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Microbial contributions to sustainable paddy straw utilization for economic gain and environmental conservation

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ABSTRACT

Paddy straw is a versatile and valuable resource with multifaceted benefits for nutrient cycling, soil health, and climate mitigation. Its role as a rich nutrient source and organic matter significantly enhances soil vitality while improving soil structure and moisture retention. The impact of paddy straw extends beyond traditional agricultural benefits, encompassing the promotion of microbial activity, erosion control, and carbon sequestration, highlighting its crucial role in maintaining ecological balance. Furthermore, the potential of paddy straw in bioenergy is explored, encompassing its conversion into biogas, biofuels, and thermal energy. The inherent characteristics of paddy straw, including its high cellulose, hemicellulose, and lignin content, position it as a viable candidate for bioenergy production through innovative processes like pyrolysis, gasification, anaerobic digestion, and combustion. Recent research has uncovered state-of-the-art techniques and innovative technologies capable of converting paddy straw into valuable products, including sugar, ethanol, paper, and fiber, broadening its potential applications. This paper aims to underscore the possibilities for value creation through paddy straw, emphasizing its potential use in bioenergy, bio-products, and other environmental applications. Therefore, by recognizing and harnessing the value of paddy straw, we can advocate for sustainable farming practices, reduce waste, and pave the way for a resource-efficient circular economy. Incorporating paddy straw utilization into agricultural systems can pave the way for enhanced resource efficiency and a more sustainable circular economy.

1. Introduction

India is experiencing rapid economic and industrial growth, leading to an increased demand for energy. Currently, most of India's energy consumption, which amounts to 151.3 GW driven from thermal sources (coal, natural gas, and oil), relies on non-renewable energy options. This heavy reliance on oil and coal poses several drawbacks, including environmental deterioration, lack of sustainability, and economic challenges since India imports these resources from other countries (Bhattacharya et al., 2021). Therefore, exploring alternative options to address these issues and promote sustainable energy sources is crucial for fostering expeditious economic and industrial growth. Biomass energy is one such non-conventional source that offers a viable solution. Biomass is a renewable energy source from living or dead plants, crop byproducts, wood, and agro-based industries (Sadh et al., 2018a, 2023). Currently, India generates approximately 683 million tons of crop residues annually. About 80 % of this amount is used for feed, fuel, or industrial purposes. However, a substantial quantity of unused surplus crop residues, around 87 million or 178 million tons, is still being burned in fields. Around 600–700 million tons of paddy straw are produced annually worldwide (Datta et al., 2020). Paddy straw, a renewable energy source, can be converted into energy through chemical and

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biological processes such as pyrolysis, gasification, and anaerobic digestion. Direct combustion is a fundamental method for producing electricity by using paddy straw. However, the efficiency of biomass power plants using combustion methods is typically around 20 %. Dried paddy straw has remarkably low moisture content, significantly improving combustion and increasing power plants' efficiency by up to 40 %. Biomass power plants typically have outputs ranging from 20 to 50 MW (Boundy et al., 2011). Although coal-based power generation remains the preferred method in India, biomass-based power generation offers greater potential. It has a lower environmental impact and a renewable and sustainable approach to power generation in the future. By embracing biomass-based power generation, India can move towards a greener, more sustainable energy future. India's target of renewable energy by 2030 is 500 GW of clean and affordable energy (MNRE, 2023) (Fig. 1). Subsequently, to expand the use of biomass for the production of bioenergy, the Indian government provides subsidies and supports the adoption of biogas plants, biofuels, bio-oils and bio-products which produce no smoke and are considered pollution-free (Roy et al., 2015).

Additionally, advancements in biomass gasification technology have led to the conversion of biomass into syngas, a more efficient energy source. Efforts are also being made to find economically and socially acceptable uses for agricultural waste, including rice straw and husks. Rice bran and broken rice, which have applications in the food industry, are not the focus of this review. However, rice straws and husks, traditionally considered waste and often discarded or burned, offer potential for fuel production and various other products. Rice husks, in particular, are easily collected and inexpensive, making them suitable for small-scale energy applications (Satpathy and Pradhan, 2023). Recent developments include the production of polymeric composite resins, polymeric lumber and solid pellets from rice husks. This review explores current practices in using rice straws and husks while presenting ideas for further comprehensive utilization. This includes considering the potential for high-value products like silica and phenolic compounds and high-volume options like ethanol and methane. However, practical considerations and compatibility with other societal factors will ultimately determine the extent of implementation for these utilization methods.

2. Rice straw as a source of bioenergy

Rice straw is a plentiful and easily accessible resource in rice-producing regions across the globe. One of the key advantages of rice straw is its high energy content compared to other agricultural residues. It contains approximately 14–16 MJ/kg (mega joules per kilogram), equivalent to about 3900–4400 kcal/kg (kilocalories per kilogram). Utilizing rice straw as an energy source offers considerable environmental benefits. It helps reduce the harmful practice of open burning, contributing to air pollution and greenhouse gas emissions. Properly harnessing rice straw for energy generation minimizes waste, and a more sustainable agricultural system can be promoted.

The utilization of rice straw depends on its specific characteristics, including bulk density, heat capacity, thermal conductivity, chemical composition (including lignin, cellulose, hemicelluloses, and carbohydrates), and thermal properties (such as calorific value). These properties are crucial when converting biomass to energy or considering animal feed and soil fertility applications.

To determine the energy efficiency of rice straw, the energy output can be divided by the heat output, expressed as either the lower or higher heating values. The heating value of paddy straw, expressed in terms of Higher Heating Value, generally falls within the range of 14.08 - 15.09 MJ/kg. Hung et al. (2019) highlighted that the heating value of rice straw is significantly lower, approximately one-third, compared to kerosene, which boasts a heating value of 46.2 MJ/kg.

Table 1

The nutritional value of paddy straw is crucial for various applications such as livestock feed, anaerobic digestion, and soil enrichment, all of which depend on its chemical makeup. Extensive research has aimed to enhance paddy straw's relatively modest nutritional content. Jenkins (1998) notes that plant biomass, including paddy straw, comprises a range of typical constituents such as moisture, ash, lipids, cellulose, lignin, hemicelluloses, proteins, water, simple sugars, hydrocarbons, starches, and other compounds. The concentrations of these components vary depending on factors such as plant species, growth stage, tissue type, and environmental conditions. Paddy straw falls under the category of lignocellulosic biomass, with an approximate composition of 38 % cellulose, 25 % hemicellulose, and 12 % lignin. Barmina et al. (2013) highlight that rice straw typically contains lower cellulose and lignin levels than other plant biomasses like softwood, while its hemicellulose

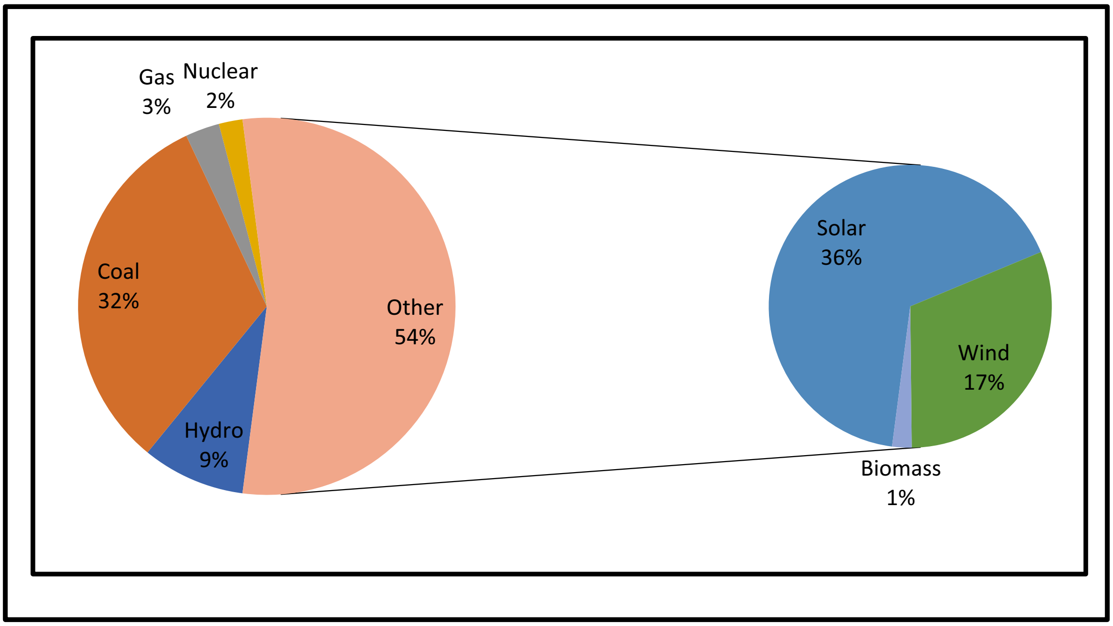

Fig. 1. Total installed capacity by 2030.

Table 1
Summary of the physical, thermal, and chemical composition of paddy straw and its ash.

Composition	Composition	Values	References
Physical composition	Moisture content	10–20 %	(Jenkins, 1998)
	Particle size	Varies	(Jenkins, 1998)
Thermal composition	Calorific values	14–18 MJ/Kg	(Ngi et al., 2006)
Chemical composition	Organic Matter	82 %	(Khanday et al., 2018)
	Crude Protein	4 %	(Ngi et al., 2006)
	Crude Fiber	37 %	(Hung et al., 2019)
	Non Fatty Ester	43 %	(Sarnklong et al., 2010)
	Total ash	18 %	(Peripolli et al., 2016)
	Calcium	0.14 %	(Sarnklong et al., 2010)
	Phosphorus	0.05 %	(Ngi et al., 2006)
	Neutral Detergent Fiber	75 %	(Sarnklong et al., 2010)
	Acid Detergent Fiber	54 %	(Peripolli et al., 2016)
	Cellulose	37 %	(Khanday et al., 2018)
	Lignin	8 %	(Hung et al., 2019)
	Silica	8 %	(Ngi et al., 2006)
Chemical composition of paddy straw ash	SiO_2	72.55–83.12 %	(Liu et al., 2011)
	K_2 O	10.06–12.60 %	(Migo, 2019)
	CaO	1.61–3.01 %;	(Jeng et al., 2012)
	Na_2 O	0.16–1.85 %	(Guillemot, 2014)
	MgO	1.74–2.02 %	(Jeng et al., 2012)
	P O_5	0.49–2.65 %;	(Liu et al., 2011)
	Al_2 O_3	0.11–1.40 %;	(Migo, 2019)
	Fe_2 O_3	08–0.85 %;	(Liu et al., 2010)
	SO_3	0.84–1.24 %	(Guillemot, 2014)
	TiO_2	0.01–0.09 %	(Jeng et al., 2012)
	Ash content	18.63–22.10 %	(Migo, 2019)
Proximate analysis	Fix C	16.75	(Migo, 2019)
	Volatile	64.24	(Duan et al., 2015)
Ultimate analysis	Ash	22.70	(Migo, 2019)
	SC	44.40	(Duan et al., 2015)
	H	5.2	(Jenkins et al., 1996)
	O	37.35	(Migo, 2019)
	N	1.18	(Duan et al., 2015)
	S	0.03	(Migo, 2019)
	Cl	0.32	(Guillemot et al., 2014)

content is relatively higher. Paddy straw is used in research in many ways to produce different products, as mentioned below in Table 2

