. SO D</td>
<td>By removing it from the region's traditional landfilling waste management system, the sustainability of energy production from agricultural and farm waste, via AD, was further strengthened.</td>
<td>Nayal et al., 2016</td>
</tr>
<tr>
<td>Beijing</td>
<td>FU: 1 ton Method: IPCC, CML, Ecoinvent Model: Simapro Waste type: Mixed manure</td>
<td>S1: BS</td>
<td>1. GH G</td>
<td>Hopefully, by improving fermentation efficiency and coordinating the operation of biogas digesters, the linked system can be maximized.</td>
<td>Chen and Chen, 2013</td>
</tr>
<tr>
<td>Vietnam</td>
<td>FU: 1 ton, 100 kg Method: Recipe 2008 Model: Simapro Waste type: liquid manure, solid manure</td>
<td>S1: BS</td>
<td>1. G 2. WP 3. FD 4. FE M</td>
<td>Biogas digesters could help to mitigate the effects of global warming if methane emissions are kept to a minimum, according to a sensitivity study.</td>
<td>Vu et al., 2015</td>
</tr>
<tr>
<td>China</td>
<td>FU: 1 ton Method: Ecoinvent, Eco-indicator 99, IPCC 2007 Model: Simapro Waste type: agricultural waste</td>
<td>S1: BS</td>
<td>1. G 2. WP 3. OD 4. AD 5. EP</td>
<td>According to the findings, the production of biogas has a positive impact on artificial environments while having a negative impact on GWPs. With time, its detrimental effects on GWPs become more pronounced.</td>
<td>Wang et al., 2016</td>
</tr>
<tr>
<td>Singapore</td>
<td>FU: 1000 ton Method: NA Model: Gabi Waste type: NA</td>
<td>S1: INC S2: AD</td>
<td>1. AD 2. EP 3. G 4. HT 5. M AE 6. OD</td>
<td>The sensitivity study also showed that by reducing water use, reducing gas engine emissions, and diverting as much FW from incineration plants to AD plants as possible, better environmental profiles might be attained.</td>
<td>Tong et al., 2018</td>
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Continued Table 1: Traditional agricultural waste management

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<tr>
<td>Indonesia</td>
<td>FU: 1 ton Method: IPCC 2013, Impact 2002+ Model: Simapro Waste type: Animal manure</td>
<td>S1: COMP S2: BS S3: COLT-BS (A)</td>
<td>1. GWP 2. AP 3. EP 4. HT</td>
<td>The findings given here suggest that the GWP was the most important factor in the environmental impact evaluation of the POME. COLT-Biogas A combined with communication posting was found to be more environmentally beneficial than the other combinations in terms of GWP.</td>
<td>Nasution et al., 2018</td>
</tr>
<tr>
<td>India</td>
<td>FU: 1 ton Method: CML 2001 Model: Simapro Waste type: Agro residue</td>
<td>S1: PRs S2: Ln S3: Cs</td>
<td>1. GWP</td>
<td>The development of biofuel processing, however, has a number of challenges in addition to the advantages mentioned above, such as scientific, technological, economic, environmental, safety, depository, policy, and so on. Therefore, thorough R&amp;D is required to overcome these obstacles. However, these negative effects can be lessened by technological development and careful planning.</td>
<td>Rahimi et al., 2022</td>
</tr>
<tr>
<td>Vietnam</td>
<td>FU: 1 ton Method: Recipe Model: Gabi Waste type: Organic manure, corn waste</td>
<td>S1: PRs S2: Br</td>
<td>1. GH 2. G</td>
<td>Due to its low cost, high efficiency, simplicity of usage, ecological integrity, and reliability in terms of public safety, biochar made from agricultural waste biomass may be a suitable replacement for managing pollutants.</td>
<td>Nguyen et al., 2019</td>
</tr>
<tr>
<td>China</td>
<td>FU: 1 ton Method: Gabi Model: NA Waste type: Oil palm kernel shell and empty fruit bunches</td>
<td>S1: Co-PRs</td>
<td>1. GWP 2. HT 3. TE 4. AP</td>
<td>In summary, these studies can serve as a resource and simple methodology for persons who are interested in advocating the use of co-pyrolysis of agricultural waste and promoting product industrialization.</td>
<td>Mo et al., 2022</td>
</tr>
<tr>
<td>Indonesia</td>
<td>FU: 1 ton Method: Gabi Model: CML-2001 Waste type: Coconut shells</td>
<td>S1: AC</td>
<td>1. GWP 2. HT 3. AP</td>
<td>The analysis of alternative scenarios suggests that by reducing the electrical energy consumptions in the process units of crushing and tumbling as well as by using electrical energy from renewable sources, such as biomass, the sustainability of activated carbon production in Indonesia could be greatly improved, reducing the contribution to global warming and local human toxicity. This would contribute to a reduction of 80% in global warming and a 60% decrease in the local impact to human toxicity.</td>
<td>Arena et al., 2016</td>
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<tr>
<td>North Vietnam</td>
<td>FU: 1 ton Method: Simapro Model: IPCC 2006 Waste type: Rice straw and husk</td>
<td>S1: OB S2: Br</td>
<td>1. CF</td>
<td>The findings suggest that the climate consequences of these double rice cropping systems in Vietnam can be reduced by stopping the burning of crop leftover in the field and using residues to generate biochar for application to soils.</td>
<td>Mohammadi et al., 2016</td>
</tr>
<tr>
<td>Vietnam</td>
<td>FU: 1 Mt Method: Simapro Model: IPCC 2006 Waste type: Rice husk</td>
<td>S1: PRs, Br S2: Br, COMP</td>
<td>1. WP</td>
<td>The findings of this LCA analysis suggest that, in comparison to open burning of rice husks during both the spring and summer rice cropping seasons, using rice husks for biochar in biochar-compost (COMBI) systems can improve climate change and health effects.</td>
<td>Mohammadi et al., 2017</td>
</tr>
<tr>
<td>China</td>
<td>FU: 1 Mt Method: Na Model: MUIO-LCA model Waste type: Feedstock</td>
<td>S1: Cr S2: Cr, Br S3: Cr, Dfp S4: Cr, Bb</td>
<td>1. GH</td>
<td>The outcomes showed that Cr-Bb outperformed the other two technologies in terms of energy generation and air pollution reduction. Efficiency in energy conversion was proposed as a crucial variable in assessing the possibility for producing bioenergy and enhancing the environment.</td>
<td>Dai et al., 2020</td>
</tr>
<tr>
<td>Japan</td>
<td>FU: 1.34 ton Method: NA Model: NA Waste type: Manure</td>
<td>S1: COMP</td>
<td>1. GH</td>
<td>On farmland on livestock farms, liquid materials (wastewater or slurry) could be applied.</td>
<td>Haga, 2021</td>
</tr>
<tr>
<td>Indonesia</td>
<td>FU: 1 ton Method: NA Model: NA Waste type: General agricultural waste</td>
<td>S1: AF</td>
<td>1. Social Ec</td>
<td>Using alternative agricultural waste as animal feed, it is possible to minimize agricultural waste, which has not previously been widely employed, and provide animal feed for the following six months in just 27 days.</td>
<td>Mufti and Fathurahman, 2022</td>
</tr>
</tbody>
</table>

