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RESEARCH ARTICLE

Insights of Circular economics practices in rice cultivation and processing - A Review

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ABSTRACT

Reusing waste through various activities and efficient and effective use of resources have led to the circular economy as a further growth opportunity. The circular economy has spread in various directions like agriculture and industry. The main focus of circular economy is to minimize or eliminate the use of non-renewable inputs in a production system and to maximize or optimize the reuse of these materials within the same system. In addition, circular agriculture is expected to reduce environmental impacts through soil regeneration and input use. Activities in rice cultivation include sowing, fertilizing, watering, and harvesting, and these activities can be done using biological and other agricultural methods in an environmentally friendly way instead of chemical fertilizers, pesticides, and herbicides, and further minimizing the accumulation of waste. Burning rice straw and husks emits lot of CO_2 into the environment. However, these can be used as raw materials for various industries. Rice residue is an excellent source of nutrients and beneficial for human health. Thus, circular economy methods can be used in rice cultivation by cultivating more productive and suitable rice varieties, reducing the amount of waste released into the environment in various ways, and using discarded waste as raw materials for industries. This study focuses on determining the applicability of circular economy methods to rice cultivation and processing. Accordingly, it appears that in the rice industry, circular economy methods are applied to reduce the release of unnecessary air and waste into the environment and effectively reuse the waste. This will create an eco-friendly and safe environment.

***Keywords**: CO_2 emission, Circular economy, Rice cultivation, Reuse, Waste*

INTRODUCTION

The increasing amount of waste in society (Chen *et al*., 2020), as well as the challenges of degraded ecosystems (Kumar *et al*., 2021), climate change (Creutzig *et al*., 2021), shortage of water, energy, and other natural resources, are now big problems in the world. Rice is considered to be one of the most important food sources in the world because about 50% of the world's human population uses rice as their staple food (Paes *et al*., 2019). During paddy cultivation, various activities such as fertilizer application, weed control, and pest control are carried out and waste including straw and husks are produced. Although the balance between increasing agricultural production and nature conservation has been maintained to some extent, the depletion of natural resources over long-term use of humans has created a major challenge in sustainable management. (Geissdoerfer *et al.*, 2017; Rufí-Salís *et al.*, 2020; Vanhamäki *et al.*, 2020). Therefore, more attention should be paid to manage and efficiently utilize the waste generated. Thus, the circular economy concept has been presented as a model that can face the contemporary challenges of waste management and resource scarcity (Prendeville *et al.*, 2014; Barbosa *et al.*, 2021). In addition, successful circular economy is a fresh facet of sustainable development, the main objective of which is to transform waste directly released into nature through various processes into resources for another action, and this concept has been adapted from living systems known as feedback-enriched systems (Nattassha *et al.*, 2020). In particular, circular economy is implemented to increase the supply chain process's efficiency and waste management efficiency and reduce the amount of resources released into the environment (Pomponi *et al.*, 2017).

Similarly, agricultural wastes can be used as fertilizers, energy, raw materials, and compounds for various industries (McCarthy *et al.*, 2019). In this circumstance, circular economy helps to create a friendly and safe environment by reducing the negative environmental impacts of agricultural activities, saving relevant resources, and improving economic performance (Stegmann *et al.*, 2020; Velasco-Muñoz, 2021). Through this, efforts are made to extract, use, and dispose of limited resources by targeting alternative production and consumption patterns. Therefore, it is essential to find out how this concept of circular economy, which is famous all over the world, is related to the various activities carried out in rice cultivation and processing.

Circular Economy

The circular economy is based on consuming less, using more sustainably produced or recyclable products, and moving towards an economy built on waste disposal models. Currently, instead of importing resources outside the system, many organizations that produce goods focus on increasing and optimizing resource reuse and reducing capital, thus prioritizing the circular economy concept. (Barros *et al.*, 2020). Therefore, circular economy aims to minimize or eliminate non-renewable sources in a production system and maximize the reuse of these materials within the same system. Moreover, it is an economy built on social production-consumption strategies that maximize service produced by circular material flows and linear nature-social-natural material and energy flow through renewable materials (Korhonen *et al.*, 2018). In addition, circular economy limits the use of resources to a level that is not harmful to nature, i.e., leads to sustainable use while minimizing the amount of waste released into the environment. The circular economy has been spread over the centuries and extended mostly within the agriculture sector. Additionally, an example of past use of this circular economy concept can be identified in using animal manure for crops in agriculture (Barros *et al.*, 2020). A recent proposal is to use them as a new model to promote business expansion and economic growth by overcoming the scarcity of raw materials and energy. This concept extends to many fields and agriculture is prominent among them. Agriculture is the industry to achieve zero waste production. Recycling practices in the agribusiness sector are a starting point for changing processes that can lead to higher performance and a circular economy. Animal manure recycling can be facilitated by sharing materials between livestock and crop farmers. Besides, being environmentally friendly and waste management follow the growth perspective of circular economy (Murray *et al.*, 2017). Economic growth is being driven through greater sustainability in the use of natural resources in both agriculture and industry. (Duque-Acevedo *et al.*, 2020; Abad-Segura *et al.*, 2021; Belmonte-Urena *et al.*, 2021). According to the United Nations, circular agriculture focuses on regenerating the soil and minimizing the environmental impact through inputs. Likewise, reducing global emissions and contributing to the fight against climate change can help ensure a reduction in land use, as well as limit the use of chemical fertilizers and waste production (Wysokinska-Senkus, *et al.*, 2020; da Silva Duarte *et al.*, 2021). Material reuse and recycling become part of routine production decisions in any action framed in the circular economy. At the global level, fruit and vegetable production is a crucial sector of the bio-economy and it is essential to keep it economically, socially, and environmentally sustainable (Abad-Segura *et al.*, 2021). Developing new varieties in the fruit and vegetable sector, fertilizer use efficiency, organic amendments, water and energy, integrated pest management systems, and disease and weed control are the activities associated with sustainable agriculture (Wei *et al.*, 2021).