3. Role of microorganisms in the formation of value-added products

Microorganisms are essential to convert paddy straw into value-added products through various processes such as fermentation and biodegradation. A diverse range of bacterial and fungal species are used to degrade the paddy straw, forming various products such as bioenergy, enzymes, alcohols, and organic compounds. Biogas can be produced from the paddy straw after carbohydrate removal through enzymatic hydrolysis and wet explosion pretreatment. As Khan and Ahring's (2020) study showed, a second wet explosion treatment incorporating NaOH is necessary for optimizing methane production to enhance lignin accessibility for anaerobic digestion. Microbial fermentation is also used to produce lactic acid, ethanol, and various enzymes. Qi and Yao (2007) studied rice straws and husks as economic resources that can be utilized to produce lactic acid for applications in the pharmaceutical, food, and chemical sectors. This entails fermentation of enzymatically hydrolyzed lignocellulosic material using Lactobacillus bacteria. Liu et al. (2022) utilized a psychrophilic microbial consortium to expedite the degradation of rice straw in field conditions. Their study revealed that incorporating rice straw through deep tillage and the psychrophilic microbial consortium significantly enhanced soil nutrient levels. Specifically, compared to other treatments, there were notable increases in soil organic matter, total nitrogen, available phosphorus, and available potassium. Particularly it was noticed that the addition of the microbial consortium in the treatment significantly elevated the soil organic matter compared to control and other treatments. The consortium effectively broke down the lignin content of rice straw while preserving cellulosic biomass under static culture at 30 °C.

The degradation of rice straw lignin is strongly correlated with certain microbial genera such as *Clostridium, Pseudomonas, and Thaurea*. These findings show that microbial resource rice straw can be used in bio pulping and other valuable products (Xu et al., 2021). Additionally, Kumar and Gaind (2019) investigated the microbial degradation of lignocellulosic biomass and the production of soluble phosphorus fertilizer. They utilized paddy straw as a medium for solid-state fermentation by phosphate-dissolving and cellulase-producing strains of *Aspergillus niger* (ITCC 6719) and *Aspergillus awamori* (F18). Adding fungal inoculation and wheat bran with the rice straw achieved the maximum solubilization of rock phosphate.

Moreover, biochar derived from rice straw demonstrated efficacy in soil remediation by mitigating the impact of heavy metals on crop growth and soil ecology. Fermentation residues from straw were shown to be suitable for preparing soil remediation agents via pyrolysis. The degradability of rice straw by filamentous fungi, such as *Trichoderma asperellum* T-1, during fermentation significantly improved the properties of biochar for cadmium-contaminated paddy soil remediation. The resulting biochar exhibited rich oxygen-containing groups, enhancing their ability to remove Cd (II) (Wang et al., 2022).

4. Bio-fuel beyond ethanol

Paddy straw, characterized by its lignocellulosic composition, emerges as an excellent raw material for bioethanol production. Its cellulose and hemicellulose content can be readily transformed into fermentable sugars, rendering it a viable candidate for the bioethanol production pathway, as evidenced by Binod et al. (2010). Bioethanol generated from paddy straw is recognized as carbon-neutral and can potentially reduce gasoline consumption, a point emphasized by Singh et al. (2016). Among the diverse utilization approaches for rice straw, the bioethanol route is hailed as the most ecologically sustainable and effective means to combat global warming (Silalertruksa and Gheewala, 2013).

However, the elevated silica and ash content in rice straw presents hurdles in ethanol production. Silica impedes enzymatic hydrolysis and diminishes ethanol yields, as underscored by Binod et al. (2010). The economic viability of bioethanol production from rice straw varies from region to region. For instance, in India, Bhattacharya et al. (2021) suggested that converting rice straw into bioethanol has been estimated to yield economic and environmental advantages. In contrast, Roy et al. (2012) observed the economic feasibility of bioethanol production from rice straw in Japan remains uncertain despite the evident environmental

Table 2
Utilization and creation of value-added products from paddy.

Paddy straw uses	Value-added products/ processes	Processes	Microorganisms	References
Energy generation	Bio- CNG	Desulphurisation, compression	*Methanobacterium*	(Schnürer A., 2016)
	Bio-Hydrogen	Biological conversion	*Gymnopus contrarius*J2, *Clostridium, Thermoanaerobacterium thermosaccharolyticum, B. cepacian* H-2, *Aspergillus nidulans* FLZ10, *Amorphothe caresinae ZN*1, *Miscanthus giganteus, Enterobacter* sp, *B. cepacian* H-2	(Agu et al., 2016; Tsai et al., 2021; Zhang et al., 2013)
	Bio- Gas	Anaerobic digestion	*Trichoderma reesei* MTCC 164 and *Coriolus versicolor, Pleurotus ostreatus, Methanobacterium*	(Phutela et al., 2011)
Alcohol production	Methanol	Fermentation	*Methylacidiphilum fumariolicum*	(Qi and Yao, 2007)
	Ethanol	Fermentation	*Saccharomyces cerevisiae, Myrothecium roridum, Trichoderma reesei, S. cerevisiae, Aspergillus oryzae*	(Duhan et al., 2013a; Sasaki et al., 2014; Sarabana et al., 2018)
	Butanol	Fermentation	*Clostridium acetobutylicum, Clostridium Thermocellum, C. saccharoperbutylacetonicum*	(Amiri et al., 2014; Kiyoshi et al., 2015)
Food preservatives, flavoring agent, curing agent	Lactic and levulinic acid production	Fermentation	*Lactobacillus rhamnosus, Actinobacillus succinogenes*	(Duhan et al., 2013b; Huy and Khue, 2016; Bevilaqua et al., 2015)
Medicals	Xylitol production	Hydrolysis, Fermentation	*C. subtropicalis, C. tropicalis, Saccharomyces cerevisiae,*	(Liaw et al., 2008; Swain and Krishnan 2015; Guirimand et al., 2016)
Industries	Lignin-derived chemicals	Hydrolysis, microbial treatment, soda process	*Botrytis cinerea, Staphylococcus aureus*	(Cui et al., 2019)
Food preservation	Sophorolipids	Solid state fermentation	*Wickerhamiella domercqiae*	(Liu et al., 2016)
Industries	Textiles	Pretreatment, strengthening	*Bacillus, Streptomyces Trichoderma, Aspergillus*	(Sen et al., 2021)
	Paper and pulp	Degradation, Strengthening, pressing	*Streptomyces, Bacillus, perostatic bacteria*	(Qu et al., 2017)
	Cardboard	Degradation,	*Streptomyces, Bacillus, perostatic bacteria*	(Qu et al., 2017)
Agriculture	Composting	Biodecomposition	*Cellulomonas cellulans, A. awamorii, Phanerochaete chrysosporium, Paecilomyces fusisporus, T. viride*	Mishra and Nain (2013) (Goyal and Sindhu 2011)
	Mashroom	Biodecomposition	*Lentinula edodes, Pleurotus* spp, *Agaricus bisporus*	(Chandra and Chaubey, 2017) (Gellerman, 2018)
	Mulching	Spreading	–	(Schmidt et al., 2015a)
Agriculture and industries	Biochar	Pyrolysis, Gasification, Torrefaction, Hydrothermal liquefaction	–	(Li et al., 2021; Pei et al., 2020; Tan et al., 2021; Harisankar et al., 2021; Brar et al., 2024)
Constructions	Building blocks	Compressing	–	(Zhao et al., 2020)
Medicals	Biopolymers	Hot pressing	–	(Wei et al., 2015)
Medicals	Biomaterials	Compressing	–	(Zhao et al., 2020)
Industries	Nano-silica	Extraction	–	(Ahmad et al., 2016)
Industries and agriculture	Lignin	Extraction	–	(Kauldhar and Yadav, 2018)
Industries	Fiberboards	Pre-treatments	–	(Theng et al., 2019)
	Paper and pulp	Pulping, bleaching	–	(Nagpal et al., 2021)
Industries and agriculture	Black liquor-derived porous carbon	Pretreated with KOH	–	(Zhu et al., 2018)
Industries	Packaging material	Pulping	–	(Ibrahim et al., 2021)

benefits. Generating biogas through the anaerobic digestion of rice straw offers an eco-friendly alternative to burning residues. This approach significantly curtails greenhouse gas emissions compared to residue burning while simultaneously enabling the sustainable recycling of nutrients by incorporating the digested sludge into the soil, as elucidated by Satpathy and Pradhan (2023). Although bioethanol exhibits potential as a biofuel, especially in high-demand regions like India, it is essential to carefully assess biofuel production's efficiency and economic viability to ensure environmental and economic benefits (Roy et al., 2012; Duhan et al., 2020). In addition to bioethanol, many other biofuels can be generated from various biomass sources, expanding the horizons of renewable fuel production. Producing bioethanol from paddy straw encompasses several key stages, including pretreatment, enzymatic hydrolysis, fermentation, distillation, dehydration, and optional denaturing.

Regarding pre-treatment methods, the alkaline approach is the most effective for sugar production from lignocellulose. Its biological effects, acting as a catalyst, significantly enhance the generation of fermentable sugars during the process (Arora et al., 2016). However, it's important to note that biological treatments tend to be slower overall than alkaline methods.

Furthermore, it's imperative to acknowledge that prospects for advancing lignocellulosic biotransformation should strongly emphasize achieving a more precise enhancement of bioethanol production. This is because pre-treatment represents the costliest operation, accounting for approximately 3 % of the total cost (Tomas et al., 2008). Genetic enhancements through co-culture systems, targeting fermentative and cellulolytic systems, offer an attractive avenue to increase ethanol production, especially under challenging conditions (Chen, 2009). Strategies such as simultaneous saccharification and fermentation, combined enzymatic hydrolysis (Liu et al., 2010), and consolidated bioprocessing are also considered cost-saving measures. The solid state fermentation of acid treated paddy straw with *S. cerevisiae, Rhizopus oryzae*, and *Mucor indicus* produced an ethanol yield ranging from 40 % to 74 % of the maximum theoretical yield, as reported by Karimi et al. (2006). For instance, Wu et al. (2016a) illustrated this through the in-situ hydrolysis of rice straw using a mixed culture of and *T. viride* and *Trichoderma reesei*, which secrete lignin-degrading enzymes and cellulose. Subsequently, fermentation was conducted with *S. cerevisiae* and *Candida tropicalis* co-immobilized in polymer beads containing sodium alginate, silicon dioxide and polyvinyl alcohol, protecting the yeasts. Additionally, Sarabana et al. (2018) recently introduced a consolidated bioprocess wherein rice straw undergoes alkaline hypochlorite pretreatment to enhance cellulase production by *Trichoderma reesei*. This pretreated material is then fermented with a culture of *Aspergillus oryzae* and *S. cerevisiae*. Integrating the production of high-value products alongside bioethanol can enhance the economics of bioethanol production. For instance, Ma et al. (2019) demonstrated this by extracting flavonoids such as kaempferol and sapigenin from rice straw in integrated processes.