Scholar and the keywords “evaluation of the life cycle of agricultural waste management,” publications for 31 LCA studies on agricultural management systems since 2012-2023 were obtained. The processing grouping is divided into two as described in Tables 1 and 2 namely traditional and advanced management using technology. Agricultural management is centered on one traditional management method that is analyzed and the use of new technology with a combination of traditional management, aims to compare the most efficient method of agricultural management. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method as a qualitative systematic review and science mapping as a quantitative and qualitative technique were used in literature studies to define and explore the aspects that influence sustainability in agricultural waste management. Fig. 1 depicts the approach used in the current investigation as a flowchart with PRISMA method. Data was gathered and examined utilizing a qualitative content analysis methodology, which offers insight into the circumstances surrounding the phenomenon under study and permits flexibility in research through the collection of descriptive and
### Table 2: Advance agricultural waste management

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</tr>
</thead>
<tbody>
<tr>
<td>Bangladesh</td>
<td>FU: 1 kg Method: NA Model: NA Waste type: General agricultural waste</td>
<td>S1: AD S2: COMP S3: LF S4: INC S5: GS</td>
<td>1. Soci al 2. Economy 3. Political</td>
<td>This study simply aims to increase understanding of the waste-related issues that have arisen in Bangladesh from various sources, and it then suggests a feasible model that may be used to achieve a zero-waste policy. The findings of this study are nevertheless intended to be applied by academics, scholars, researchers, policymakers, and practitioners to future endeavors to support the proposed model prior to the adoption of the zero-waste policy to attain sustainable development goals.</td>
<td>Ahmed et al., 2023)</td>
</tr>
<tr>
<td>Indonesia</td>
<td>FU: 1 ton Method: Ecoinvent 3.1, Recipe Waste type: Feedstock collection</td>
<td>S1: Br S2: Brq</td>
<td>1. GH 2. PM 3. Social 4. Economy</td>
<td>In this instance, the benefits of carbon sequestration in the soil and the economic worth of improved agricultural production outweigh the drawbacks of biochar production for the environment and the expenditures associated with it.</td>
<td>Sparrevik et al., 2014)</td>
</tr>
<tr>
<td>Philippines</td>
<td>FU: 1 kg Method: Ecoinvent 3.1 Model: Gabi Waste type: Rice straw, rice husk, coconut husk, coconut shell, cattle manure</td>
<td>S1: Cs S2: Gs S3: AD</td>
<td>1. GH 2. ME 3. HT 4. TET 5. POF</td>
<td>The findings indicate that AD is generally the most environmentally friendly alternative, exceeding the competition in 14 of the 18 impact categories. Nearly all of the effects of AD are net-negative, indicating that they should be avoided. This is because manure is used more effectively than when it is dumped in water or left on the ground. The global warming potential of AD can range from 170% lower to 41% higher than that of the diesel generator, depending on the feedstock.</td>
<td>Aberilla et al., 2019)</td>
</tr>
<tr>
<td>Thailand</td>
<td>FU: 1 ton Method: IPCC Model: Simapro Waste type: date palm waste</td>
<td>S1: Br</td>
<td>1. GW 2. P</td>
<td>When the adsorption capacities of the two adsorbents were evaluated, it was discovered that biochar performs on par with activated carbon.</td>
<td>Shaheen et al., 2022)</td>
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Continued Table 2: Advance agricultural waste management

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<tbody>
<tr>
<td>China</td>
<td>FU: 2.1 Mt, Method: IPCC 2007, Model: OpenLCA, Waste type: Straw</td>
<td>S1: PRs, S2: Gs, S3: Br, S4: Brq</td>
<td>1. P, GW</td>
<td>However indirect carbon abatement processes arising from biochar application could significantly improve the carbon abatement potential of the pyrolysis scenario. Likewise, increasing the agronomic value of biochar is essential for the pyrolysis scenario to compete as an economically viable, cost-effective mitigation technology.</td>
<td>Clare et al., 2015</td>
</tr>
<tr>
<td>China</td>
<td>FU: 1 ton, Method: CML-2000, Model: Simapro, Waste type: Agricultural straw</td>
<td>S1: Br, S2: PRs</td>
<td>1. P, GW</td>
<td>A careful investigation revealed that the GWP categories are significantly impacted by the uncertainties of energy usage and agricultural straw yield.</td>
<td>Yang et al., 2020</td>
</tr>
<tr>
<td>Malaysia</td>
<td>FU: 1 ton, Method: Recipe, Model: Gabi, Waste type: Organic manure, corn waste</td>
<td>S1: Gs, S2: Ln, S3: PRs, S4: BS, S5: Cs</td>
<td>1. P, GW</td>
<td>Nevertheless, ongoing research is being done to address the gaps in the state-of-the-art technologies and boost their effectiveness and profitability.</td>
<td>Lee et al., 2019</td>
</tr>
<tr>
<td>Indonesia</td>
<td>FU: 1 ton, Method: EASETECH, Model: NA, Waste type: Empty fruit bunch</td>
<td>S1: PRs</td>
<td>1. P, CF</td>
<td>For instance, some of the benefits of emissions reduction may be countered by the deforestation and land-use changes associated with oil palm farming. To maintain the overall sustainability of the biochar export program, it is critical to take into account and mitigate these negative effects.</td>
<td>Robb and Dargusch, 2018</td>
</tr>
<tr>
<td>Thailand</td>
<td>FU: 1 ton, Method: IPCC, Model: Simapro, Waste type: Manure and general agricultural waste</td>
<td>S1: BS</td>
<td>1. P, GW</td>
<td>Biomethane has the lowest well-to-wheel GHG emissions of all the biofuels (by less than one third).</td>
<td>Koido et al., 2018</td>
</tr>
<tr>
<td>Malaysia</td>
<td>FU: 1 ton, Method: ReciPe, Model: Simapro, Waste type: Agricultural waste general</td>
<td>S2: LSS</td>
<td>1. P, GW</td>
<td>The production and milling of fresh fruit bunches for palm biodiesel and large-scale solar installations (electrical installation) are two environmental hotspots that have the potential to cause environmental burdens of up to 15–51% in terms of human non-carcinogenic toxicity, human carcinogenic toxicity, global warming, marine ecotoxicity, water</td>
<td>Phuang et al., 2022</td>
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</table>
visual data. The authors used the operator to search the SCOPUS database to find a suitable database covering the environmental effects of processing agricultural waste using the LCA approach. “TITLE-ABS-KEY (Agricultural Waste AND Agricultural Waste Recycle AND Life cycle assessment AND Asian).” The study was evaluated based on the following criteria: i) study area; ii) functional unit; iii) system boundary; iv) sensitivity analysis; v) environmental impact category; vi) potential comparison waste management strategy; and vii) key gaps and findings. Conference evaluations lack the requisite peer review to be recognized as a reliable source of information because they are not held to the same standards as journal articles. viii) Old conference evaluations: Conference reviews made before 2012-2023 may be regarded as out of date because more recent research has been undertaken. After reading the title, citation details, abstract, keywords, and the complete content, the author undertakes a thorough study analysis to establish credibility, dependability, and trustworthiness.

**Review scheme**

Critical evaluations focused on the fundamental elements of LCA for managing agricultural waste, such as the definition of objectives and scope, functional units, assumptions, selection of effect categories, and essential parameters/factors. Several LCA studies focusing on Asian nations have led to the discovery of these components. A logical ranking of the best technologies/policies was developed after categorizing the studies according to their distinctive nature and the treatment strategy used. Recommendations and the consequences of the best waste management techniques are provided based on numerous technological, environmental, and socioeconomic issues. This study is limited to agricultural waste, such as animal waste; agricultural wastewater, such as animal urine; and various plant residues (leaves, stems, and other plant parts remaining after harvest) with a gate-to-gate system (agricultural waste management). This selection aimed to ensure consistency in the life cycle analysis methodology. This includes selecting relevant inputs and outputs as well as modeling environmental impacts. This consistency supports the accuracy and sharpness of the research results. Therefore, collection and transportation are beyond the scope of this study.