Limitations of Rice Cultivation

A world-popular crop known botanically as Oryza, rice is a monocotyledon plant. According to Reversat and Destombes (1998), plants belonging to the Oryza genus consist of two cultivated species and 21 wild species. Of these cultivated species, *Oryza sativa* originated from Asia and *Oryza glaberrism* from Africa. *O. sativa* is grown commercially in 112 countries and has a high yield and better grinding quality. In contrast, *O. glaberrism* is a semi-aquatic plant and can grow in water up to 5 meters deep (Vergara, 1985). Rice is most prevalent in Asian countries; more than 90% of the world's rice is produced in Asia and it is one of the staple foods of Southeast Asia (Das, 2017). Activities in rice cultivation include variety selection, land preparation, sowing/transplanting, fertilizing, irrigation management, and harvesting (Crawford and Shen, 1998; Rani and Rampal, 2016). Harris *et al.* (2002) pointed out that agriculture usually produces crop residues, commonly known as biomass residues. Plant residues left in the field after harvesting are crop residues and agro-industrial residues are formed by cleaning, filtering, and grinding as a by-product of post-harvest processes. The major biomass wastes produced in the rice industry are straw and rice husk, which are crop and agro-industrial residues. The stalk of the rice plant left as field residue during rice harvesting is identified as rice straw (Jeng *et al.*, 2012). The main problem of rice cultivation is that every year rice cultivation in the world produces about 1,370,000 million tons of waste consisting of rice straw and husk. These represent the largest share of total paddy production. Moreover, for every kilogram of rice grain produced, 0.28 kg of rice husk and 1.1 kg of rice straw are produced (Yusof, 2008).

Rice production is a multi-step process, as white rice has an outer bran and an even outer husk (Vinoda *et al*., 2015). Although there are several methods of rice processing based on modern technologies available in different countries, the basic principles of production are observed to be the same. Rice harvesting, cleaning, milling, de-husking, sizing, grading, and shipping are steps involved in typical rice production (Asati, 2013). The rice husk is removed during the milling process, which is a by-product of rice production. Often in Asian countries, harvesting involves open field burning, eliminating the rice straw. According to a survey, it was found that in Thailand, 90% of rice straw is burned outdoors (Tipayarom and Oanh, 2007). Rice husk is also usually disposed of by open burning in the field like rice straw. Such practices waste energy and pose environmental and health threats to the public. Additionally, increased CO_2 emissions from these open-field burning activities accelerate atmospheric temperature and contribute to global warming (Kamath and Proctor, 1998).

Rice Cultivation Practices Related to Circular Economy

Fertilizer usage

Reusing plant debris, intercropping, etc. helps to reduce the amount of fertilizers applied in addition to crops. This mainly leads to lower production costs and increased environmental friendliness. Using rice husks or their by-products as fertilizer reduces fertilizer costs, helps reduce CO_2 emissions by burning waste, and is environmentally friendly (McCarthy *et al*., 2019). Rice husks have low concentrations of P, S, and Zn with high concentrations of elements Si, N, and K. Si fertilization increased uptake of K (Jin *et al*., 2020) along with P, N, and Si (Pati *et al*., 2016; Cuong *et al*., 2017). Through this, the additional fertilizer to be given to the field can be reduced and economic benefits can be obtained. Similarly, this can reduce the risk of N_2O emissions and the cost of NPK fertilizers. Biofertilizer mixed with manure/straw compost has significantly reduced N losses during composting due to its effect on nutrient uptake. Like straw, biochar can increase N uptake and prevent NH_3 volatilization, and this effect from biochar is magnified by straw's high absorption capacity. It has also been shown that adding biochar to compost can reduce total N loss by 52% (Dong *et al*., 2015).

As Sarkar *et al*. (2017) pointed out, the nutrient supply capacity and productivity of paddy soils have been reduced through continuous and intensive cultivation of modern rice varieties. Although applying fertilizers alone cannot maintain soil fertility and crop productivity, their proper combination is considered one of the best management options for sustainable rice production. Thus, Integrated Plant Nutrient System (IPNS) is aptly identified as an appropriate combination of mineral fertilizers, organic fertilizers, crop residues, compost, N-fixing crops, and biofertilizers.

Although organic matter supplies the carbon requirement of the soil, its lack of use under long-term continuous rice cultivation badly affects the biochemical properties of the soil (Naher *et al.*, 2019). When comparing urea and green manure, the nitrogen (N) uptake rate by rice was higher in green manure (Clement *et al.*, 1998). Often the soil where rice is grown is severely carbon deficient and macronutrients such as N, P, and K are also at a minimum level. Although organic fertilizers play a significant role in traditional agriculture, the attention given to them by modern agriculture has decreased due to the decrease in the cost of organic fertilizers and the decrease in the price of chemical fertilizers. However, steps should be taken to reduce the use of these chemical fertilizers in the agricultural industry because of the heavy damage caused to the environment. Various agricultural methods can be followed for this. One method of using *Sesbania rostrata* plants is also grown as an intercrop in rice cultivation. The plant can grow in submerged conditions and fix atmospheric N_2 through roots and stems. Through this, the amount of chemical N fertilizer used in rice cultivation can be reduced. Moreover, several studies have shown that 5-6 tons of Sesbania dry biomass can replace the total demand for chemical N fertilizers in rice production (Naher *et al.*, 2019).

It has been shown that applying green manure in paddy cultivation improves the carbon status of the soil and increases the yield by 9–11% compared to chemical fertilizers. Therefore, using inorganic and bio-organic fertilizers in sustainable and environmentally friendly rice production is more effective. Sesbania, a legume, is used as a green manure in rice cultivation either by cropping before paddy or as an inter- or mixed-crop with rice (Gill *et al.*, 2009). Similarly, Sesbania facilitates crop emergence in areas with atmospheric nitrogen fixation and soil crust problems (Chaudhary *et al.*, 2018; Singh *et al.*, 2007). In addition, Singh *et al.* (2007) reported that this Sesbania coculture reduced broadleaf and grass weed density by 76–83% and 20–33%, respectively, and total weed biomass by 37–80% compared to a rice monoculture.