Arora et al. (2016) have demonstrated that biological pretreatment is a viable method for preparing rice straw, achieving a high level of cellulose conversion comparable to steam pretreatment. Incorporating alkali extraction proved effective in eliminating degraded soluble lignin and other soluble inhibitors, consequently leading to an improved release of sugars from holocellulose. This pretreatment method resulted in cellulose enrichment. However, when higher solid loadings were used, challenges arose in conducting enzymatic hydrolysis. This, in turn, led to lower sugar concentrations and subsequently reduced ethanol yields.

4.1. Bio-methane

Bio-methane, also known as biogas, can be efficiently produced from rice straw through the anaerobic digestion process, which involves the action of different microbes and microbial consortiums. Bio-methane, derived from biomass, is a clean and renewable energy source, contributing to approximately 15 % of global energy consumption (Zealand et al., 2017). Compared to non-renewable fossil fuels, biomass-based bio-methane emits fewer air pollutants and less CO_2 per unit of energy. Optimizing the anaerobic digestion process parameters is crucial for maximizing bio-methane production from rice straw. Zealand et al. (2017) found that a lower feed frequency to the anaerobic bioreactor was more effective due to the slow hydrolysis rate of straw digestion, which can be hindered at high feed rates. They observed that units fed less frequently (once every 21 days) exhibited a higher ratio of biogas synthesis than those fed more frequently (five times every seven days). Straw size also plays a significant role in methane production during anaerobic digestion. Dai et al. (2020) evaluated different straw sizes and found that the highest methane gas production occurred with a straw size of 0.075 mm, which was 1–8 times greater than the production from larger straw sizes (20 mm). Pretreatment of rice straw can enhance methane synthesis. The pretreatment resulted in a significant reduction in cellulose crystallinity, leading to improved methane production.

Furthermore, treatment with a consortium of lignin-degrading bacteria can enhance bio-methane yields from rice straw. Shah et al. (2019) isolated lignin-degrading bacteria from rice straw and found that the treated straw exhibited increased methane yields. They attributed this improvement to the reduction in straw elasticity through the action of laccase and ligninase enzymes. In addition, the co-digestion of cow dung and rice straw has shown positive results in biogas production. Successfully co-digesting these materials resulted in the observation of higher methane content in the biogas. Various pretreatment methods have been investigated to improve methane yield from paddy straw. For example, Sandhu and Kaushal (2019) have optimized steam explosion pretreatment Bio-CNG, and Shah et al. (2019) found a 62 % increase in cumulative methane yield compared to untreated straw. Alkaline microwave pretreatment by Qian et al. (2019) increased biogas yield by approximately 25 % by optimizing the AD process parameters, pretreatment methods, and co-digestion strategies, which can significantly enhance bio-methane production from rice straw, offering a sustainable energy solution.

Biogas, generated through anaerobic digestion, primarily consists of methane, carbon dioxide, and smaller amounts of nitrogen, hydrogen sulfide, and water vapor. Methane can be directly used as fuel for cooking and heating, converted into electricity through generators, or compressed and used as an alternative fuel for vehicles. In Europe, biomass sources, including decentralized agricultural plants, household waste, and dedicated energy crops, accounted for 57 % of biogas production in 2011, utilizing centralized biogas plants and co-digestion facilities. Anaerobic digestion is considered one of the cleanest methods for deriving energy from biomass (Shen et al., 2018).

4.2. Bio-hydrogen

Bio-hydrogen, with its high energy yield of 122 kJ/g, is considered a promising fuel for the future. The global demand for hydrogen is rapidly increasing and is projected to contribute about 10 % of total energy by 2025. Bio-hydrogen production offers an environmentally friendly technique that can contribute to carbon neutrality (Staffell et al., 2019). Bio-hydrogen can serve as a clean and sustainable energy carrier, particularly in fuel cells for electricity generation without greenhouse gas emissions. It is produced by autotrophic and heterotrophic microorganisms, including algae and bacteria (Sheng et al., 2018). Various pathways exist for bio-hydrogen generation, such as light-dependent and light-independent processes. Autotrophic pathways rely on solar energy, converted to hydrogen through photosynthetic reactions mediated by photosynthetic algae, bacteria, and some protists. In heterotrophic environments, organic compounds can be transformed into lower organic substrates, producing hydrogen (Mishra et al., 2022). Heterotrophic conversion can be categorized into photo-fermentation, performed by photosynthetic prokaryotes, and dark fermentation, performed by anoxic bacteria that convert carbohydrates to hydrogen. Dark fermentation, which involves hydrogen production from organic matter by bacterial activity, offers the dual advantages of energy generation and waste reduction (Kumar et al., 2014). Kim et al. (2014) researched hydrogen production from rice straw under anaerobic conditions. They observed that mixing rice straw with sewage sludge at an optimal carbon-to-nitrogen (C/N) ratio of 25:1 resulted in maximum hydrogen production (0.74 mmol/g-VS). Native anaerobic bacteria in the sludge served as seed cultures for hydrogen production. The study also reported hydrogen yields of 0.72 ml and 1.02 ml at 8.0 h and 4.0 h retention times, respectively.

Liu et al. (2013) utilized wastewater as a seed culture and pretreated paddy straw with sulfuric acid for hydrogen synthesis. They found that *Clostridium* facilitated hydrogen synthesis through acetate and butyrate pathways. Sheng et al. (2018) employed an edible fungus (*Gymnopus contrarius*) to pretreat paddy straw without agitation for 15 days. Subsequently, the pretreated straw was fermented by *Thermosaccharolyticum thermoanaerobacterium* at 55 °C for 96 h, resulting in over 74 % hydrogen production (5.71 molg^{-1}) compared to untreated straw. These studies demonstrate the potential of paddy straw as a substrate for bio-hydrogen production, highlighting the importance of optimizing conditions and utilizing appropriate microorganisms or pretreatment methods to enhance hydrogen yields (Sheng et al., 2018).

4.3. Bio-CNG

Bio-CNG, or compressed bio-methane, is a methane-rich compressed fuel produced from refined biogas with a methane content of over 97 % and compressed at 20–25 MPa loads. It shares similar fuel properties, economy, engine performance, and emissions characteristics with conventional compressed natural gas (CNG) (Chang et al., 2008). Biogas, derived from the decomposition of degradable materials like crop residues, municipal waste, and kitchen waste, undergoes a cleaning and processing process to become bio-CNG. Bio-CNG offers a cleaner alternative to conventional fuels like gasoline and diesel, significantly reducing carbon dioxide levels by only 2–8 % (Lubken et al., 2010). It's important to note that the availability, feasibility, and commercial viability of bio-CNG and other biofuels can vary depending on factors like feedstock availability, technological advancements, and supportive government policies. Ongoing research and development efforts focus on improving bio-CNG production's efficiency and sustainability to expand its utilization further (Ray et al., 2016). Bio-CNG production from paddy straw is an area of interest in renewable energy and sustainable waste management. Paddy straw can be effectively utilized for bio-CNG production through anaerobic digestion. The process involves the breakdown of organic matter in the absence of oxygen, producing biogas mainly consisting of methane and carbon dioxide (Krar, 2018). Research has focused on optimizing the anaerobic digestion process to enhance methane production and improve the overall efficiency of bio-CNG generation. Factors such as feedstock characteristics, process parameters, and pre-treatment techniques are crucial in determining the bio-CNG yield from paddy straw. Kim et al. (2014) observed that mixing paddy straw with sewage sludge at an optimal carbon-to-nitrogen (C/N) ratio resulted in maximum hydrogen production during anaerobic digestion.

Additionally, research has highlighted the importance of process optimization to maximize bio-CNG production from paddy straw. Factors such as temperature, pH, retention time, and inoculum selection have been investigated to improve methane production efficiency (Kumar et al., 2015). It is worth noting that challenges such as the high lignocellulosic composition of paddy straw and the presence of inhibitory substances can impact the bio-CNG production process. Researchers are actively investigating strategies to overcome these challenges and optimize bio-CNG production from paddy straw (Kaur et al., 2020).

5. Paddy straw bioenergy technologies

Bioenergy is a form of energy derived from various biological sources, with biomass being a primary feedstock. In the agricultural sector, paddy straw holds significant potential as a valuable substrate for bioenergy production. India, in particular, exhibits a diverse range of biomass resources suitable for biofuel production and power generation applications. The conversion of biomass to energy involves various processes that depend on factors such as the type and quantity of biomass feedstock, environmental conditions, and economic considerations. Two main technology pathways are employed to drive bioenergy: thermochemical and biochemical/biological conversions.

Mechanical extraction, such as esterification, is another technology utilized for biomass energy production, such as rapeseed methyl ester biodiesel production. Thermal conversion processes encompass pyrolysis, biomass gasification, combustion, and liquefaction. These processes utilize heat to transform biomass into energy carriers (Singh et al.,2013). On the other hand, biochemical and biological conversion pathways involve using enzymes, microorganisms, or fermentation processes to convert biomass into energy products (Nguyen et al., 2016). Regarding paddy straw (rice straw), various bioenergy technologies can be employed to convert it into useful forms of energy. These include anaerobic digestion for biogas production, direct combustion for heat and power generation, and bioethanol production through fermentation of sugars derived from cellulose and hemicellulose. Each of these technologies offers unique advantages and challenges regarding efficiency, scalability, and environmental impact.

5.1. Biochemical conversion

Paddy straw can undergo biochemical conversion processes to produce biofuels like bioethanol or bio-butanol. This involves breaking down the cellulose and hemicellulose components of the straw into fermentable sugars, which are then converted into liquid biofuels through microbial fermentation (Fig. 2). There are several types of biochemical conversion methods used to transform the paddy straw into useful products such as anaerobic digestion, fermentation.