**Classification of LCA studied on basis economy analysis**

In this subcategory of LCA studies, the environmental and economic impacts and various agricultural waste

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<tr>
<td>China</td>
<td>FU: 1 ton</td>
<td>S1: PRs</td>
<td>1. AP</td>
<td>consumption, and the scarcity of fossil fuels.</td>
<td>Zhu et al., 2022)</td>
</tr>
<tr>
<td></td>
<td>Method: ReciPe</td>
<td>S2: AD</td>
<td>2. EP</td>
<td>A popular management technique for reaching carbon neutrality in a circular economy, addressing both environmental and social problems, is to pyrolyze agricultural leftovers into biochar.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Model: Simapro</td>
<td>S3: GS</td>
<td>3. GW</td>
<td></td>
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<tr>
<td></td>
<td>Waste type: Agro residue</td>
<td>S4: Cs</td>
<td>P</td>
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<td></td>
<td></td>
<td>S5: Ln</td>
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<tr>
<td>China</td>
<td>FU: 2136 ton</td>
<td>S1: AD</td>
<td>1. GW</td>
<td>According to the LCA, both large-scale (LBP) and BS plants demonstrated good environmental sustainability in terms of reducing pollutant emissions and producing clean energy.</td>
<td>Wang et al., 2018)</td>
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<tr>
<td></td>
<td>Method: Weighthing</td>
<td>S2: GS</td>
<td>P</td>
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<td>Waste type: manure</td>
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treatment solutions were compared. To determine the most effective and sustainable approach for handling agricultural waste in certain situations, researchers examined the lifecycle effects of various waste treatment techniques. This study was evaluated and classified based on technology and economics. It starts by classifying the technology, where the LCA study concentrates on assessing the technological aspects of agricultural waste management. This requires an evaluation of the effectiveness, performance, and environmental impact of various waste treatment systems, including waste-to-energy processes, anaerobic digestion, and composting. Furthermore, the economic aspects and evaluation of available alternative agricultural waste management methods are the main focus of LCA research in this category, requiring cost evaluations associated with various waste management approaches, comparing the financial feasibility of different treatment technologies, and exploring the potential savings or benefits of adopting more sustainable and affordable waste management techniques. Fig. 2 illustrates those various countries, from low- to high-income countries, have substantial differences in agricultural waste produced per person yearly, which also impacts the management costs. The average total agricultural spending per farm in the US in 2020 was $182,130, an increase of 2.6% over the average of $177,564 in 2019 (Smith et al., 2020). Although these statistics cover many farm operations, a sizeable amount of these expenses may be devoted to waste management activities. Additionally, food waste is predicted to cost the US restaurant industry $162 billion annually (Blum, 2020; Read and Muth, 2021). The financial impact of the food industry’s waste, which is closely tied to agricultural waste even though this figure is not solely devoted to managing agricultural waste, is apparent. Leaders in the recycling sector are investing in waste management strategies, indicating that money is being invested to create and implement effective waste management systems.

Mapping of the study area and evolution of LCA studies in Asia

Thirteen Asian countries meet the requirements for LCA analysis on agricultural waste management, and China is the most dominant country for agricultural waste management analysis. Despite China’s tremendous industrial and technological developments, agriculture plays an important role in its economy. Waste management is a crucial issue that must be addressed because of the country’s high dependence on agriculture. As a result, it also impacts a demanding environment where the
handling of agricultural waste can negatively impact the environment, resulting in air and water pollution. China has stepped up its research efforts to identify sustainable solutions to this problem because of its growing awareness of environmental challenges. Fig. 3 shows the distribution of the LCA studies (shown in brackets) selected for evaluation in Qatar (1), China (9), Indonesia (5), Turkey (1), Beijing (1), Vietnam (4), Singapore (1), Thailand (2), Malaysia (3), India (1), Japan (1), Bangladesh (1), and Philippines (1). Most LCA were observed in 2020 and 2018, while the least LCA were observed between 2012-2014 and 2017, all of which had the same number of LCA, namely one study. The number of LCAs increased from 2016 to 2020, and the LCA studies identified in 2021 and 2023 were neither classified for analysis nor accessible. The number of LCAs is expected to increase in 2019 and 2022, as shown in Fig. 4. due to various factors such as the general public’s understanding of environmental challenges, climate change, environmental degradation, and the scarcity of natural resources, which has grown over time. The need for LCA research is growing as more businesses, governments, and members of the public
recognize the importance of gauging how products and activities affect the environment. Furthermore, laws and guidelines are being presented, and more nations and regulatory bodies are beginning to enact stricter environmental regulations, which may include demands that LCA be conducted on specific products. This motivates businesses and industries to conduct LCA research as part of their regulatory compliance and identify areas where their environmental performance can be enhanced. For the second Focus on Sustainability, throughout 2018–2020, sustainability rose to the top of the priority list for many organizations and industrial sectors. To make operations more sustainable, businesses are utilizing LCA as a valuable tool for assessing and controlling how human activities affect the environment.

Changes in the LCA can be attributed to waste-related issues in specific years, the amount of engagement in the scientific community, and the availability of functional units for projects involving municipal solid waste (MSW) management (Budihardjo et al., 2023b; Yadav and Samadder, 2018). This trend highlights the significance of utilizing LCA to evaluate the environmental impacts of MSW management. The global uptake of LCA studies and the ISO 14044:2006 standard for LCA methodology are growing (Khandelwal et al., 2019). Moreover, research, regulatory changes, and adoption of ISO standards have improved LCA implementation (Laurent et al., 2020).

This review focuses on the main elements of LCA for MSW management, such as the definition of objectives and scope, functional units, assumptions, choice of effect categories, and critical parameters/factors. Several LCA investigations conducted in Asia led to the discovery of these components. A logical ranking of the best technologies/policies was developed after categorizing the research according to their distinctive characteristics and treatment methods. Recommendations and consequences of the best waste management techniques are based on numerous technological, environmental, and socioeconomic concerns.

Scope definition analysis
This section analyzes the vital aspects of the research results that have been collected, such as functional units, system limitations, the models used, the path categories analyzed, sensitive parameters, and the reasons for implementing the technology.

 Functional unit
LCA includes functional units (FU) as fundamental vital points that require attention. The measured performance of the production system was used as a reference for the output produced (McAuliffe et al., 2020; Haumahu et al., 2023). The included LCA comparisons usually had the same FU to obtain fair results for each comparison of the technologies used. Limiting and having the same FU as a whole provides a general understanding of current waste management issues, necessary developments, processes that can be replaced with raw materials, and the replacement of fossil energy with natural energy, such as solar energy, so that it has an impact on sustainability, reduces management costs, and reduces emissions from an economic and environmental standpoint (Chen et al., 2021; Saravanan et al., 2021). Fig. 5 shows the FU for the cited agricultural waste management practices. The functional unit used in the studies cited in general was 1 ton (23 of 31 studies). Some used 1 Mt and more than 1 Mt (3 of 31 studies) and <1 ton and >1 ton for the remainder.

To accurately reflect the true intent of LCA and enable fair comparisons between various goods or services, the choice of a FU must be carefully considered (Corominas et al., 2020). One ton is one of the most popular FU alternatives in LCA due to: i) industry standard: in certain industries or sectors, one ton is a commonly used measure of production or performance. For example, ton is the standard unit to report production quantities in industrially produced materials such as steel, cement, and paper; ii) Practical and easy to measure: Using ton as the FU can result in easier calculations and easier to perform in LCA analysis because it is easier to measure and compare; iii) Consistency: using ton as the FU allows for consistency in LCA analysis because different products or services can be compared on a similar scale with the same weight (ISO 14040, 2006; ISO 14044:2006). It is crucial to remember that FU selection should consider specific LCA objectives and encompass the entire extent of the goods or services being assessed (Marmiroli et al., 2021). Depending on the goal and setting of the LCA, another FU may occasionally be more suitable. It is also important to understand the dynamic nature of the study, which means that over time, the procedures and methods...
employed in LCA may also change (Mio et al., 2022). Consequently, a different set of FU may be chosen for each LCA instead of one ton.