Limitations of nutrient management in rice related to circular economy are farmers' minimal knowledge and indifference towards eco-friendly fertilizer use, but the primary objective is to achieve high yield in a short period of time (Kapoor *et al.*, 2020). These circular economy activities play an important role in the environmentally friendly restoration of various causes of nutrient management in rice cultivation such as over-cultivation, imbalance in fertilizer use, little or no return of crop residues to the soil, and soil degradation (Chojnacka *et al.*, 2020). These methods reduce the amount of unnecessary waste added to the environment and prevent the accumulation of chemical compounds that are harmful to the environment.

Integrated rice farming

Integrated farming can also control toxic compounds released into the environment. Mofidian and Sadeghi (2015) combined duck farming and rice farming to establish a rice-duck industrial chain and found that the rice-duck industrial chain can significantly reduce methane emissions compared to conventional paddy fields. In addition, they found that while monoculture emissions are generally higher in the morning and evening, these rice-duck industries reduce methane emissions. These rice-duck farming methods eliminate the need for pesticides by maximizing the use of resources, thereby reducing the unnecessary accumulation of waste in the environment (Li *et al.*, 2019).

Rice-fish farming has also been found to be environmentally friendly and profitable (Cagawan, 2000; Berg, 2002; Gupta *et al.*, 2002). By introducing fish to rice paddies, the need for pesticides to control pests will be reduced, farm income can be increased, and agricultural products can be diversified. Thus, integrated farming systems are believed to help farmers increase their farm income and promote sustainable agriculture and rural development (Vromant *et al.*, 2002). Channabasavanna *et al.* (2007) reported that fish contribute for controlling insect pests and weeds in rice cultivation, thereby improving rice yield by 35% by meeting their nutritional needs and establishing good spatial cooperation. Rice-fish farming systems in Asia reduce the need for additional fertilizers by facilitating soil nitrogen fixation (Lu and Li, 2006) and optimizing water use (Frei and Becker, 2005).

Through integrated farming, producing one component creates high levels of complementary effects for other enterprises. For example, cow feed produces milk, while dung, urine, and waste produce farm fertilizer and energy for crops and fish ponds. Sludge deposits in the fish pond are used as fertilizer for crops. In addition to improving soil physical and biological properties, farmyard manure can replace up to 25% of recommended N, P, and K for crops. In the event of power outages, the water in the fish pond can be used by gravity. Integrated nutrient management can increase grain productivity by 0.5–1.0 tons per hectare. Moreover, 20–30% of fishpond embankment can be used for growing eggplant and fruit trees, which provides adequate soil cover to control soil erosion and makes the system economically viable (Gill *et al.*, 2009).

Intercropping/crop rotation

The cultivation of two or more crops in the same space is defined as intercropping (Andrew and Kassam, 1976). This intercropping makes more efficient use of all resources compared to monoculture. Many plants can be intercropped, and cassava and rice are used as intercrops. When paddy cultivation is done alone, soil pest effects occur, but in combined cultivation, the situation changes. It is easy to improve soil fertility through nitrogen fixation in rice-legume intercropping. Intercropping systems also control soil erosion by preventing raindrops from hitting bare soil (Seran and Brintha, 2010). According to Seran and Brintha (2010), the intercropping system is more profitable than the mono-cropping system. Rice-based cropping system is also widely used in several countries with cereals, oilseeds, cotton, sugarcane, green manures, vegetables, etc. Generally, rice is intercropped with mung, sesame, maize, finger millet, or other minor millets. The seeds of successive crops like dal, cowpea, and berseem are sown in maturing rice crops. Sequential cropping is the successful cultivation of crops like barley, wheat, and rice. Peas can be intercropped with dry-seeded lowland (semi-dry) rice, and cowpea leaves are used as green manure. Furthermore, this cultivation reduces weed pressure in rice (Rana *et al*., 2018). Grain yield is significantly higher when intercropping with or without soybeans (Wangiyana *et al*., 2019). According to Dulur *et al*. (2019), when rice was intercropped with groundnut instead of monocrop, a higher number of panicles per bunch and many filled grains were recorded in rice. Crop rotation of rice with other crops such as wheat, mustard, cowpea, and maize can reduce the amount of methane released by altering the anaerobic and aerobic phases (Baghel *et al*., 2020).

Pest control

As the demand for rice increases due to the ever-increasing population, farmers around the world are increasing plant density in their management schemes, which is increasing populations of certain pests. Increasing pest damage is among the major threats to achieving high rice yield, even with management strategies such as fertilizer management, irrigation management, and management of agrochemical inputs in rice (Litsinger *et al*., 2011), causing problems in achieving high rice production (Prasad *et al*., 2017). Frequent overuse of insecticides and herbicides has resulted in environmental and economic impacts. Moreover, the continued use of various chemicals such as insecticides, herbicides, and fungicides, leaching of nutrients into groundwater, and greenhouse gas emissions from agricultural soils have severely degraded the natural ecosystem (Parras-Alcántara *et al*., 2013). The focus is on allelopathy in searching for ways to control pests using natural methods in an environmentally friendly manner, alleviating these conditions to some extent. Allelopathy is a method of controlling insect pests and weeds or using microorganisms such as viruses, fungi, bacteria, protozoa, and nematodes as biocontrol agents and bio-based integrated pest management currently focuses on this (Kumawat, 2022). As this method has the advantage of achieving balance in pest control in the long term, natural predators can consume significant amounts in the short term without affecting the growth and yield of the main crop (Jetter and Paine, 2004).