5.1.1. Anaerobic digestion

Anaerobic digestion is a biological process in which microorganisms

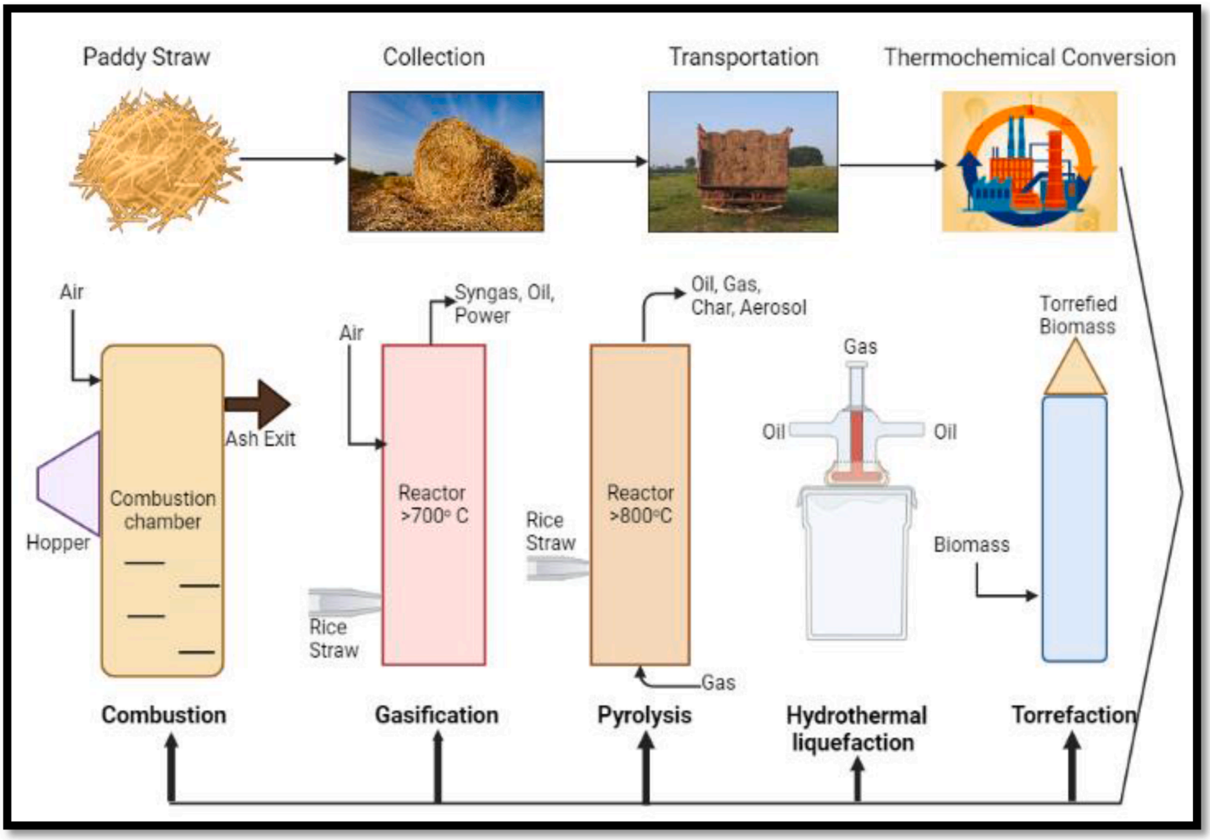

Fig. 2. Different thermochemical conversion methods.

decompose organic matter without oxygen to produce biogas. Rice straw can be anaerobic digestion with other organic waste, such as animal manure and food waste, to produce methane (Makádi et al., 2012). Biogas, regarded as a sustainable energy source, constitutes a significant outcome of the anaerobic digestion of organic substances. The substrate used, and various factors associated with the anaerobic digestion process shape this gas mixture's composition. Common constituents in biogas mixtures encompass O_2, N_2, H_2S, CH_4, CO_2, and other gas components (Deublein and Steinhauser, 2011). In a simplified breakdown, anaerobic digestion can be categorized into four key phases: hydrolysis, acidogenesis (responsible for acid production), acetogenesis (which generates acetic acid), and methanogenesis (the phase where methane is produced), as described by Chandra et al. (2012).

Anaerobic digestion is a reliable technology for digesting rice straw, a readily available agricultural residue. It has been observed that rice straw can be efficiently digested under both mesophilic (moderate temperature) and thermophilic (high temperature) conditions, although mesophilic conditions are more commonly used in practice. Supplementing trace elements of rice straw during digestion has been found to improve methane productivity, although the effectiveness of some elements remains inconclusive. Maintaining a low organic loading rate in the anaerobic digestion process is recommended, as a high organic loading rate can lead to complications resulting in reduced methane productivity. Hydrolysis is a rate-limiting step in anaerobic digestion, and pretreatment techniques can enhance biogas production by increasing solubility and reducing complexity (Chen et al.,2007).

Co-digestion of rice straw with low C/N ratio substrates like cow manure, chicken manure, or food waste can balance the C/N ratio of the anaerobic digestion system, resulting in improved bio-methane yield. However, careful selection of co-substrates is crucial for achieving optimal results. Since rice straw has a high total solids content (90–96 %), solid-state anaerobic digestion (SS-AD) is recommended, and using liquid-state digestate as an inoculum can be beneficial (Li et al., 2015).

In a study conducted by Liu et al. (2019a), solid-state anaerobic digestion of paddy straw was carried out for 58 days at (35 °C) and 34 days at (55 °C). During the process, both digesters displayed similar patterns in daily methane production, characterized by an initial asymmetric spike followed by a decrease. However, the digester, which has a 55 °C temperature, exhibited an earlier peak on day eight and a higher peak, generating 1.63 liters of daily methane production. This finding indicated that thermophilic conditions resulted in a faster initial methane production than mesophilic conditions. Furthermore, the methane yields in the thermophilic condition reached 133.3 L/kg-VS, surpassing those achieved under mesophilic conditions by approximately 20 % (110.6 L/kg-VS). The study's findings indicated that employing thermophilic digestion for rice straw was more favorable than mesophilic digestion, enabling shorter reaction times and producing higher methane yields. It's worth noting that the cumulative methane yields from solid-state anaerobic digestion of straw were slightly lower than values previously reported (140–150 L/kg-VS) in a study that utilized liquid anaerobic digestion effluent as the inoculum for thermophilic yard trimmings with a 45-day incubation period (Li et al., 2015).

Results indicated that both digesters exhibited similar patterns, with an initial rapid increase followed by only slight fluctuations. Methane content increased to approximately 50 % and then displayed minor fluctuations, indicating that the process maintained a relatively stable state without experiencing inhibition of methanogenic activity (Liu et al., 2019b). In addition, the reason why the methane concentration did not exceed 50 % may be that it is difficult to degrade the fiber substrate. For instance, the methane content of the pilot scale SS-AD using rice straw as substrate could exceed 55 % or more (Yang et al., 2019).

Table 3

Table 3
Different microbes involved in different processes of anaerobic digestion.

Process	Species name	Reference (s)
Hydrolyzers	*Pseudomonas Bacillus, Clostridium, Micrococcus, Flavobacterium, Chloroflexi, Thermotogae, Firmicutes, Bacteroidetes, Proteobacteria,* and *Spirochaetes.*	(Nguyen et al., 2016)
Acidogens	*Firmicutes, Bacteroidetes, Proteobacteria,* and *Actinobacteria. Clostridium* (Firmicutes), *Peptococcus* (Firmicutes), *Bifidobacterium* (Actinobacteria), *Desulfovibrio* (Proteobacteria), *Corynebacterium* (Actinobacteria), *Bacillus* (Firmicutes), *Pseudomonas* (Proteobacteria), and *Desulfobacter* (Proteobacteria)	(Shiratori et al., 2006)
Acetogens	SAO-*Pseudothermotogalettingae, Thermacetogenium phaeum, Syntrophaceticusschinkii,* and *Spirochaetes* Non- SAO - *Clostridium aceticum*	(Zhou et al., 2017)
Methanogens	Methanobacterium, Methanosarcina barkeri, *Methanosarcina* sp., (Methanococcus)*, rods* (Methanobacterium)*,* short rods (Methanobrevibacter)*, Spirillaceae* (Methanospirillum)*, Sarcina* (Methanosarcina)*,* and *filiform* (Methanothrix), Desulfotomaculumthermobenzoicum, Thermosyntrophicum*,* and Desulfovibrio	(Wang et al., 2018)
Cellulase	Bacteria- Trichonympha, Clostridium, Actinomycetes, Bacteroides succinogenes, Butyrivibrio fibrisolvens, Ruminococcus albus, and Methanobrevi bacterruminantium Fungi- Fusarium, Myrothecium, Chaetomium, Trichoderma. Penicillium and Aspergillus.	(Milala et al., 2005)
Xylanase	Bacteria- *Bacillus subtilis, Clostridium thermocellum,* and *Cellvibrio japonicus*. Fungi- *Aspergillus niger* and *Trichoderma reesei*	(Dodd et al., 2011)
Laccase	Bacteria- S.lavendulae, S.cyaneus*,* and Marinomonas mediterranea Fungi- *Basidiomycetes,* Phanerochaete chrysosporium, Theiophoraterestris, Lenzites, Betulina and white-rot fungi such as Phlebia radiate, Pleurotus ostreatus, Trametesversicolour, Trichoderma, T. atroviride, T. harzianum, T. longibrachiatum, Pycnoporus cinnabarinus, and Pycnoporuss anguineus Ascomycetes- Monocilliumindicum	(Bilal et al., 2019)
Fermentation of carbohydrate	Pseudomonas mendocina, Bacillus halodurans, Clostridium hastiforme, Gracilibacterthermotolerans, B. halodurans, G. thermotolerans, and T. haemolytica	(Nguyen et al., 2016)

5.1.2. Fermentation

Fermentation of paddy straw involves the microbial conversion of carbohydrates into various end products through a controlled biological process (Sadh et al., 2017a, 2017b, 2017c; Saharan et al., 2018). Han, 1975 concluded that rice straw underwent fermentation with the microbial strains *Alcaligenes faecalis* and *Cellulomonas* sp. After fermentation, various components were analyzed, including microbial cells, undigested residue, and both chemically treated (using NaOH or NH_4OH) and untreated rice straw. In a typical fermentation run, it was observed that 75 % of the rice straw substrate was effectively digested of the total substrate weight that disappeared during the process, and 18.6 % was recovered as microbial protein. The microbial cell fraction comprised approximately 37 % protein and 5 % crude fiber, while the undigested residue comprised 12 % protein and 45 % crude fiber.

Mechery et al. (2021) focused on hydrogen production from hydrolysates of alkali and acid-pretreated rice straw, employing a locally isolated *Proteus mirabilis*, a facultative bacterium in dark fermentation. The acid and alkaline pretreatments increased the total sugar content within the hydrolysates, enhancing hydrogen (H_2) production. Notably, the acidic hydrolysate exhibited a superior performance in terms of hydrogen yield compared to the alkaline hydrolysate. It achieved a maximum cumulative hydrogen volume of 833.43 ± 21.72 mL H_2, representing a remarkable 3.33-fold increase compared to the untreated substrate. The study identified that an initial pH of 6 was optimal for the acidic hydrolysate, yielding 1.03 mol H_2 / mol of glucose. Similarly, a temperature of 34 °C was identified as the most favorable for hydrogen production in the case of the acidic hydrolysate, producing 1.00 mol H_2 /mol of glucose.

An alkali solution pretreatment to rice straw led to a significant increase in the content of fermentable sugars, raising it from 56.3 % to 80.0 %. The optimized enzyme cocktail demonstrated remarkable effectiveness, yielding 75.3 g/L in total fermentable sugar production during the hydrolysis of alkali-treated rice straw, with a high hydrolysis efficiency of 94.1 %. A multivariate analysis considering various cellulolytic activities identified a combination of commercial enzyme reagents as ideal for saccharifying the straw. In a simultaneous saccharification and fermentation process, utilizing 100 g/L of the treated rice straw with the optimized enzyme cocktail and the fungus *Mucor circinelloides* under aerobic conditions, an ethanol concentration of 30.5 g/L was achieved within 36 h (Takano and Hoshino, 2018). It's important to note that various factors, including the choice of microorganisms, fermentation conditions, and process optimization, can influence the fermentation process (Sadh et al., 2018b). Different microorganisms and techniques may be employed depending on the specific end product desired from the fermentation of paddy straw, such as bioethanol, organic acids, or biogas.