**System boundaries and use LCA methods**

System constraints, commonly called “analytical constraints,” are important for the LCA method’s early phase. System boundaries are crucial factors affecting the overall results of an analysis (Bonilla-Alicea and Fu, 2019; Kajtaz, 2019). This is defined as the processing/management stage, which depends on what is being analyzed, including the operation phase, inputs, outputs, and operating time options for agricultural waste management (Sharma et al., 2023). System boundaries determine the entry and exit of process units or component variables from the analysis performed (Abbasi et al., 2022). This stage must consider the duration, scope, and study objectives, and the decision to exclude input/output processes must be explained (Onat and Kucukvar, 2022). System constraints should ensure that all relevant processes and the possibility of realizing their environments are considered in the evaluation. A proper definition of system boundaries carries the risk of offloading from one phase of the life cycle to another. Furthermore, the software or model used is a computer-based tool for collecting, organizing, and analyzing data, simulating systems from life cycle flows, and analyzing the impacts that will occur (Kenett et al., 2023). Furthermore, LCA of various activities can be performed without the help of software. However, the experts greatly assisted in their work, such as obtaining, compiling, and analyzing various inventories. Common tools often used in LCA analysis, such as Simapro and Gabi, which have complete facilities as well as adequate choices for LCA analysis, such as characterizing and evaluating environmental impacts to examine life paths, such as urban waste management and agricultural waste, and can be accessed or subscribed to obtain unlimited premium services (Budihardjo et al., 2023b). Other software has been developed specifically for LCA waste management, such as the Environmental Assessment System for Environmental Technologies (EASETECH), Integrated Waste Management, and Open LCA, and other newer experimental software programs, such as the MUJO-LCA model. Comprehensive data collection is required for LCA in all aspects of agricultural management, including the production of raw materials and the handling, processing, and disposal of waste (Trummer et al., 2022). The general LCA analysis steps are as follows: i) Goal and scope determination: The program user determines the objectives of the analysis and specifies the parameters for the solid waste management system assessment and review;
ii) Lifecycle inventory: Information on inputs and outputs is compiled and entered into a program. It contains information on the amount and type of energy consumed, raw material quantities and types, emissions, and other characteristics of each process; iii) Characterization of the environmental impact: The collected data explain how each phase of the waste management system affects the environment; and (iv) Interpreting the results: To understand the relative contributions of each stage of the waste management system to the overall environmental impact, the LCA results were assessed (ISO 14040, 2006; ISO 14044:2006). The software used in the cited research that will be compared and examined is shown in Fig. 6. To satisfy low-cost and environmentally friendly economic sectors, all LCA analyses seek to streamline agricultural waste management. With rates of 25.81%, 6.45%, and 48.39% for Gabi, Open LCA, and SimaPro, respectively, two studies that used the EASETECH and MUIO-LCA software also saw usage. However, in 16% of the studies, using software for analyzing environmental effects was left unexplained. Furthermore, 16% of studies did not employ any software for their environmental impact analyses for the following reasons: i) financial restrictions, licensed LCA software can be fairly priced, and research resources might not be enough to cover purchasing costs. Researchers may employ a manual approach or straightforward tools, such as spreadsheets or self-programming code, in such situations; ii) Flexibility and control. Under certain circumstances, it may be desirable to have complete control over the entire LCA process, including the figures and techniques employed. Researchers may feel constrained by their ability to alter or modify the existing software to meet their study objectives; and iii) Creation of a special methodology: In some cases, researchers may be motivated to create a unique LCA approach that has not yet been implemented in the software. Under such circumstances, they may have to create a special computational tool to match their study goals.

The LCA software selection depends on the research objectives, equipment acquisition costs, the data held, and program usage (Manco et al., 2023; Petrillo et al., 2022). LCA software is also often used in the implementation of environmental management systems as it has many benefits beyond environmental impact analysis, such as economic analysis, weak-point assistance, opportunities for improvement at a stage that has a high impact, and opportunities to replace cheaper or environmentally inefficient processes.

Fig. 6: Analysis of LCA research and growth
friendly fuels (Deepak et al., 2022). Therefore, the LCA method could accurately identify stages with poor impact and performance. Moreover, the LCA method provides decision-makers with a tool for making complex choices and providing relevant and accountable information for reporting (Torkayesh et al., 2022). By providing actual data and scientific analyses regarding the impact of agricultural waste management environmental systems, LCA ensures that each approach is evidence-based and sustainable. The LCA method can also help decision-makers contribute to reducing economic impacts and developing an effective waste management system so that an environmental management system can be developed.

**Impact categories selection**

The selection of impact categories is one of the objectives for determining whether the selected application is in accordance with the desired target; however, if the impact category analyzed is broader, it will provide a more detailed analysis to achieve a sustainable system (Khanali et al., 2022). Fig. 7 shows the number of impact categories most often used to meet technology goals. The Global Warming Potential (GWP) impact category is used most commonly, at 80–94%, because it covers climate change issues and is required to consider potential environmental implications. This is in line with the research by Pratibha et al. (2019), where the main indicators of sustainability cover technologies with low GHG emissions were classified as GWP. In the context of GWP, key stages in the life cycle contributing to GWP, such as raw material extraction, production, transportation, use, and end-of-life disposal, should be identified to reduce GWP. When these are met, the potential trade-offs between environmental impacts will help decision-making for more sustainable alternatives. Therefore, evaluating the reduction in methane emissions caused by the breakdown of agricultural waste can be reduced when suitable management techniques, such as composting or anaerobic digestion, are used. Furthermore, the second impact analysis is the potential for human toxicity and ozone depletion of 30–45%, while the analysis of other impacts such as social, economic, ozone depletion, and photochemical ozone formation. An LCA can reveal the type and amount of toxic substances released during the life cycle of a product. These findings highlight the life cycle stages that contribute significantly to the impact of toxicity in humans. For example, the use of pesticides or other chemicals in agriculture may contribute to human toxicity, highlighting the importance of sustainable practices and using alternative ingredients. Moreover, ozone depletion in a city reveals the extent to which a product or process contributes to ozone layer depletion, highlighting certain substances or
manufacturing processes with high ozone depletion potential. Sustainable alternatives that minimize or eliminate the use of ozone-depleting substances can be identified, thereby contributing to more environmentally friendly practices. Sustainability outcomes depend on the balance between various environmental impacts. For example, a product or process may have a lower ozone depletion potential but a higher toxicity in humans, or vice versa. LCA should consider these trade-offs and help identify strategies to minimize negative impacts while maximizing positive ones. Agricultural waste management significantly affects climate change, resource depletion, and ecosystem health. Burning agricultural residues or neglecting trash may release methane and exacerbate global warming. When agricultural waste is not recycled, soil erosion and synthetic fertilizer use deplete resources (Khanali et al., 2022). This method reduces soil fertility and agricultural production. Water contamination and habitat degradation due to improper waste management threaten ecosystem health (McAuliffe et al., 2020). Sustainable waste management, such as composting and anaerobic digestion, is beneficial. Renewable energy from waste biogas reduces gas emissions from glasshouses. Recycling agricultural waste improves soil organic matter, lowers synthetic fertilizer use, and supports sustainable farming. The rest of the analysis, which is rarely used, can potentially help further studies to suggest substituting materials, raw materials, fuels, and the development of tools for managing agricultural waste to achieve a sustainable solution (Budihardjo et al., 2023b). This is because, when measuring the total energy used in each life cycle of the technology used, high energy use can significantly impact natural resources and GHG emissions.