Agronomic practices controlling pests include growing resistant and maturing varieties, early seeding, close planting, weed control, especially with stunt and tungro viruses, crop and field sanitation, and post-harvest plowing to prevent egg deposition on the soil surface. These methods are environmentally friendly and minimize the release of harmful compounds into the environment. Natural enemies of insects and pests such as predators, parasitoids, pathogens, and microbial insecticides are used for biological control of pests. These organisms attack and destroy insects and pests (Naeem-Ullah, 2020). Ladybug has been identified as the natural enemy of rice stem borers. Most of the insect pests of rice in Malaysia are kept in low populations due to the influence of their natural enemies, such as caterpillars, dragonflies, spiders, and mirid predators and the presence of such predators reduces the risk of spread of rice pests and their presence is known to indicate the quality of the rice field (Ooi, 2015). Acting as a major predator of insect pests, spiders play an important role as natural predators by reducing the density of insect pests in rice fields (Sebastian *et al.*, 2005; Fahad *et al.*, 2021). Currently, about 128 species of insects have been identified in rice cultivation, but only 15-20 insect species have been identified as economically harmful insects (Makkar *et al.*, 2019). Different traditional, physical, biological, and chemical methods can be adopted to control these insect species. In biological pest control, the pest population is controlled using natural repellents that fight against pests. Although not all pest populations can be fully managed by biological approaches, an integrated pest management strategy that integrates many pest control methods in an ecologically safe system is effective and environmentally sound (Bale *et al.*, 2008). In rice cultivation in the southern region of West Bengal, India, the application of integrated pest management techniques has significantly increased rice production (Satpathi *et al.*, 2012). The widespread use of synthetic pesticides is easy. However, it reduces the natural enemy communities and disrupts the ecological balance, allowing the pest population to grow more efficiently at a particular time (Bale *et al.*, 2008).

The soil-borne fungus *Rhizoctonia solani*, which is currently a major threat to rice production worldwide, has been identified as one of the most destructive disease causing mircrorganism of rice (Groth and Bond, 2006). Fungicides are widely used to control this fungus (Groth and Bond, 2006; Li *et al.*, 2014). The implication is that excessive use of fungicides has a greater impact on human health and increases production costs (Wilson *et al.*, 2021). Biofumigation using biocidal compounds, brass elements added to the soil during the breakdown of plant material, is an alternative biological approach to disease management and many studies have shown that it can control the soil-borne plant pathogenic fungi *Rhizoctonia* spp and *Gaeumannomyces graminis* (Handiseni *et al.*, 2017; Sarhan *et al.*, 2020).

Weed management

There are various weeds associated with rice crops (Chauhan, 2013). Further, these weeds have reduced global rice yields by up to 32% (Rao *et al.*, 2007). Among the weed control methods, prevention and limitation of the spread of weeds and seeds are considered to be the most basic methods, and among the preventive measures in rice cultivation, the use of clean weed-free seeds, clean land, and proper maintenance of irrigation and cleaning of farming equipment are the most important (Buhler, 2002). Adopting water conservation practices in rice has been identified as a major problem because it creates a water and air environment more favorable for weeds. Under such circumstances, an integrated approach to weed management is critical (Chauhan, 2013). Adjustments in seeding rate and planting geometry can also provide significant weed control (Anwar, 2011). Moreover, weed control can be environmentally friendly by reducing chemical fertilizers and applying green manures, and some green manures have the ability to secrete specific chemicals into the soil that inhibit weed seed germination (Blackshaw *et al.*, 2001; Mohler *et al al.*, 2012). In addition, environmentally friendly methods of weed control such as manual weeding and mechanical methods including hoeing are very effective in reducing the use of chemicals that harm the environment (Bahadur, 2015). Moreover, land preparation is an extremely important environmentally friendly weed control practice in rice cultivation. Activities like ploughing, and submerging the soil are done during land preparation, and through this, weed seeds are destroyed as well as germination is controlled. A majority of *Echinochloa colona* (L.) Link seeds were found to be destroyed after plowing (Puckridge *et al.*, 1988). Seed priming, inclusion of cover crops in rotation, fertilizer management, and consideration of critical weed-crop competition period are considered effective tools for integrated weed management in rice (Buhler, 2002; Mennan *et al.*, 2012). Predators, microbes, and weed competitors are used to kill or reduce weed populations. Biocontrol agents of weed species in rice cultivation are listed in Table 01. This environmentally friendly, safe, and economical approach is the best option to combine with other techniques in agriculture (Charudattan, 2001; Müller-Schärer *et al.*, 2004; Juraimi *et al.*, 2013). Correspondingly, no residual effects of bioherbicide have been observed in soil or plants.

Furthermore, applying specific bioherbicides indicates that specific weeds can be managed effortlessly (Xuan *et al.*, 2005). Biological weed management in rice is a practical option and empowers the circular economy if the microbes/predators are selected correctly and at the right time and dose. Allelopathy is an environmental, physiological phenomenon of the release of potent secondary metabolites by another plant or microbe living in its vicinity to promote or suppress the growth and metabolism of a plant or microbe. These allelochemical secondary metabolites have great potential to influence growth due to physiological interventions (Jabran *et al.*, 2015; Farooq *et al.*, 2020). Rice is an allelopathic crop that releases biocidal allelochemicals that can suppress weeds.

Table 01: Biocontrol agents of weed species in rice cultivation

Target weed species	Biocontrol agent/bioherbicide	References
Fimbristylismiliacia, Cyperus iria	Common carp and grass carp	Juraimi (2013)
Echinochloa crus-galli (L.) P. Beauv (Barnyard grass) *Leptochloa chinensis*	*Exserohilum monocerus* *Cocholiobolus lunatas* (Fungi) *Setosphaeria sp*. Cf. rostrata	Thi *et al*. (2008)
Many weeds	Turtles, fish, ducks, geese, and pigs	Ismail *et al*. (2012)
Oryza sativa f. Spontanea Roshev., *Echinochloa colona* (L.) Link., *Euphorbia hirta* L., *Ageratum conyzoides* L.	*Parthenium hysterophorus* L.	Motmainna *et al*. (2021)
Lolium multiflorum, E. crus-galli, Digitaria sanguinalis, Setaria italic (L.) P. Beauv.	*Ammi visnaga (L)* Lam	Travaini *et al*. (2016)
Conyza canadensis (L.) Cronquist., *Conyza bonariensis* (L.) Cronquist	*Juglans nigra* L.	Shrestha (2009)
E. crus-galli, Lolium perenn L.	*Aglaia odorata* Lour. Leaf extract	Kato-Noguchi *et al*. (2016)
Medicago sativa	*Ailanthus altissima* (Mill.) Swingle	Tsao *et al*. (2002)
Cucumis sativus L., Sorghum bicolor (L.) Moench.	*Fusarium fujikuroi*	Daniel (2018)