These biochemical conversion methods offer environmentally sustainable pathways for converting biomass into renewable energy and value-added products, contributing to developing a bio-based economy and reducing reliance on fossil fuels.

6. Vitality and fertility of the soil

Paddy straw is crucial in enhancing soil vitality and fertility through various mechanisms. Paddy straw is a rich source of organic matter, and when it is incorporated into the soil, it serves as a valuable reservoir of nutrients. As the straw undergoes decomposition, it gradually releases essential nutrients, including nitrogen, phosphorus, potassium, and micronutrients. These nutrients become available to plants, promoting their growth and well-being (Lu, 2015). According to Satpathy and Pradhan (2023), paddy straw improves soil structure by increasing its capacity to retain water and nutrients. When rice straw is integrated into the soil, it aids in creating pore spaces and enhancing soil aggregation, which leads to improved aeration and water infiltration. This enhanced soil structure provides an optimal environment for plant roots to uptake nutrients.

Paddy straw serves as a formidable erosion control measure. When left on the soil surface, it acts as a protective shield, diminishing the impact of raindrops and preventing the loss of soil particles through runoff. By mitigating erosion, paddy straw safeguards the integrity of topsoil and prevents nutrient depletion. Paddy straw, when present on the soil surface, acts as natural mulch, reducing water evaporation from the soil. This feature is especially beneficial in arid or hot climates, as it helps to conserve soil moisture. Effective moisture retention is critical for sustaining plant growth, particularly during water scarcity or drought. Paddy straw is a substrate for beneficial soil microorganisms, such as bacteria, fungi, and earthworms. These microorganisms play a pivotal role in decomposing the straw and breaking down complex organic compounds into simpler forms readily accessible to plants. Their activities enhance soil health, nutrient cycling, and fertility (Schmidt et al., 2015b). Incorporating paddy straw into the soil contributes to carbon sequestration, which involves capturing and storing carbon dioxide from the atmosphere. The organic carbon within the straw is sequestered in the soil, thus mitigating climate change by reducing greenhouse gas emissions. Farmers can adopt practices like straw incorporation, mulching, or composting to maximize paddy straw's advantages. However, it is crucial to consider local agricultural practices, soil conditions, and crop rotation strategies to ensure the optimal utilization of paddy straw while maintaining a balance between nutrient recycling and potential pest or disease issues.

7. Biodegradable polymers and biomaterials

There are great prospects for using rice straw as a building material because of its fibrous character, low thermal conductivity, and low density (Zhao et al., 2020). A new thermal insulation material was developed from rice straws with the help of hot pressing comprised a thickness of 40 mm, a low density of 200–350 kg/$m^3$and a thermal conductivity of 0.051–0.053 W/(m K). Rice straw-based thermal insulation boards (RSTIB) promise incorporation into construction materials, particularly for enhancing energy conservation, such as wall or ceiling insulation. Ongoing research has unveiled that several factors influence the thermal conductivity of these boards, including board density and ambient temperature. Moreover, it has been observed that a reduction in particle size is correlated with an elevation in thermal conductivity.

In contrast, the particles' moisture content (MC) does not substantially impact thermal conductivity. A comparative analysis between high-frequency hot-pressing and traditional hot-pressing techniques has shown that the former significantly reduces the pressing duration and enhances the internal bonding strength of the boards. In a specified range, augmenting the particle moisture content enhances the mechanical properties of the boards, albeit at the expense of their dimensional stability.

Furthermore, boards with higher densities exhibit improved mechanical and physical attributes. However, reducing particle size beyond a specific range enhances board properties while simultaneously diminishing their insulating capabilities. Wei et al. (2015) have disclosed that the optimal characteristics of RSTIB can be achieved by maintaining the particle moisture content of 14 %, a board density of 250 kg/m^3, and utilizing particles of an L-type size.

An environmentally friendly and energy-efficient process has been developed to convert paddy straw into pure and high-yield value-added products such as lignin and nano-silica. Nano-silica and lignin play a significant role in the medicinal and biological field. Nano-silica is used in SiO_2-based biomaterials like resins, biological membranes, and catalysts (Ahmad et al.,2016). Likewise, lignin from paddy straw also has auspicious applications in making composites, adsorbents, bio-plastics, carbon fibers, and dispersants (Norgren and Edlund, 2014). The process involves the removal of polysaccharides and other impurities from the straw with the acid pretreatment (H_2SO_4). Subsequently, lignin and nanofoam silica formed from the pretreated paddy straw with the help of delignification with an alkali mixture ($NaOHeH_2O_2$). From paddy straw, an average size of 17 nm silica with a yield of 9.26 % was simultaneously separated from lignin extraction. Nano silica produced from the methods above appears spherical and uniform in shape. Concurrently, lignin was irregular in shape and size. Therefore, the developed process was favorable for sustainable and clean pilot-scale production of nano-silica and lignin from rice straw waste biomass (Kauldhar and Yadav, 2018)

Elwan et al. (2006) found that paddy straw ash can be used in the fabrication of bricks as a pore-forming agent and can also be used in pozzolanic addition. Paddy straw ash can be used as an alternative raw material for producing ceramic triaxial instead of ceramic inert (quartz) and fluxing (mainly feldspar), which are costly. The most suitable paddy straw ash was obtained at 800 °C for two hours. At this condition, chlorine content is very low (0.59 %) and high content of SiO_2 (79.62 %), alkaline oxides (10.53 %), and earth alkaline oxides (CaO) (2.80 %). Due to its composition, this ash can be used instead of sodium feldspar in the aforementioned ceramic (Guzmán et al.,2015).

Zhu et al. (2017) conducted research in which rice straw was pretreated with KOH aqueous solution, and the resulting liquid was used to synthesize a black liquor-derived porous carbon (BLPC) in which KOH acts as both lignin extraction solvent and chemical activation agent. The addition of melamine into the black liquor leads to an increase in the surface area (2646 m^2 g^{-1}) and pore volume (1.285 cm^3 g^{-1}). It promotes the formation of nitrogen covalent bonds in the carbon materials (N-BLPC). When used as an additive, melamine has dual roles as a nitrogen source and pore modifier of the carbon material. The as-prepared materials have specific capacitances of 242Fg^{-1} (BLPC) and 337Fg^{-1} (N-BLPC) when used as electrodes in 6 M KOH electrolyte at a current density of 0.5 Ag^{-1}. The assembled N-BLPC-based symmetric supercapacitor shows stable cycling (>98 % retention after 3000 cycles at 10 Ag^{-1}). Both materials exhibited good performance as supercapacitor electrodes and had specific capacitances.

Another green mechanical technique has been proposed to produce rice straw fibers with improved properties. The rice straw is a good alternative raw material for producing medium-density rice straw fiberboard (Theng et al., 2019). The proposed rice straw fiber processing technology improves the permeability and diffusion of urea-formaldehyde resin into straw fibers, resulting in increased internal bond strength and reduced water absorption of the produced fiberboard. By increasing the density of the fiberboard and the content of urea-formaldehyde resin, the flexural properties of the manufactured fiberboard are improved in terms of modulus of rupture and elastic modulus, as well as internal bond strength. This is due to the increased contact points between the fibers and the forming of a permanent bond with high fiber-to-fiber retention at higher board densities and resin contents.

The newly proposed technique has many advantages over conventional techniques (Kouchaki-Penchah et al., 2016). As these techniques avoid chemical and heat treatment, they eventually reduce the production area and cost. This reveals that the rice straw fiberboard panels produced by the newly proposed technology are of high quality and may be subject to strong competition from other commercial fiberboards (El-Kassas and Elsheikh, 2021; Saharan et al., 2024).

8. Biochar

Biochar can be produced from rice straw through various thermochemical conversion methods, including pyrolysis (Zong et al., 2021), torrefaction or carbonization (Tan et al., 2021), hydrothermal liquefaction (Harisankar et al., 2021), and gasification (Pei et al., 2020). The properties of biochar depend significantly on process conditions like temperature, pressure, reactor setups, and catalysts used. Pristine rice straw tends to have a higher ash content (8.5–20.4 %) compared to other types of straw, such as wheat straw (5.0–8.5 %), barley straw (7.4 %), corn straw (5.1–7.9 %), and sugarcane straw (4.1 %) (Wang et al., 2020a).

Following thermochemical treatments of rice straw transformed it into biochar with improved physical, chemical, and structural attributes (Fig. 3). These characteristics make rice straw-derived biochar a promising precursor for adsorbents (Wang et al., 2020b). Rice straw biochar finds practical application in treating aquaculture wastewater within integrated rice-fish (agro-aquaculture) polyculture systems due to its proximity and efficacy in removing common pollutants like phosphorous and ammonia (Li et al., 2021). Notably, Rice straw biochar has demonstrated favorable removal efficiencies for pesticides (e.g., imidacloprid, atrazine) (Xiang et al., 2020) and pharmaceutical residues (e.g., estrone) (Monga et al., 2022) originating from aquaculture facilities (Kolodziej et al., 2004).