Furthermore, for the economic sector, such cost cuts are expected by analyzing potential cost savings from effectively managing agricultural waste, considering opportunities for waste-based goods, and decreasing disposal costs (Chepeliev et al., 2022). Resource recovery evaluates the financial value of materials recovered from trash, such as compost, that can be used to produce bioenergy or improve soil (Haque et al., 2023). Market development, which measures the market expansion of waste-derived goods, stimulates economic opportunities in the agricultural waste management sector followed by health and safety (D’Agaro et al., 2022). Analyzing how well waste management decreases health risks for farmers, employees, and people in the area by minimizing exposure to dangerous substances is required (Mehmood et al., 2022). This sector is also covered by community engagement, which assesses the potential to create new employment opportunities and generate income through waste management practices and value-added products by examining local community involvement and awareness of waste management initiatives, encouraging a sense of responsibility and ownership and improving livelihoods. Support for conformity with laws and regulations is required for systematic application, and legal compliance assesses how well agricultural waste management operations adhere to current waste and environmental rules and whether policies are well-aligned. It also analyzes how national and international policies, such as pledges to the environment and sustainable development goals, connect with waste management initiatives. By considering these impact categories, stakeholders may build thorough plans for efficient agricultural waste management that address environmental, economic, and social concerns while fostering sustainability and resilience in agriculture.

Key sensitive parameters

Sensitivity analysis is used to determine how various characteristics or variables affect the results of agricultural waste management. This section discusses agricultural waste management and its effects on environmental, economic, and social issues. However, these studies typically include additional criteria (Awasthi et al., 2022). The amount of agricultural waste produced substantially impacts the total waste management plan, and some studies indicate a waste generation rate of 30–55%, as this is a widespread issue (Karić et al., 2022). The scalability of the waste management system can be evaluated, and the critical point at which alternative waste treatment methods are required can be identified by analyzing the sensitivity to changes in the rate of waste formation (Sabet et al., 2023). Agrochemical containers, crop residues, animal dung, and other waste products are produced by diverse agricultural activities in addition to the composition of agricultural waste. The most important waste streams can be identified by analyzing their sensitivity to changes
in waste composition, and their management can then be based on the potential for resource recovery and environmental impact (Ganesan and Valderrama, 2022). Additionally, selecting from a range of processing technologies, such as anaerobic digestion, incineration, composting, and other cutting-edge technologies, as shown in Fig. 8 is the most widely discussed topic. The compatibility of these technologies in multiple situations can be determined using sensitivity analysis, which considers energy efficiency, GHG emissions, nutrient recovery, and economic viability (Zoppi et al., 2023). Sensitivity analysis can evaluate the impact of changes in the market prices of agricultural and waste-derived products (such as bioenergy and biological fertilizers), which is another factor that is rarely considered (Bhatt et al., 2023). This analysis can determine prospective revenue sources and impact the economic viability of waste management solutions. Government laws and regulations can significantly impact how agricultural waste is managed; however, there is a lack of sensitivity analysis. Different policy scenarios, such as financial incentives for garbage recycling or fines for improper waste disposal, can be designed using sensitivity analysis to determine their impact on waste management decisions (Ma et al., 2023). The last and most debated component is social acceptance, which overlaps with existing conditions, the workplace, and stakeholders’ willingness to engage. Sensitivity analysis can help with the adoption of sustainable waste management, which can be influenced by public perception and engagement.

Important sensitive criteria for agricultural waste management

Identifying and prioritizing sensitive criteria are essential in agricultural waste management to ensure efficient and long-lasting waste treatment procedures. These criteria are crucial because they significantly impact the development of waste management methods. The following are some delicate factors for managing agricultural waste, listed in order of importance: i) Waste Composition: It is crucial to comprehend the makeup of agricultural waste. The viability and efficacy of various waste management strategies can be affected by variations in nutrient content, moisture levels, and the ratio of organic to inorganic elements; ii) Resource Recovery Potential: It is important to evaluate the possibility of recovering resources and energy from agricultural waste. Technologies that effectively transform trash into useful goods, such as compost for soil improvement or biogas from anaerobic digestion, are widely desired; iii) Environmental impacts: The effects of agricultural waste management systems on the environment should be carefully considered. Minimizing emissions, reducing GHG emissions, and avoiding soil and water pollution are important factors to consider when choosing the best waste management techniques; iv) It is important to consider the applicability, compatibility, and ability of the technology to handle particular forms of agricultural waste. To achieve the best outcomes, the technology should be chosen considering the waste composition and regional context; v)
Economic Viability: Agricultural waste management strategies must be economically viable. The long-term sustainability of waste management projects is significantly influenced by their cost-effectiveness and potential for resource recovery to generate income; vi) Local Context and Socioeconomic Factors: Successful implementation and community involvement in waste management programs depends on taking into account the local context, involving social acceptance, existing infrastructure, and economic conditions; vii) Energy Restoration: To maximize the advantages of energy generation, the efficiency of energy recovery systems such as biogas yield from anaerobic digestion should be adequately analyzed; viii) Market Demand and Supply: A successful circular economy must consider the supply and demand dynamics of items made from recycled agricultural waste. Compost, biochar, or other recycled goods are used properly when viable markets are identified; ix) Transportation distance: Reducing travel distances between waste-generation sites and management facilities lowers carbon emissions and transportation expenses; x) Life Cycle Assessment: Carrying out a thorough LCA enables a holistic assessment of the environmental effects linked to various waste management solutions, facilitating well-informed decision-making. Agricultural waste management strategies can be created and implemented to maximize resource recovery and environmental consequences and fit with each region’s distinctive characteristics by prioritizing these delicate criteria and considering how they interact.

Guideline best practices for recycle agricultural waste management

The best handbook for managing agricultural waste offers a thorough overview of important factors that must be considered (Bureau and Antón, 2022). It addresses several crucial topics, such as waste classification, resource recovery, sustainability, public awareness, and regulatory considerations (Tseng et al., 2022). Although the recommendations contain insightful advice, several areas should be strengthened and elaborated, and the type and volume of agricultural waste produced on agricultural land must be carefully evaluated (Budihardjo et al., 2023a). This process aids in identifying waste-management issues and growth prospects. Subsequently, waste stream characteristics were grouped according to their composition, biodegradability, and possibility of recycling or reuse. The stage of “Reduce and Prevent Waste Generation” needs to be given more attention because it can motivate farmers to use precision farming methods to maximize resource use and decrease overproduction, which then results in reduced waste production (Starek-Wójcicka et al., 2022). It can also encourage the implementation of effective irrigation techniques, pest control strategies, and nutrition management strategies to reduce agricultural by-products (Tedesco et al., 2023). If the phases cannot be shortened owing to strong demand, another option is to reduce waste in the livestock industry by encouraging people to compost organic waste products, such as agricultural residues, manure, and kitchen scraps, to produce nutrient-rich soil amendments. Encouraging farmers to use a zero-waste strategy, such as recycling agricultural packaging or switching to bioenergy generation from waste, is necessary. To support this, it is necessary to dispose of trash responsibly (Qin et al., 2022). Agricultural waste should not be burned in an open environment as it releases dangerous air pollutants. Promoting controlled combustion or looking into different disposal options, such as anaerobic digestion is required. To avoid pollution, one must ensure that the waste disposal sites are far from vulnerable ecosystems and water bodies (Pantusa et al., 2023). Recycling and resource recovery, which promote the recycling and reuse of agricultural waste, such as converting crop residues into animal feed or biofuel production, and exploring the potential to create value-added products from agricultural by-products, such as biodegradable packaging materials or natural fertilizers, continue to implement sustainable concepts (Koul et al., 2022; Kumar Sarangi et al., 2023). Collaboration and education are necessary for executing sustainable ideas. Cooperation should be encouraged among farmers, scientists, government organizations, and waste management professionals to create better approaches for managing agricultural waste (Farooq et al., 2022). Additionally, it is necessary to conduct workshops, training sessions, and awareness campaigns to inform farmers about the significance of sustainable waste management techniques. Compliance with the regulations is required for their application. Ensuring that all agricultural waste management techniques adhere to applicable local, regional, and federal laws.
and regulations is necessary (Hemidat et al., 2022). Farmers should be encouraged to adopt effective waste management practices by adhering to any changes in waste management regulations. Finally, monitoring and assessments are required to ensure that this concept is feasible. Installing mechanisms to monitor waste production and disposal methods can help with the success of waste management plans. Regularly evaluating the effects of waste management projects on agricultural productivity, environmental safety, and long-term economic viability is important. Agricultural waste management is a crucial component of sustainable agriculture. As per these recommendations, farmers can effectively manage their waste, reduce their adverse environmental effects, and convert it into useful resources. Adopting effective agricultural waste management methods benefits individual farms and helps develop a robust and environmentally conscious agricultural industry.