Allelopathy is an environmental, physiological phenomenon in which a potent secondary metabolite is released by another. These allelochemical secondary metabolites have a great potential to affect the growth of a plant or microorganism through physiological interventions to promote or suppress its growth and metabolism (Jabran *et al*., 2015; Farooq *et al*., 2020). Rice is an allelopathic crop that releases biocidal allelochemicals that can suppress weeds, as well as rice genotypes with high allelopathic potential. Similarly, extracts of six leaves of rice plants have been found to inhibit the growth of duckweed and lettuce (*Lactuca sativa* L.) (Ebana *et al*., 2001). Furthermore, research has shown that there is a possibility of suppressing weeds by incorporating rice waste with high allelopathic activity. For example, rice straw has been found to inhibit germination of the dominant weeds *Avena ludoviciana* and *Phalaris minor* Retz (Young *et al*., 1989; Tamak *et al*., 1994). Furthermore, the weed growth inhibitory content of allelopathic compounds in plants such as *Medicago sativa, Piper methysticum*, *Azadirachta indica* (neem), *Ageratum conyzoides, O. sativa,* and *Bidens* *pilosa* (Table 2) inhibited rice weed growth. The following plant species (Table 3) have been found capable of reducing weeds and increasing rice yield.

Table 2: Allelopathic crops used in rice cultivation

Allelopathic crops	Functions	References
Buckwheat (*Fagoprum esculentum*), Velvetbean (*Mucuna pruriens*), Hairy vetch (*Vicia vilosa*), and Convolvulaceae (*Tricolor batatas*)	Use as cover crops and support to weed reduction	Batish *et al.* (2001)
Mucuna spp., Canavalia spp., Trifolium spp., Brassica spp., and *Ipomoea spp.*	Use as green manure and help to weed control	Batish *et al.* (2001)
Alfalfa (*Medicago sativa*), Oats (*Avena sativa*), Pearl millet (*Pennisetum glaucum*), and Rice (*Oryza sativa*)	Weed reduction	Dilday *et al.* (1994), Weston (1996)
Sunflower (*Helianthus annuus*)	Control *Parthenium hysterophorus* weed	Dilday *et al.* (1994), Weston (1996), Kohli (1993)
Maize (*Zea mays*)	Weed reduction	Hasan *et al.* (2021)
Barley (*Hordeum vulgare*)	Use as cover crops and support to weed reduction	Batish (2001)
Crimson clover (*Trifolium incarnatum*), Subterranean clover (*Trifolium subterraneum*)	Use as cover crops and support to weed reduction	Weston (1996), Batish (2001)
Sorghums (*Sorghum spp.)*	Use as cover crops and support to weed reduction	Dilday *et al.* (1994), Batish (2001)
Rye (*Secale cereale*)	Use as cover crops and support to weed reduction	Batish (2001)
Sweet potato (*Ipomoea batatas*)	Use as cover crops and support to weed reduction	Weston (1996)
Wheat (*Triticum aestivum*)	Use as cover crops and support to weed reduction	Dilday *et al.* (1994)

Use of new improved rice varieties

Although pure rice varieties have been cultivated successfully, there is a shift towards hybrid cultivars with improved yield potential, climate change tolerance, and resistance to pests and diseases (Nalley *et al.*, 2016; Futakuchi *et al.*, 2021) Further, these hybrid cultivars can compete against weeds and have better nutrient uptake and drought tolerance due to more extensive root systems (Peng *et al.*, 2009; Yang *et al.,* 2019). Breeding rice varieties tolerant to water-deficit reduces the risk of yield loss, irrigation costs, and CH_4 emissions. Moreover, these hybrid varieties have high water use efficiency and high yield (Brodt *et al.*, 2011; Futakuchi *et al.*, 2021). These improved cultivars have reduced CH_4 generation in rice by shifting photosynthesis to above-ground biomass rather than roots (Balakrishnan *et al.*, 2018; Kim *et al.*, 2018). Furthermore, new cultivars containing genes suitable for obtaining Cd (Yan *et al.*, 2019; Zhou *et al.*, 2019) and other multi-essential elements have recently been introduced. This is considered a very growth opportunity in rice cultivation. Their drought tolerance is indicated mainly by the deep root systems that easily access deep water bodies (Uga *et al*., 2013).

By cultivating these hybrid rice varieties, the environment is protected by reducing the amount of chemical fertilizers, pesticides, and weed killers used for cultivation and reducing the amount of waste released into the environment, which is related to CE.

Table 3: Plant species which have capable of reducing weed and increasing rice yield

Plant species	Target weeds	References
Billy goat weed (*Ageratum conyzoides* L.)	Many weeds in rice field *Amaranthus spinosus* L.	Vyvyan (2002), Macias *et al*. (2007), Duke *et al*. (2015)
Chinese taro (*Alocasia cucullata*)	*Nerium oleander, Helianthus tuberosus, Echinochloa crus-galli* (Barnyard grass), *Monochoria vaginalis* (Monochoria)	Khanh *et al*. (2005)
Stylosanthes guianensis	Many weeds in rice field	Khanh *et al*. (2005)

Water management techniques

Cultivation of rice in an aquatic environment or subject to water management can control weed growth and reduce their competition for nutrients (Arao *et al*., 2009). Moreover, these water management decisions significantly affect field greenhouse gas emissions and the content and distribution of toxic metal (loid) s in grain (Arao *et al*., 2009; Linquist *et al*., 2015). Rice submergence reduces the quantity of herbicides required for weed control, thus reducing costs, and reducing the release of chemical waste into the environment and this supports circular economy.