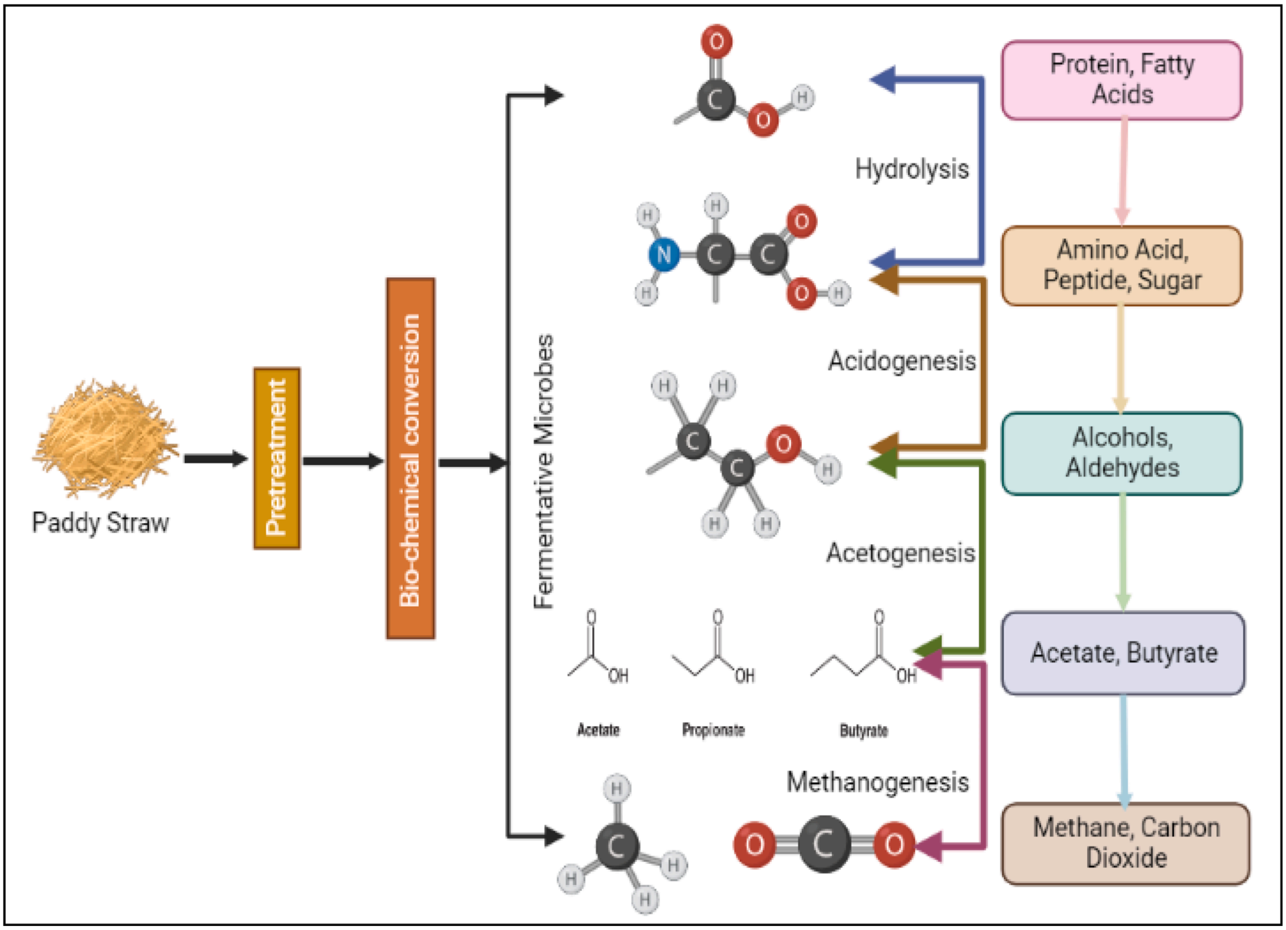

Fig. 3. Different stages of biochemical conversion.

Zhuang et al. (2022) provide insightful reviews on the performance of biochar for wastewater treatment, considering ecological benefits and removal mechanisms, respectively, with a focus on constructed wetlands. The pyrolysis temperature plays a pivotal role in shaping the residence time, chemical composition, and structural attributes of biochar. Biochar produced at 400 °C typically exhibits alkaline properties and a high cation exchange capacity, rendering it suitable for utilization in fertilizer applications and soil enhancement. Rice straw-derived biochar, in particular, displayed turbostratic crystallites at 400 °C, with a heightened degree of aromatization observed at 500 °C, as documented by Wu et al. (2012).

Furthermore, biochar application significantly influences soil physicochemical characteristics, microbial communities, and enzymatic activities. In soils enriched with 10 mg kg^{-1} of biochar, urease, alkaline phosphatase, and overall microbial function activities were observed. Biochar application contributes to enhanced carbon sequestration and plant growth and reduces emissions of N_2O and CH_4, with net greenhouse gas potential (GWP) reduction ranging from 0.16 to 19-fold. Nevertheless, it's worth noting that the contribution of Negative Emissions Energy Balance to CO_2 costs remains relatively small, largely due to the low emissions trading price of CO_2, as discussed by Bi et al. (2021). Introducing biochar into rice production systems over eight years led to a 12 % increase in the Net Present Value of rice production, accompanied by a 27 % reduction in non-renewable energy intensity, as Mohammadi et al. (2017) reported.

The incorporation of 41.5 metric tons per hectare (t ha^{-1}) of rice husk charcoal (on a dry weight basis) led to a substantial 33 % increase in rice grain yield, particularly in irrigated conditions (Shackley et al., 2013). Notably, biochar exhibits a noteworthy greenhouse gas (GHG) reduction potential, with a value of -0.94 metric tons of CO_2 equivalent per ton of straw. In China, a significant Net Present Value (NPV) of USD 20.98 per ton of straw, including carbon income, has been reported for the base yield of crop straw, according to Li et al. (2018).

Biochar application has exhibited its effectiveness in reducing the carbon footprint of summer rice cultivation, with an initial reduction of 26 % in the first year compared to traditional practices. This reduction increased to 49 % for spring rice and 38 % for summer rice after eight years of continuous biochar application, as highlighted by Mohammadi et al. (2016). Moreover, in India, Kumar and Bhattacharya (2021) reported a substantial net profit of 18 % per hectare by converting rice straw into biochar.

In addition to its positive agronomic impacts, biochar plays a crucial role in enhancing soil fertility, facilitating carbon sequestration, and mitigating greenhouse gas emissions. It can serve as a viable and economically sustainable alternative to residue burning.

9. Farming methods, including mushroom growing

Carbon sequestration in soil is widely acknowledged as a valuable approach for mitigating greenhouse gas emissions and enhancing soil quality. In contrast, the burning of paddy straw contributes to carbon emissions into the atmosphere, exacerbating the greenhouse gas issue. Soil organic carbon plays a pivotal role in the global carbon cycle, significantly indicating soil quality and sustainability. It contributes to nutrient supply and bolsters soil's physical and biological properties. Introducing rice straw into the soil has demonstrated its potential to augment organic carbon content.

Empirical studies have shown that soil organic carbon levels tend to remain relatively constant under the conditions of intensive rice cultivation, even in cases where rice straw is harvested from the fields. Long-term continuous cropping experiments at the International Rice Research Institute (IRRI) in the Philippines over 50 years demonstrated that soil organic carbon content remained unchanged, even without aboveground biomass and nitrogen fertilizer application. However, in cropping systems where rice is rotated with upland crops, soil organic carbon content declines when no crop residues are reintegrated. Majumder et al. (2008) documented decreased soil organic carbon levels when crop residues were not incorporated. In a study conducted in Bac Giang Province, Vietnam, soil organic carbon levels remained constant when straw was removed, but an increase was witnessed when straw was reintroduced.

Similarly, continuous straw incorporation into lowland rice soils showcased a cumulative positive effect on soil organic carbon due to the slower decomposition of organic matter. The addition of straw has consistently demonstrated its capacity to enhance soil organic carbon, particularly in rainfed upland rice systems or when lowland rice is part of a rotation with upland crops. Gangwar et al. (2006) observed higher soil organic carbon content and improved water infiltration when rice straw was integrated into the soil, compared to its removal or burning.

9.1. *Mushroom production*

Mushroom production from paddy straw is a popular and environmentally friendly method of utilizing agricultural waste. Paddy straw can serve as a substrate for growing various types of mushrooms, including species like oyster mushrooms (*Pleurotus* spp.*)* and shiitake mushrooms (*Lentinula edodes*). Typically, four techniques are employed for preparing beds in mushroom cultivation: the bed method, heap method, cage method, and spiral method. The choice of method hinges on the farmer's preference and ease of implementation. Among these approaches, the cage method is a favored option, and it is gaining popularity among numerous cultivators. Here is a general overview of the process (Fig. 4). Paddy straw, used for mushroom cultivation, undergoes a systematic preparation process. Initially, the straw is chopped into small pieces and soaked in water for a specific duration, typically 24 to 48 h. This soaking step serves to rehydrate and condition the substrate (Biswas, 2014).

Following this, the rehydrated paddy straw may necessitate sterilization or pasteurization to eliminate potential competitors or pathogens that could impede mushroom growth. Sterilization is typically achieved through steam or high-pressure methods, while pasteurization entails subjecting the substrate to lower temperatures for a designated period (Chandra and Chaubey, 2017). After sterilization or pasteurization and subsequent cooling, mushroom spawn is introduced. Spawn consists of a substrate that has been previously inoculated with mushroom mycelium, which represents the vegetative growth stage of the mushroom. Spawns can be procured commercially or prepared in-house through laboratory techniques. Subsequently, the substrate bags or containers are placed in a controlled environment with specific temperature and humidity conditions to foster mycelial growth. During this incubation period, the mycelium proliferates within the substrate, forming a network of white thread-like structures. Casing, although optional, is a step primarily employed for specific mushroom species, such as button mushrooms (*Agaricus bisporus*). This stage involves spreading a layer of casing material, often a mixture of peat moss and vermiculite, over the colonized substrate to create a favorable microenvironment for mushroom fruiting. The mushrooms begin to develop once the mycelium has thoroughly colonized the substrate, and environmental conditions are optimized for temperature, humidity, and light. The duration of the fruiting period varies depending on the mushroom species and can span several weeks. Effective maintenance of these environmental conditions during this phase is critical for successful fruiting (Eguchi et al., 2015). Harvesting commences when the mushrooms reach the desired size and maturity. Typically, this is done manually, with mushrooms carefully cut or twisted from the substrate. The harvested mushrooms are sorted, packaged, and readied for distribution or consumption (Biswas, 2014).

10. Carbon sequestration

The inclusion of rice straw in soil has been acknowledged as a beneficial method to enhance soil quality and address the challenges of climate change. Studies have shown that straw incorporation enhances

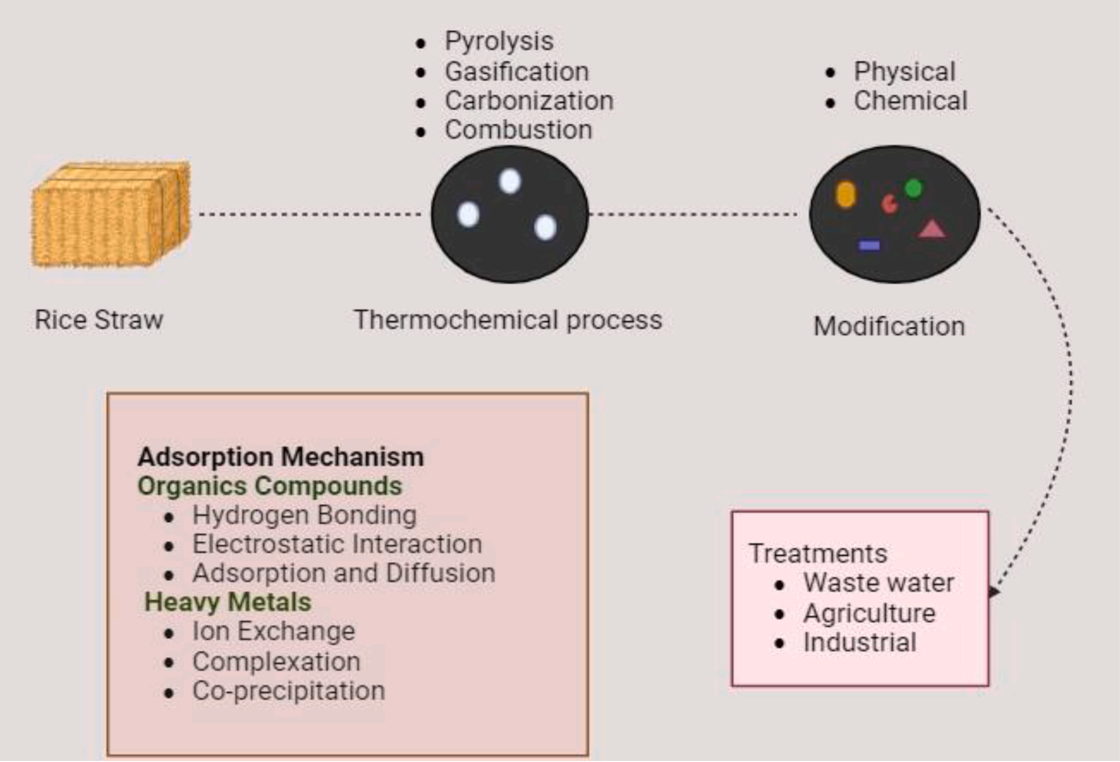

Fig. 4. Biochar process with uses (Foong et al., 2022).

nutrient cycling and promotes soil organic carbon sequestration (SOC). Adding rice straw has been found to improve soil SOC, pH, and nutrient availability compared to initial soil conditions (Thammasom et al., 2016). However, the rate of nutrient release from straw decomposition varies depending on soil type and season.