**Reviewed Technology**

The existing conditions and advanced technologies have diversified the technologies used for agricultural waste management. The various types of technologies and quantities frequently used in these studies are shown in Fig. 9. Various methods that have been developed and implemented for agricultural waste have changed significantly from landfilling methods to becoming energy sources, such as biochar, biogas, briquettes, and various methods that produce energy, such as solar and electricity. However, several methods lack technology, such as animal feed. Many methods still use thermal scenarios such as gasification, pyrolysis, and combustion. Overall, these results have a variety of methods with various approaches, from traditional to advanced, which are analyzed by LCA experts to assess potential environmental impacts.

**Suggested agricultural waste management technologies/facilities**

This section summarizes the various methods for managing traditional and advanced agricultural waste in Asia, as shown in Figs. 10 and 11, apart from those analyzed, because they do not meet the criteria. Asia has many traditional practices because

![Diagram](image-url)
Fig. 10: Traditional agricultural waste management

Fig. 11: Advance technology agriculture waste management
farmers often do not have access to resources, machinery, and contemporary technologies (Chaudhary et al., 2023). Traditional farming techniques are usually more practical for small-scale farmers with limited resources because they are more accessible and affordable (Mizik, 2023). Traditional agricultural practices have changed over time to accommodate certain local factors, such as climate, soil type, and resource availability, which is another reason why many traditional methods are still in use (Chimi et al., 2022; Samela et al., 2022). These techniques frequently fit the particular needs and challenges of a region (Ezugwu et al., 2022). Traditional agricultural methods are frequently taught and passed down from parents to younger generations in farming families or communities because of the lack of knowledge and skill transfer. This information transfer ensured the continuation of customary practices. There is also a connection between nature and sustainability, as traditional agriculture frequently emphasizes both concepts. By improving soil fertility, water conservation, and organic pest management, these techniques can support long-term ecological equilibrium (Vasseyghian et al., 2022). Moreover, cultural identity and food security have emerged. Local cuisine may be influenced by traditional crops and farming methods, which may be culturally important (Baldi et al., 2022). Maintaining traditional agricultural practices helps preserve cultural identity and food security. Although traditional agricultural management has numerous advantages, it is crucial to understand how sustainable and current agricultural innovations can improve and supplement conventional approaches (Muhie, 2022). An integrated approach incorporating conventional knowledge with contemporary technologies is necessary to increase productivity, efficiency, and environmental sustainability in Asian agriculture (Kannan et al., 2023). Governments, researchers, and organizations can play significant roles in assisting farmers in adopting sustainable and cutting-edge agriculture, while respecting and protecting traditional knowledge.

play a significant role in assisting farmers in adopting sustainable and cutting-edge agricultural.