Post-harvest handling

Along with improving rice production to meet the daily population growth, it is very important to reduce crop losses due to various causes, rice losses due to insect infestation, and various damages that can be caused to paddy and rice. Through that, there is a possibility of limiting the amount of waste released into the environment (Qu *et al*., 2021). Grain losses occur during post-harvest handling (packing, storage, and transportation), and minimizing these losses requires suitable packaging materials, proper storage facilities, and transportation. This preserves grain quality and controls contamination by insects or fungi (Müller *et al.,* 2022). After harvesting, there is a risk of spoilage of the grain due to various factors such as biotic and abiotic factors during storage before reaching the consumer. Biotic factors such as insects, rodents, mites, fungi, bacteria, and various abiotic factors such as moisture, temperature, and lack of sunlight can cause post-harvest losses directly or indirectly (Abass *et al.,* 2014; Mesterházy *et al.*, 2020). However, according to Bett and Nguyo (2007), most of the post-harvest losses are caused by insect pests during storage.

Insects that damage rice grains include rice weevil (*Sitophilus oryzae* L.), grain weevil (*Sitophilus granarius* L.), lesser grain borer (*Rhyzopertha dominica* F.) and angoumois grain moth (*Sitotroga cerealella* O.). *S. oryae* and *S. cerealella* have been found to cause more damage (Mason *et al.*, 2012). Through this loss of nutritional value, commercial loss as well as quality deterioration of wealth, and there is a possibility of developing grain spoilage due to an increase in temperature and water content of grain stock due to insect activity (Adler *et al.,* 2007; Zulaikha *et al.,* 2021). Meanwhile, the use of fumigating chemicals, mainly fumigants, during storage is common worldwide, but their excessive use causes environmental problems and risks to human health (Lee *et al.*, 2003; Chou *et al.*, 2022). As a solution to such problems, biopesticides as well as new environmentally friendly practices to reduce post-harvest damage are used as a good alternative to protect grains (Herrera *et al.,* 2018). Similarly, some of the various environmentally friendly post-harvest loss reduction strategies used in rice are summarized in Table 4.

After the paddy is harvested, it is transferred to rice mills to be processed into white or brown rice to make it fit for consumption. A lot of straw, husk, and bran waste is released during this rice milling process. Similarly, there are several grinding processes such as single-stage grinding and multi-stage grinding and the amount of waste released by those methods varies (Illankoon *et al.*, 2023).

Rice By-products and Their Applicability in Circular Agriculture Practices

Rice straw

Rice straw comprises panicle rachis, leaf blade, leaf sheath, and stem. The average ratio of rice grain to rice straw is 1: 1.25 (Haefele *et al.*, 2011). About 20% of this straw, released into the environment in the past and burned, is currently used as a raw material in various industrial products (Kadam *et al.,* 2000). As Zhang *et al.* (2013) pointed out, rice straw is currently used as a raw material for the paper and pulp manufacturing industry. More than 80% of the remaining straw is often used as mulch for various crops and the rest can be buried or burned to add nutrients to the soil. Although rice straw burning is the fastest method of straw disposal, it increases the amount of greenhouse gases in the air and causes environmental pollution (Hamed *et al.*, 2012). Rice straw is used as part of the nutritional requirements of ruminants in many rice-producing countries (Dong *et al.*, 2019). However, the digestibility of rice straw is reduced due to its low protein content, presence of phenolic properties, and high silica and lignin (Van Soest, 2006).

Table 4: Environmentally friendly postharvest loss reduction strategies used in rice

Eco-friendly postharvest loss reduction strategies	Details	References
Traditional methods	Mechanical removal of infected grains or pods includes squeezing, shaking, and re-attachment of grain which disturbs the insects and reduces their activity. Exposure of grain to sunlight, treatment of grain with cow urine (a traditional practice in southwestern Ethiopia), and control of insect damage by adding salt to grain. Control of beetle population by using fumigants made from a mixture of fresh cow dung and sugarcane compost moistened with 60% moisture content. Management of beetle infestation through harvesting immediately after physiological maturity.	Mendesil (2007); Baidoo *et al.* (2014); Tadesse (2020)
Control by environmental parameters	**Temperature** Control of insect infestation by keeping grain storage temperature range 13-35°C Heat treatment using hot air can prevent insect and other pest damage, but if the process is not done properly, the quality of the grain can deteriorate. Fermenting means removing excess heat by keeping the product temperature at or below 15°C, and the grain temperature should not exceed 20°C. It can reduce the development rate of insects. Grain damage can be minimized by successfully storing the grain in	Fields *et al.* (1992); Champagne *et al.* (2004); Lazzari *et al.* (2010); Morales (2017); Katta *et al.* (2019); Paul *et al.* (2020); Tadesse (2020)

	a clean condition, i.e., without various impurities such as chemicals and insects.	
	Storage atmosphere Storing grain under protected conditions, i.e. in an oxygen-free environment, often prevents insect eggs from hatching. Using vacuum packaging removes all air and creates a low-pressure environment that protects the wealth from insects, while the lack of O_2 and excess CO_2 kills any remaining insects in storage. The use of modified atmospheres (Active modified atmosphere packaging) can alter the amount of common gas constituents oxygen, nitrogen, and carbon dioxide that are lethal to insects. On its antifungal properties from CO_2 in the atmosphere Suppresses insect eggs, early larvae. A nitrogen-rich environment is capable of completely killing *Tribolium confusum* (all life stages), *Oryzaephilus surinamensis* (larvae and adults), *Sitophilus granarius* (L.) (adults) and *Rhyzopertha dominica* (adults). Ozone can affect all stages of the life cycle of insects. Ozone has been found to be capable of removing pesticide residue from rice grains. Hermetic bags are safe pesticide-free and sustainable grain storage that improves overall grain quality and seed viability.	Guenha *et al*. (2014); Ávila-Lovera *et al*. (2017); Amoah and Mahroof (2019); Boopathy *et al*. (2022); De Sousa *et al*. (2023)
Inert materials	Inert materials such as fly ash, sand and other mineral powders fill the free space between grain stacks, which hinder insect movement and are environmentally friendly. The use of materials such as coffee husks, wood ash, and sawdust can cause dehydration of insects.	Debnath *et al*. (2011); Jean *et al*. (2015); Tadesse (2020); Kar *et al*. (2021)