In addition to its role in nutrient recycling, paddy straw serves as a source of essential elements such as sulfur (S), potassium (K), and micronutrients like zinc (Zn). For situations where sulfur-free fertilizers are used, rice straw can be particularly important in replenishing sulfur levels in the soil. However, long-term application of rice straw may reduce the availability of Zn, highlighting the need for proper nutrient management strategies (Ghosh et al.,2018). Furthermore, rice straw plays a significant role in the phosphorus cycle in soil. Studies have shown that Phosphorous balances become negative when rice straws are removed or burned, but incorporating rice straw into the soil improves the dynamics of plant-available P (Zhang et al., 2018). Incorporating biochar derived from rice straw into degraded soils has also positively affected soil properties. The continuous addition of rice straw biochar increased soil pH, cation exchange capacity, and SOC content over four seasons (Cabriga, 2021).

Whether sequestered in soils or emitted as greenhouse gases, the total carbon credited varied, ranging from a minimum of -0.97 t CO_2 eq/ha. India is also advancing in carbon trading initiatives, exemplified by the pioneering efforts of the Indian Agricultural Research Institute (IARI) and the International Wheat and Maize Improvement Center (CIMMYT) in collaboration with GrowIndigo India Ltd. This collaboration, involving leading agricultural firms Mahyco and Indigo Ag, aims to establish a marketplace for carbon trading among Indian farmers (Mukherjee 2022).

Enhanced agricultural management practices, such as strategic tillage methods, are anticipated to mitigate global warming by augmenting soil organic carbon (SOC) sequestration and/or reducing greenhouse gas emissions in agricultural lands (Liu et al. 2021; Pu et al. 2022). The dry residue returned to the soil was calculated as a proportion of the straw yield reintroduced to the field. Carbon (C) input was estimated based on a concentration of 0.45 kg C per kg dry matter of rice. Maximum carbon sequestration reached 1.56 t/ha/year when straw was incorporated, compared to 1.28 t/ha/year when straw was used as mulch. Furthermore, soil fertility showed improvement by 14.8 kg/ha/year when straw was used as mulch and by 12.1 kg/ha/year when straw was incorporated into the soil.

Another study assessed the total carbon input, bulk density, and change in SOC stock from aboveground biomass over seven years under various treatments (Sapkota et al. 2017). The change in SOC stock over seven years was found to be 4.66 t/ha and 2.98 t/ha when straw was incorporated and used as mulch, respectively. Research by Kakraliya et al. (2021) also demonstrated that straw incorporation and mulching improved soil sequestration by 1.55 t/ha/year and 1.25 t/ha/year, respectively

10.1. *Effects on climate*

Addressing the pressing concerns surrounding global climate change, focusing on greenhouse gas (GHG) emissions, has emerged as a paramount issue in the twenty-first century. The sources of GHGs are diverse, encompassing both natural processes and human activities. Notably, within the agricultural sector, the release of methane (CH_4) and nitrous oxide (N_2O) assumes critical importance due to their substantial global warming potentials of 28 and 265 relatives to CO_2 over a century, respectively (Singh et al., 2021). A pivotal report by Huang et al. (2018) underscores the drastic escalation of these gases since the industrial revolution, with CH_4 levels surging from 722 to 1830 ppb and N_2O levels rising from 270 to 324 ppb.

Given the imminent challenge of augmenting global agricultural production, the necessity for increased utilization of nitrogenous fertilizers looms large. The ramifications of these alarming trends are far-reaching, necessitating urgent global action to curtail these GHG emissions and mitigate their harmful impact on climate change. One key sector within agriculture that warrants attention is rice cultivation, which occupies more than 11 % of the world’s agricultural land area and remarkably contributes to 10.1 % of total agricultural GHG emissions. When placed within the broader context of global anthropogenic emissions, rice production accounts for approximately 1.3 % to 1.8 % of gross emissions, as elucidated by Agarwal (2017). This substantial emission footprint emanates from diverse aspects of the rice production process, encompassing water management techniques, fertilization strategies, cultivation methodologies, and post-harvest residual waste management.

11. Circular economy

The circular economy concept is gaining global support as countries strive to identify alternative energy sources, reduce reliance on fossil fuels, and mitigate global warming. Utilizing renewable energy sources, such as biomass, is seen as a strategic approach to achieving sustainable development goals, particularly SDG7, which aims to provide access to clean, secure, reliable, and affordable energy (Cuong et al., 2021; Sadh et al., 2023). The concept of a circular economy involves transforming production and consumption systems to minimize material and energy losses through extensive reuse, recycling, and recovery (Morseletto, 2020). Transitioning to a circular economy requires significant transformations in product and business processes. The negative impacts of landfilling, the dependence on resource extraction, and the emergence of new business models that compete with traditional recycling firms pose challenges to adopting the circular economy concept. However, many countries have taken steps to shift from a linear economy to a recycling and circular economy, recognizing the need to optimize resource utilization and reduce environmental impacts. The circular economy is anticipated to become the dominant economic model in the future (Fig. 5).

Strategies for balancing industrial and economic growth, environmental protection, and resource-efficient measures are necessary to transition to a circular economy successfully. Waste valorization for bioenergy, particularly through anaerobic digestion technology, has gained attention due to its cost-effectiveness and environmental benefits, including greenhouse gas reduction (Patwa et al., 2021). However, it is essential to analyze the environmental performance of agricultural waste throughout its life cycle, considering the adverse environmental impacts associated with agricultural production phases, such as greenhouse gas emissions. The circular economy approach allows for assessing the overall impact of the full supply chain process of agricultural waste valorization for bioenergy. Life cycle assessment (LCA) is a suitable tool for evaluating the environmental performance of circular product designs and large-scale changes, aligning with the objectives of the circular economy and reducing environmental consequences (Schwarz et al., 2021).

12. Microbial dynamics in paddy fields: impacts and research frontiers

Incorporating microbes into paddy fields is a fascinating area of agricultural research with significant implications for sustainability, crop yield, and environmental health. This approach aligns with the principles of integrated pest management and natural farming, emphasizing the importance of biodiversity in agricultural practices. However, like any agricultural innovation, it presents opportunities and challenges, thus highlighting several gaps that invite further research. Here's a look at the effects of microbial incorporation in paddy fields and the research gaps that arise:

12.1. Positive effects of microbial incorporation

12.1.1. Enhanced soil fertility

Beneficial microbes improve soil health by fixing atmospheric nitrogen, solubilizing phosphorus, and decomposing organic matter into nutrients accessible to plants. This natural nutrient cycling reduces the need for chemical fertilizers.

12.1.2. Disease suppression

Certain microbes act as biological control agents against pathogens, reducing the incidence of diseases in paddy fields. This decreases the reliance on chemical pesticides, leading to more sustainable farming

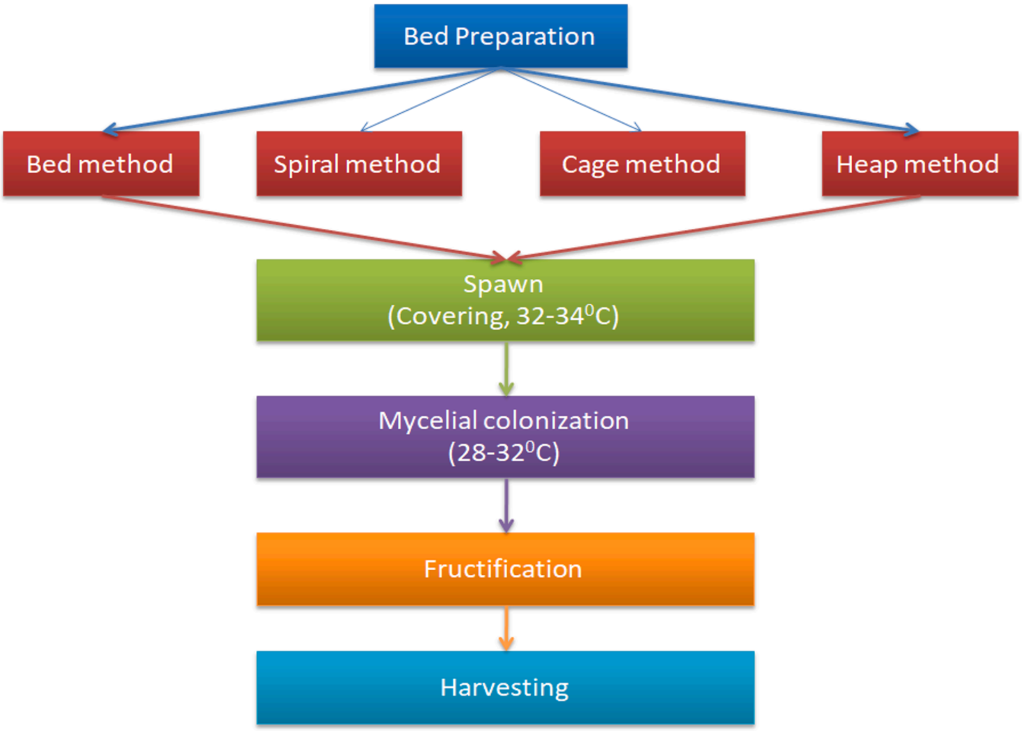

Fig. 5. Straw mushroom production process.

practices.

12.1.3. *Increased crop yield*

The improved nutrient availability and disease resistance lead to enhanced crop growth and higher yields.

12.1.4. *Environmental sustainability*

By reducing the need for chemical inputs, microbial incorporation helps mitigate soil and water pollution, thus preserving biodiversity and promoting a healthier ecosystem.

12.1.5. *Resilience to climate change*

Some microbes enhance plant tolerance to abiotic stresses (drought, salinity, extreme temperatures, etc.) making crops more resilient to climate change.

12.2. *Possible negative effects*

12.2.1. *Potential for pathogen outbreaks*

If not carefully managed, introducing non-native microbes could disrupt local ecosystems, potentially leading to the outbreak of new diseases.

12.2.2. *Uneven benefits*

The effectiveness of microbial inoculants can be highly variable, depending on the environmental conditions, soil type, and crop variety, which might result in uneven benefits.

12.2.3. *Long-term impacts uncertain*

The long-term impacts of introducing certain microbes into the ecosystem are not fully understood, raising concerns about potential unintended consequences.

13. Research gaps

While incorporating microbes into paddy fields offers promising benefits, it opens up numerous avenues for research to fully understand and optimize these interactions for sustainable agriculture. Addressing these research gaps will be critical in advancing microbial technologies in farming and ensuring food security in the face of global challenges.