Owing to several factors, such as the frequent need for considerable initial outlay and ongoing expenses, there are few advanced technologies in Asia. It may be difficult for small-scale farmers and rural populations across Asia, who constitute a significant portion of the agricultural sector, to afford this technology. Apart from technological matters, there is also the understanding that all agricultural waste will decompose by itself. The adoption process is impeded by upfront costs (Shaikh et al., 2022). Lack of Awareness and Knowledge: Many farmers and other rural stakeholders may be unaware of the advantages of cutting-edge agricultural waste management systems (Fielke et al., 2022). To persuade farmers with more expansive agricultural holdings to directly utilize crop waste, animal manure, and pruning materials instead of synthetic fertilizers, it is necessary to emphasize the advantageous outcomes regarding economics, the environment, and agriculture. On-farm organic resource utilization can substantially reduce input expenses for producers with larger farmland holdings. Alternatives to purchasing synthetic fertilizers that are frequently available on-site, sourced locally at reduced or non-existent expenses, and consist of crop refuse, animal manure, and pruning materials. In contrast to synthetic fertilizers, which may provide instantaneous nutrient availability but have the potential to deteriorate soil health gradually, organic materials impart long-term fertility to the soil through direct application. This method generates organic matter and ensures sustainable long-term productivity. Understanding how these technologies enhance waste management procedures is hampered by a lack of informational and educational resources. Technology and regional context adaptation: many cutting-edge waste management systems have been created outside Asia, and it may be difficult to adapt them to the particular requirements and conditions of Asian agricultural settings (Shokri and Fard, 2023). Although this can take time, localizing and modifying technology to meet regional demands is necessary. Cultural and traditional elements: the culture and heritage of many Asian communities are firmly rooted in traditional agricultural methods. Traditional approaches may have to be abandoned when a new technology is implemented, leading to resistance or skepticism. Furthermore, it is known that organic waste, including agricultural waste, naturally decomposes; however, recycling amplifies this organic process and derives multiple benefits from the waste. Composting is a prevalent recycling technique that involves the intentional decomposition
of organic agricultural waste in a controlled environment, generating a nutrient-dense compost that functions exceptionally well as an organic fertilizer. Compost enhances soil structure, optimizes water retention, and supplies vital nutrients to plants, thereby improving soil fertility and the overall health of crops. Implementing anaerobic digestion and composting as methods for recycling agricultural waste contributes to mitigating greenhouse gas emissions that would otherwise accumulate in landfills during natural decomposition. Methane, a highly potent greenhouse gas, is produced under landfill-like anaerobic conditions. Diverting organic waste from landfills by recycling reduces emissions and alleviates the adverse effects of climate change. Furthermore, agricultural waste recycling promotes sustainable agricultural practices by mitigating environmental impacts, reducing dependence on synthetic fertilizers, and enhancing soil health, enhancing the productivity and long-term resilience of agricultural systems. Governments, research institutes, the commercial sector, and non-governmental organizations must collaborate to address this challenge. Accelerating the adoption of cutting-edge technology for agricultural waste management in Asian nations would require stimulating public-private partnerships, developing awareness campaigns, offering financial support, and promoting information exchange (Kountios et al., 2023). By removing these obstacles and encouraging environmentally friendly technologies, Asian countries can utilize cutting-edge waste management techniques to build a more resilient and sustainable agricultural industry (Iwuozor et al., 2022). Effective agricultural waste management is essential for resource conservation, environmental preservation, and sustainable farming (Kharola et al., 2022). The most effective technologies and facilities for managing agricultural waste emphasize resource efficiency, environmental sustainability, and a circular economy (Onyeaka et al., 2023). Farmers and waste management stakeholders can dramatically reduce waste, produce renewable energy, increase soil fertility, and contribute to a more sustainable and robust agricultural sector using these technologies. Fostering cooperation among the public, corporate, and academic sectors can also promote innovation and the adoption of cutting-edge waste management techniques. Implementing a waste management system that integrates several waste processing methods, such as recycling, composting, biochar, and biogas production from anaerobic digestion, is necessary. By incorporating recycling, composting, biogas production from anaerobic digestion, and biochar production, an integrated approach to agricultural waste management was established, focusing on establishing a circular and sustainable system within the agricultural domain. Recycling entails repurposing by-products, including animal manure and crop residues, thereby decreasing dependence on external inputs and minimizing the environmental impact. Composting transforms organic waste into compost abundant in nutrients, thereby completing the nutrient cycle and improving the overall health of the soil. Biochar production is achieved by pyrolyzing organic materials, enhancing nutrient availability, water retention, and soil quality, thereby contributing to sustainable agriculture. Concurrently, biogas generation through anaerobic digestion serves the dual purpose of organic waste treatment and renewable energy provision for on-farm utilization, thereby adhering to the tenets of self-reliance and a diminished ecological footprint. The aforementioned integrated approach prioritizes waste valorization, establishment of closed nutrient cycles, and a holistic strategy that tackles the dual challenges of waste disposal and resource efficiency in the agricultural system. Using a biotechnological process called anaerobic digestion, organic wastes such as agricultural residues, animal manure, and food scraps are transformed into digestate and nutrient-rich biogas (Manikandan et al., 2023). Although the digestate can be used as a natural fertilizer, biogas can also be used to generate heat and electricity from renewable sources. Anaerobic digestion is an eco-friendly method of waste management because it reduces waste volume and GHG emissions, with studies showing a net saving in GWP emissions of -31.6 kg CO₂ (Budiardjo et al., 2023b). Composting is the second approach that is widely utilized and sustainable and has an impact of less than -2900 kg CO₂ eq/t when combined with anaerobic digestion (Li et al., 2018). Composting is a biological process that converts organic waste into nutrient-rich humus. Composting facilities make it easier for agricultural waste to decompose under controlled conditions and produce high-quality compost (Badawi, 2023). Compost can be used to
improve soil quality, retain water, and increase nutritional content. Compost is produced effectively and safely owing to large-scale composting facilities. Biomass and bioenergy crops, which use agricultural waste, such as crop residues and wood chips, as raw materials for bioenergy production, are widely used in the cited research (Rashedi et al., 2022). Biomass waste is transformed into biofuels, such as bioethanol or bio-oil, and syngas by gasification or pyrolysis. Biofuels have the potential to replace fossil fuels, reduce GHG emissions, and support a circular economy (Kovacs et al., 2022). Biochar manufacturing facilities employ pyrolysis to create biochar, a stable form of carbon, from agricultural waste. Mohammadi et al. (2017) showed little environmental impact in reducing the carbon footprint of spring and summer rice by 26% and 14%, respectively. Biochar is a soil additive that improves soil fertility, water retention, and nutrient availability. Additionally, long-term carbon sequestration in the soil helps slow climate change. Plants process agricultural waste and other types of garbage, transforming it into energy, often electricity and heat, using the waste-to-energy (WTE) strategy (Rani et al., 2023). Modern WTE techniques, such as incineration with energy recovery, guarantee the effective and safe disposal of trash while also capturing energy from the burning process and having less impact on the environment with a GWP of −5 kg CO2 eq/t (Tong et al., 2018; Priyambada et al., 2023). Recycling facilities for agricultural waste focus on removing and processing recyclable components from waste streams such as plastics, metals, and paper. Additionally, recycling facilities are looking into novel ways to transform agricultural waste into value-added goods, such as composite materials or biodegradable packaging (Mujtaba et al., 2023). However, many technologies will be ineffective without integrated farming systems that employ a comprehensive approach to waste management and use agricultural waste on-site to promote soil health, boost livestock feed, and produce renewable energy. For instance, animal excrement can be nutrient-rich, and plant residues can be used as animal feed. Decentralized waste management is required to support various approaches and the ensuing environmental effects. Waste management systems promote waste processing at the farm or local level. This approach lowers the cost of transportation, shortens the distances across which waste must be transported, and makes it easier to recycle and reuse the waste locally. Finally, smart technologies such as sensors and the Internet of Things (IoT) should be adopted for effective waste management. These technologies can be incorporated into waste management systems for waste collection, monitoring of composting or anaerobic digestion processes, and ensuring effective resource use. Minimizing agricultural waste at source is imperative for fostering sustainable and resource-efficient farming practices. Farmers can optimize inputs, such as water, fertilizers, and pesticides, by utilizing precision farming technologies, including sensors and GPS-guided equipment, thereby mitigating the risk of environmental damage and over-application. Incorporating biological control methods such as Integrated Pest Management (IPM) practices reduces the dependence on chemical pesticides, thereby decreasing the environmental impact of agriculture. Diversification and crop rotation disrupt the cycle of pests and diseases, improve soil fertility, and reduce the need for excessive chemical inputs. By optimizing harvesting practices, including selective and opportune harvesting, the risk of postharvest spoilage and over-ripening-related losses is reduced to that of mature and healthy harvested crops. Furthermore, implementing cold chain management for perishable produce, establishing adequate storage facilities, and investigating on-farm processing alternatives all contribute to the reduction of postharvest waste.

Gaps and critical findings in implementation
A useful approach for assessing the environmental effects of agricultural waste management systems and facilities is LCA. Although LCA has been used to analyze several waste management strategies, including those specific to agricultural waste, certain significant gaps and discoveries still require attention for a more thorough analysis. It might be challenging to gather complete and accurate data for the entire lifecycle of agricultural waste management technology. Information gaps exist in areas such as trash collection, transportation, treatment, and disposal. The LCA findings may be inaccurate because of missing or conflicting data. Agricultural practices differ significantly based on geography, crop type, and management strategies. This variability must be considered in LCA studies of agricultural waste management to reflect the
environmental effects of various waste management solutions appropriately. Limited Attention to Secondary Effects: The direct environmental effects of waste management are frequently the focus of LCA studies, but they may overlook secondary effects such as indirect land-use change, habitat damage, and biodiversity effects. It is crucial to consider these secondary effects in a more comprehensive analysis. The impact assessment approach is the final step, frequently leading to gaps. In LCA, picking an appropriate impact assessment methodology is crucial for an LCA. To achieve consistency and comparability among studies, designing specialized impact assessment procedures for agricultural waste management is necessary. In LCA studies emphasizing the significance of source segregation and pretreatment of agricultural wastes, separating sources and pretreatment has been one of the criteria for a crucial comparison. The quality of recycled materials or energy recovered from trash can be improved through proper source segregation, which enables more effective waste management procedures. The possibilities of energy recovery are as follows: Anaerobic digestion, biochar, and pyrolysis are the most common agricultural waste management techniques and have shown substantial promise for energy recovery through LCA. Using this technology, farms can generate biogas, charcoal, or bioenergy that can be used on-site or fed into a grid. Recycling nutrients and improving soil quality: Agricultural waste can be recycled back into the soil as organic amendments, boosting soil fertility and lowering the demand for fertilizers. Examples of such wastes include crop residue and animal manure. The relevance of nutrient recycling and its beneficial effects on soil health have been emphasized in LCA studies, but this has not been covered in depth in the aforementioned research. To achieve sustainability, a circular economic strategy to manage agricultural waste can result in more sustainable procedures. LCA studies have shown the possibility of reducing overall environmental effects and resource consumption by reusing and recycling waste materials. To promote sustainable waste management and aid in the transition to a more resource- and environment-friendly agricultural sector, it is important to fill the identified gaps and consider the major findings of the LCA study for agricultural waste management.