	The use of wood ash as inert dust causes death by suffocation of insects.Grains treated with various inert materials such as ash and fossil shields can protect grain viability. Silica gives good results to protect grains from insects and prevent insect growth and using silica nanoparticles is more efficient.	
Essential oil	Orange oil is used as an alternative agent to control insect pests. Using an emulsion of cinnamon oil with anhydrous ethanol can prevent rice weevil infestation. Essential oil obtained from *Citrus limonum* is used. Basil, cinnamon, eucalyptus, mandarin, oregano, peppermint, and tea tree oils can be used alone or in combination to control grain pests. Eucalyptus essential oil has insecticidal and repellent properties. *Achillea biebersteinii*, *Achillea fragrantissima*, and the oil obtained from *Ageratum conyzoides* is active against grain-injurious *Sitophilus oryzae*, *Rhyzopertha dominica*, and *Tribolium castaneum*. *Carlina acaulis* essential oil is used as an insecticide.	Nenaah *et al.* (2014); Hossain *et al*. (2019); Guettal *et al*. (2021); Chou *et al*. (2022); Kavallieratos *et al*. (2022); Shi *et al*. (2022); Zargari *et al*. (2020)
Biopesticides in packaging	*Tinospora cordifolia* leaf powder is used as a biopesticide in packaging. Low-density polyethylene membranes impregnated with supercritical CO_2 and terpenes are used in the storage and transportation of ketones, seeds, kernels and derivatives. Chitosan-coated paperboard is used in packaging to prevent insect infestation.	Soujanya *et al*. (2018); Pandey *et al*. (2022); Silva *et al.* (2022)

Application of radiations	Insects can be killed by using infrared heating with an electric emitter. Heating rice under infrared radiation to 60°C can kill *Sitophilus zeamais* and *Tribolium castaneum.* Rice weevil control can be achieved by using an irradiation inhibition treatment during rice storage.	Follett *et al.* (2013); Duangkhamchan *et al.* (2017); Pei *et al.* (2018)

Using these straws as more industrial raw materials not only reduces the cost of production but also helps to solve the problems arising from the release of waste into the environment. It has also been established that compost can be produced using rice straw, which restores and revitalizes soil N fertility instead of providing essential nutrients directly to plants. In addition, straw can be used for various purposes, especially, mushroom production, packaging material processing, briquettes, rope production, vermicompost, pellets, paper, biogas production, and animal feed. Rice straw and rice husks are also used as a very cost-effective growing medium. By subjecting this rice straw to combustion (electricity and heat), anaerobic digestion (biogas), pyrolysis (biogas and oil), and gasification, it is possible to generate electric power and heat (Gadde *et al.*, 2009). It is important to combine rice production and electricity generation using rice straw to improve utilization, and electricity generation using rice straw has a high potential for economic and greenhouse gas emission reduction (Shafie *et al.*, 2014; Park *et al.*, 2021).

Reuse of rice husk

Global rice production in 2020 is estimated at 499.31 million metric tons and for every 1 kg of rice produced, approximately 0.28 kg of rice husk is generated (Das *et al.*, 2022). Depending on the variety of rice, climatic conditions, and geographical factors, the amount and nature of the constituents contained in the rice husk varies. The main components of rice husk are cellulose, hemicellulose, lignin, and minerals. Similarly, due to the burning of these rice husks without being used for various needs, various environmental problems are caused due to excessive CO_2 and greenhouse gas emissions to the environment. Turning this rice husk into activated carbon with good adsorption properties can avoid waste disposal and management problems and is environmentally friendly. Activated carbon produced from rice husks can be used for water and wastewater treatment. This value-added product will also lead to market development (Ludueña, 2011).

Rice husk can be used to produce biochar which can absorb nitrogen compounds and reduce its mineralization. The properties mentioned above of rice husk are also considered an indirect mechanism leading to the absorption of nitrogen compounds with ion exchange sites, thereby reducing its mineralization and NH_3

emissions (Alarefee *et al.*, 2023). Thus the use of rice husk is low cost, effective for pollutant treatment, biodegradable, and environmentally friendly. Therefore, it is concluded that treated rice husk can be recommended as a biomaterial for pollutant removal (Zhao *et al.*, 2022). Correspondingly, treated rice husk is used as biomass for heating purposes due to its high heating value (Omo-Okoro, 2018). Furthermore, rice husk-fired boilers can generate steam for the rice mill itself (Kapur *et al.*, 1996). A problem here is that the black smoke emitted through the incomplete combustion of the opposite rice husk has adverse environmental effects.

Rice husk ash

Rice husk ash is produced as a by-product of burning rice husks as fuel to generate energy. It is important to utilize this rice husk ash, which cause massive waste generation, energy loss, and environmental pollution (Liu *et al.*, 2012). Moreover, due to their carcinogenic and bioaccumulative nature, the generation and disposal of these rice husk ash are problematic, and it is imperative to convert them into valuable products and channel them into revenue generation (Kumar *et al.*, 2016). In their study, Hwang and Huynh (2015) showed a fruitful observation that rice husk ash can be used as a pozzolanic material in the production of high-strength concrete and refractory bricks. Using this rice husk ash in cement production reduces costs and improves its properties, such as reduced setting time, increased compressive strength, and chemical resistance (Zain *et al.*, 2011). Moreover, rice husk ash, a rubber vulcanizing agent, a beer clarifying agent, oil, and a waste product for the silicon chip industry, can be used as raw materials. Ettah (2018) stated that due to the unique properties of rice husk ash, such as low bulk density, low thermal conductivity, and high melting point, it is used in making Tundish powder. However, these properties of rice husk ash can be achieved only if rice husk ash is burned in properly temperature-controlled and well-designed burners after a specific grinding process (Zain *et al.*, 2011).