13.1. *Microbial interactions*

Understanding the complex interactions between introduced microbes, native soil biota, plants, and pathogens remains a significant challenge. Research could focus on mapping these interactions to optimize the benefits of microbial incorporation.

Tailored microbial solutions

There’s a need to develop microbial consortia tailored to specific environmental conditions, crop varieties, and farming practices to ensure consistency in benefits.

13.2. *Impact assessment*

Long-term studies are required to assess microbial incorporation’s sustainability and ecological impact in paddy fields, including any potential negative effects on soil health and local biodiversity.

13.3. *Economic viability*

More research is needed to evaluate the cost-effectiveness of microbial incorporation compared to conventional farming practices, considering the potential reduction in chemical inputs and increased crop yields.

13.4. *Technology and knowledge transfer*

Bridging the gap between research findings and practical application is crucial. There’s a need for effective strategies to transfer knowledge and technologies to farmers, including training on the use and management of microbial products.

14. Cost-effectiveness

For medium and small-scale farmers, the practical feasibility of incorporating microbes into paddy fields hinges on balancing the initial and ongoing costs against the potential for increased yields and savings on chemical inputs. While there are upfront costs and challenges, long-term benefits, including improved soil health, higher yields, and environmental sustainability, can make microbial incorporation cost-effective. Support from government programs, agricultural extension services, and non-governmental organizations in subsidies, training, and access to microbial technologies can significantly enhance the feasibility of this approach for resource-poor farmers. Localized research and pilot projects are crucial to demonstrating the cost-effectiveness and practicality of microbial incorporation in specific contexts, helping to tailor solutions to the needs of small and medium-scale farmers. The cost-effectiveness and practical feasibility of microbial incorporation into paddy fields, especially for medium or small-scale farmers, depend on factors including the initial costs, ongoing maintenance, the availability of microbial inoculants, and the potential for increased yields.

14.1. *Initial and ongoing costs*

14.1.1. *Initial investment*

The initial cost includes the purchase of microbial inoculants and, potentially, the equipment needed for application. Even a modest initial investment can be prohibitive for many small-scale or resource-poor farmers. However, some microbial products can be produced locally or on-farm, which could reduce costs.

14.1.2. *Maintenance and application*

The cost of regularly applying microbial inoculants must be considered. Some microbial treatments may require specific application methods or multiple applications per growing season, which could increase labor costs.

14.2. *Yield increase and savings on inputs*

14.2.1. *Increased crop yield*

Microbial inoculation can increase crop yields by enhancing soil fertility, improving plant health, and reducing disease. Higher yields can translate into higher income, offsetting the costs of the microbial products.

14.2.2. *Reduction in chemical inputs*

One of the most significant potential savings is the reduced need for chemical fertilizers and pesticides. Biological nitrogen fixers or biocontrol agents can decrease the reliance on these expensive inputs, leading to considerable cost savings over time.

15. Availability and accessibility

15.1. *Availability of microbial inoculants*

Accessing quality microbial products can be challenging in some regions. Local production and distribution of microbial inoculants could make this technology more feasible for small-scale farmers.

15.2. Knowledge and training

Effective use of microbial inoculants requires knowledge and skills. Farmers need training on properly applying these products to maximize benefits, which could involve additional costs or time investments.

16. Market factors

16.1. Market demand for sustainable products

There is a growing market for crops produced with environmentally sustainable practices, including microbial inoculation. Farmers may be able to command higher prices for their products, improving cost-effectiveness.

17. Problems and challenges

Efficiently utilizing paddy straw (rice straw) to create value is challenging. Several obstacles must be overcome to maximize its potential. Firstly, the collection and harvesting of paddy straw can be a complex and costly task. The sheer volume of straw generated, combined with the dispersed nature of rice fields and labor-intensive collection methods, necessitates the development of mechanized harvesting and baling techniques. Transporting paddy straw from the fields to processing facilities presents logistical complexities. The bulky and low-density nature of straw requires appropriate handling, storage, and transport infrastructure to minimize losses and maintain quality. Establishing an efficient supply chain is vital for successfully utilizing paddy straw. Another challenge arises from the seasonal availability of paddy straw. It is primarily abundant during the rice harvesting season, creating a gap in year-round availability. Effective storage methods, such as baling and preservation techniques, are needed to bridge this gap and enable continuous utilization of paddy straw.

Paddy straw also poses challenges due to its high silica content. Silica can cause machinery abrasion and erosion, increasing maintenance and wear costs during processing and utilization (Kaur et al., 2017). Pre-treatment methods like ash removal or silica separation may be necessary to mitigate these adverse effects (Aquino et al.,2020). Additionally, paddy straw has a relatively low energy density compared to other biomass feedstocks. This can affect its cost-effectiveness for energy production. Advanced conversion technologies, such as gasification or pyrolysis, may be required to enhance energy density and improve overall efficiency (Singh and Kumar, 2019).

Furthermore, the lack of infrastructure and suitable technology for paddy straw utilization hinders value creation. Establishing processing facilities like bio-refineries or biomass power plants is essential to converting paddy straw into valuable products. Research and development efforts are needed to optimize technologies tailored for paddy straw utilization. Addressing these challenges and finding innovative solutions will pave the way for paddy straw's efficient and sustainable utilization, unlocking its value for various applications (Fig. 6).

Fig. 7.

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Baljeet Singh Saharan: Conceptualization, Writing – review & editing, Supervision. **Deepika Dhanda:** Conceptualization. **Neelam Kumari Mandal:** Validation, Formal analysis. **Ramesh Kumar:**

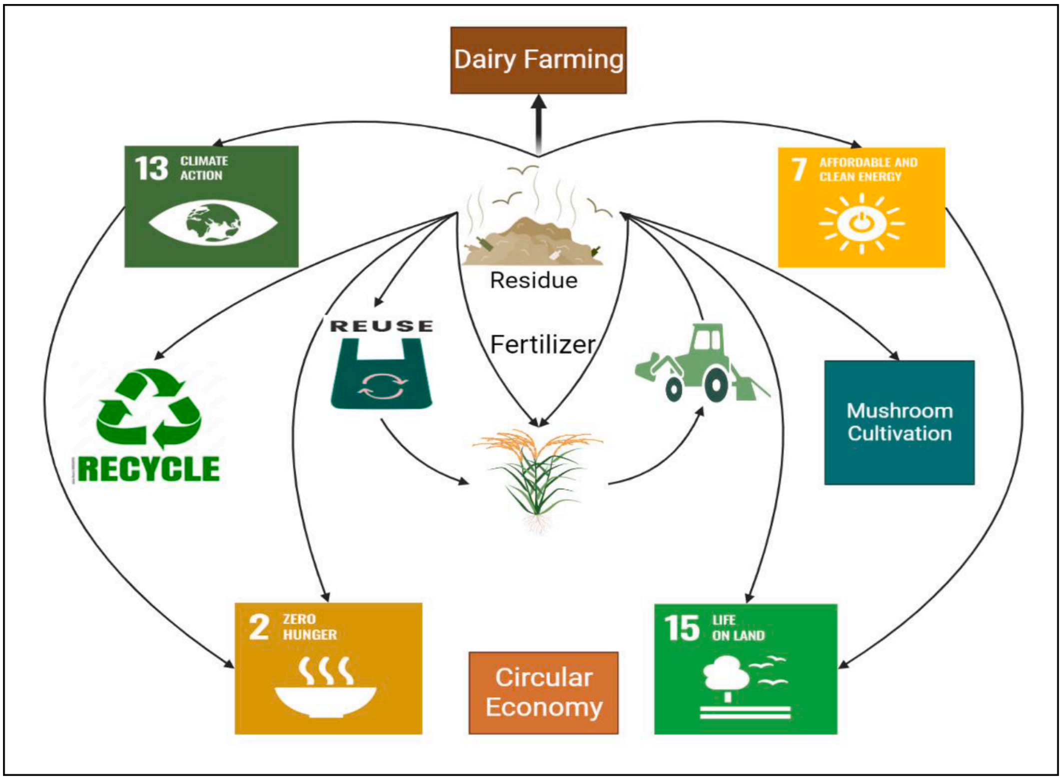

Fig. 6. Paddy straw management through circular economy.

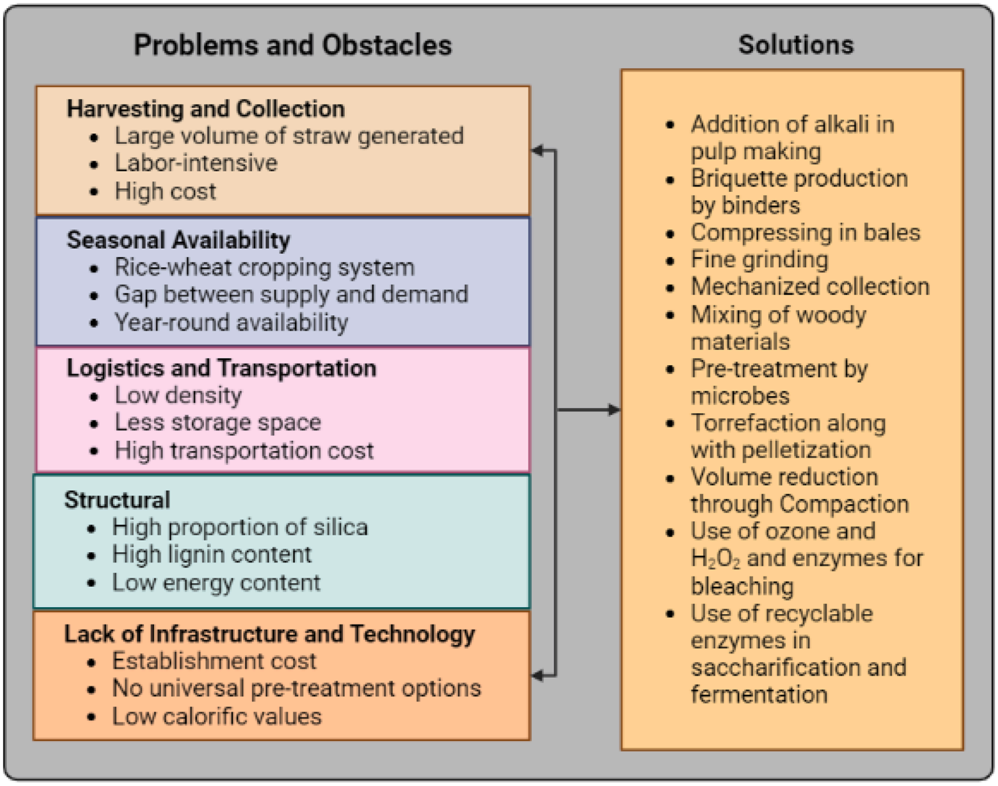

Fig. 7. Problems and obstacles during paddy straw management and their solutions.

Supervision. **Deepansh Sharma:** Formal analysis. **Pardeep Kumar Sadh:** Data curation. **Dilfuza Jabborova:** Writing – original draft. **Joginder Singh Duhan:** Validation, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no conflict of interest that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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