**RECOMMENDATION**

Asian nations can address the issues with managing agricultural waste while creating a more resilient and sustainable agriculture industry by incorporating interactive and sustainable solutions. Governments, communities, and other stakeholders must work together if they are to manage agricultural waste appropriately over the long term. Encourage farmers, local communities, researchers, and policymakers to work together actively to discover regionally unique problems with agricultural waste management and create specialized solutions. Participation from the community encourages a sense of responsibility, which results in more efficient and sustainable waste management techniques. Invest in programs that develop the capacity of waste management stakeholders and educate farmers about sustainable waste management techniques. Training sessions may concentrate on appropriate waste segregation, composting methods, anaerobic digestion, and other cutting-edge agricultural technologies appropriate for Asia. Implementing an integrated waste management system that includes recycling, composting, biochar, and anaerobic digestion biogas production. Recycle, compost, biogas from anaerobic digestion, and biochar synthesis create an integrated approach to agricultural waste management that promotes a circular and sustainable system. By recycling byproducts like animal manure and crop leftovers, dependence on external inputs and environmental effect are reduced. Making nutrient-rich compost from organic waste completes the nutrient cycle and improves soil health. Pyrolyzing organic materials produces biochar, which improves soil quality, water retention, and nutrient availability for sustainable agriculture. Self-reliance and reduced environmental impact are achieved by generating biogas from anaerobic digestion of organic waste and providing renewable energy for on-farm use. The integrated method prioritizes waste valorization, closed nutrient cycles, and a holistic approach to agricultural waste management and resource efficiency. The holistic approach guarantees effective management of various waste streams and maximizes resource recovery. Promoting the use of biogas production methods that generate the fuel from agricultural waste, such as plant leftovers and animal dung. A renewable energy source for rural communities, biogas can be electricity, heating, and cooking. Promotes on-farm
composting and composting of agricultural waste as a natural, inexpensive way to recycle organic matter. Vermicomposting and Composting. As a result, the soil is more fertile, fewer chemical fertilizers are needed, and fewer greenhouse gas emissions are produced. To encourage farmers and waste management facilities to adopt sustainable practices, offer financial incentives and policy support. Environmentally friendly waste management systems can be adopted more quickly if the government offers subsidies, tax breaks, and favorable legislation. Can encourage the successful implementation of waste management practices by facilitating technology transfer and knowledge sharing across Asian nations. The adoption of sustainable solutions can be accelerated by regional cooperation. The circular economy’s concepts should also be included into strategies for managing agricultural waste, with a focus on waste reduction, reuse, and recycling. Encouraging the creation of agricultural waste-derived value-added goods including biochar, bio-based materials, and biodegradable packaging. Spend money on research and development to create and enhance agricultural waste management methods. Accept cutting-edge waste-to-energy techniques, intelligent waste collection systems, and other developing technology. The importance of sustainable agricultural waste management and its benefits for the environment, human health, and rural livelihoods should be made more widely known. Campaigns for proper waste management can be promoted through education and behavior change.

CONCLUSION

Life cycle thinking has emerged as an innovative and comprehensive viewpoint that considers the entire recycling process to evaluate the potential and true implications of agricultural waste recycling. The core idea of “sustainable” is life cycle thinking, an original and comprehensive strategy that goes beyond conventional linear evaluations. This study demonstrated the significance of context-specific techniques in recycling agricultural waste. Adapting waste management solutions to local conditions and resource availability is essential because agricultural practices vary between locations. Identifying and prioritizing sensitive criteria are essential when choosing agricultural waste management to ensure efficient and long-lasting waste treatment procedures. Various methods developed and implemented for agricultural waste have changed significantly from landfilling methods to becoming energy sources, such as biochar, biogas, briquettes, and various methods that produce energy, such as solar and electricity. This review provides insights into how recycling agricultural waste can dramatically lower GHG emissions, conserve resources, and improve soil fertility. Composting, anaerobic digestion, and pyrolysis are used to create biochar, a waste recycling method that holds promise for sustainable waste management. In addition to efficiently managing agricultural waste, these technologies help generate electricity and sequester carbon, thereby advancing the objectives of climate change mitigation and circular economy. Widespread adoption of sustainable waste management techniques can be facilitated by integrating community involvement, capacity building, and policy assistance, allowing farmers and local communities to participate actively. Environmentally friendly waste management systems can be adopted more quickly if the government offers subsidies, tax breaks, and favorable legislation. This can encourage the successful implementation of waste management practices by facilitating technology transfer and knowledge sharing across Asian nations. Regional cooperation can accelerate the adoption of sustainable solutions. Although LCA has been used to analyze several waste management strategies, including those specific to agricultural waste, certain significant gaps and discoveries still require attention for a more thorough analysis. It might be difficult to gather complete and accurate data for the entire lifecycle of agricultural waste management technology. Limited Attention to Secondary Effects: The direct environmental effects of waste management are frequently the focus of LCA studies, but they may overlook secondary effects such as indirect land-use change, habitat damage, and biodiversity effects. It is crucial to consider these secondary effects in a more comprehensive analysis. To promote sustainable waste management and aid in the transition to a more resource- and environment-friendly agricultural sector, it is important to fill the gaps that have been identified and consider the major findings of the LCA study for agricultural waste management.

AUTHOR CONTRIBUTIONS

S. Sumiyati is responsible for making whole
concept. B.P Samadikun is responsible for finding out the outline of each manuscript analyzed in managing agricultural waste, determining searches, compiling concepts, reviewing all manuscripts. A. Widiyanti is responsible for finding out the outline of each manuscript analyzed in managing agricultural waste, determining searches, compiling concepts, reviewing all manuscripts. S. Al Qadar reviewed the final report. A.S. Puspita is responsible for preparing drafts, journal analysis sources and reviewing the entire manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>%</td>
<td>Per cent</td>
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<tr>
<td>AC</td>
<td>Active carbon</td>
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<td>Anaerobic digestion</td>
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<td>Animal Feed</td>
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<td>AP</td>
<td>Acidification potential</td>
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<td>Brq</td>
<td>Briquette</td>
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<td>CF</td>
<td>Carbon footprint</td>
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<td>COMP</td>
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<td>Dfp</td>
<td>Direct-fired power</td>
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<td>Directorate General of Higher Education, Research and Technology</td>
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<td>Ds</td>
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<td>Freshwater eutrophication</td>
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<td>Global warming potential</td>
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<td>Incineration</td>
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<td>Integrated pest management</td>
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<tr>
<td>KEMENDIKBUD</td>
<td>Ministry of Education, Culture, Research, and Technology</td>
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kg CO₂ kilogram of carbon dioxide
kg CO₂ eq/t kilogram of carbon dioxide equivalent per ton
IoT Internet of Things
LBP Large biogas scale production
LCA Life cycle assessment
LF Landfill
Ln Liquefaction
LSS Large scale solar
MAE Marine Aquatic Ecotoxicity
MEP Marine eutrophication potential
Mt Metric ton
OB Open burning
OD Ozone Depletion
pm10 Particulate matter 10nm
PO photochemical oxidation
POCP Photochemical ozone creation potential
POF Photochemical ozone formation
PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRs Pyrolysis
RCYCL Recycle
RD Resource depletion
SOD Stratospheric ozone depletion
TE Terrestrial ecotoxicity
TETP Terrestrial ecotoxicity potential

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