In addition, the ash contains rice husks and rice husk ash as silica contributors (Song *et al.*, 2014), so this rice husk ash can be used for silica sheets, polymer, and electronics industries. Moreover, this silica is widely used to produce electronic circuits, transistors, and diodes, especially in the electronics industry. Permatasari *et al.* (2016) concluded that rice husk can be an alternative to silica. Adam *et al.* (2013) indicated that pure silica can be produced after removing mineral acid residues and using rice husk ash to add alcohol.

Reuse of rice bran

Rice bran is widely used in food and pharmaceutical industries to increase consumer demand by producing healthy foods. Rice bran consists of 80% carbohydrates, 2% proteins, 7–8% fatty acids, 7% dietary fiber, and 7% minerals and is produced as a by-product of white rice production. Although rich in nutrients due to lipase, unrefined rice bran is unsuitable for human consumption (Gul *et al*., 2015). About 90% of the rice bran thus obtained is used as cattle feed and the rest is used for extraction (Schramm *et al*., 2007). In the food industry, microwave treatment (Ramezanzadeh *et al*., 1999), extraction and dry heat treatment (Gul *et al*., 2015), ohmic heating (Lakkakula *et al*., 2004), parboiling and autoclaving (Rosniyana *et al*., 2009), toasting (da Silva *et al*., 2006) and gamma irradiation are used to stabilize rice bran and prepare it for use (Shin and Godber, 1996). About 12–13% of rice bran is oil, of which 4.3% consists of beta-sitosterol, gamma-oryzanol, and tocotrienol (Gul *et al*., 2015). Rice bran oil extracted from rice bran benefits human health and is an excellent source of nutrients such as tocopherols, sterols, and tocotrienols (Sugano and Tsuji, 1997; Gul *et al*., 2015).

Discussion

Considering population growth, the global population is estimated to exceed nine billion by 2050 (Samal *et al*., 2022), and total global food demand is expected to increase by 35 to 56% between 2010 and 2050 (Makungwe *et al*., 2021). With the increase in population, people have to face many problems in meeting their basic needs due to the decrease in arable land and lack of non-renewable resources to meet their housing needs. Further, environmental pollution increases due to harmful gases and waste released into the environment due to various informal human activities. Moreover, the loss of agricultural land has increased due to urban growth, and thus rice production faces a number of serious challenges (Satterthwaite *et al*., 2010; Pandey *et al*., 2015). Mainly circular economy has been identified as an effective method to reduce these problems and thus follows the "resources – products – recycling" method (Naqvi *et al*., 2018; Dagevos and Lauwere, 2021).

The challenge of transitioning to a circular economy model through developing and deploying new knowledge and harnessing technical know-how to a sustainable process while innovating agricultural activities remains ongoing (Abad-Segura *et al*., 2020). That is, the primary purpose of the circular economy concept is to reuse or recycle the by-products of rice production, processing, and consumption in the food system of agriculture, especially rice cultivation, and to direct the use of non-edible biomass as raw materials for animal feed, fertilizer, and other industries. For this purpose, the adverse effects on the environment can be reduced by preparing the land, supplying water, using different cultivation methods, weed control, pest control, efficient use of fertilizers, planting new varieties as well, as reducing harmful gas emissions from rice cultivation.

Since rice is the staple food of more than half of the world's population and is the second most cultivated grain crop in the world, if the cultivation is not done properly, the impact that can occur on the environment is high. That is, the amount of waste and gas released through this and the impact on the environment is also high. Therefore, it is important to continue cultivation and production to achieve the objectives of CE, which help protect the environment and obtain economic benefits (Gardetti, 2019; Ferrero *et al.*, 2022). The waste generated in the rice production cycle mainly includes rice straw, rice husk, and rice husk ash. This residue produces 0.41 to 3.96 kg of rice straw and 20 to 33% of rice husk grain weight per kg of rice. About 80% of the world's rice straw is disposed of through waste burning, but the resulting pollution has caused health and environmental problems. Many countries have implemented new regulations to limit burning activities in the field (Ye *et al.*, 2011; Lim *et al.*, 2012). However, silica from rice production waste can be used as a raw material for various industries. Further, this rice waste can be used for energy production, as fertilizer, for animal feed and other specialty foods such as silage, for crops such as wildflowers, and various industries such as paper products (Liu *et al.*, 2012; Brand *et al.*, 2017; Chou *et al.*, 2022). Nitrogen and water have been identified as significant limiting factors for rice yield (Bouman *et al.*, 2007). However, short-term rains have caused many economic and environmental impacts due to heavy N fertilization in China (Co *et al.*, 2012) and pesticide use in Vietnam (Devkota *et al.*, 2019). Over application of other nutrients, such as N, P, and K, can cause ecosystem problems and reduce yield and net profit over time (Smil, 2004). Therefore, regardless of the short-term benefits, it is necessary to minimize the harmful gases emitted into the environment through a long-term correct vision, control the harmful wastes released into the environment, and use land, water, fertilizers, etc. optimally. Through this, circular economy can be used more effectively in rice production. It will create an environment-friendly and economically viable environment (Devkota *et al.*, 2019).

CONCLUSION

The population is increasing day by day but at the same time, many problems arise due to scarcity and depletion of resources. Furthermore, the ecological balance breaks down due to release of harmful waste into the environment through direct and indirect human activities. Todays most talked about circular economy is based on consuming less, using more sustainably produced or recyclable products, and moving towards an economy built on waste disposal models.

Considering the relationship of this concept with rice cultivation and production, first, the activities carried out in rice cultivation, such as water control, efficient use of fertilizers, different cultivation methods, integrated cultivation methods, pest control, use of improved rice varieties, and proper recycling of waste, etc. By doing it efficiently and in an environmentally friendly way, the amount of waste released into the environment can be reduced, and there is also the possibility of getting additional economic gains. That is, the available resources should be used sustainably. Moreover, many of the wastes thrown away during rice production, such as straw, rice husks, rice stalks, etc., can be used for various products such as fertilizer, paper, planting material, animal feed, in the production of ceramics as well as in energy generation. Through these activities, the amount of waste released into the environment during paddy cultivation can be reduced, and by using that waste for new products, economic benefits can be obtained, and the environment is also protected. The various activities of rice cultivation and production can be clearly linked with the CE.

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