

The potential utilisation of rice biomass for biochar to support sustainable rice farming development in Indonesia

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Abstract. As a rice-producing country, Indonesia has abundant rice biomass in the forms of rice straw and rice husk (hull). Nevertheless, this resource has not been utilised to its fullest potential. This paper aims to assess the potential utilisation of rice biomass for biochar to support sustainable rice farming development through circular economics. A literature review method was applied in this paper, exploring the relevant articles published primarily in journals within the last ten years. The study results show that biochar serves as a soil amendment, and its application on agricultural land can improve soil properties and soil fertility, resulting in higher crop productivity and enhancing sustainability. Based on rice production data released by BPS-Statistics Indonesia, it is estimated that approximately 10.10 million tons of rice husk and 83.29 tons of dry rice straw are generated annually during 2018–2022, which can potentially be processed into 33.04 million tons of biochar. Applying 2 tons of biochar per hectare can increase rice productivity by at least 4%, resulting in a potential increase in rice production of at least 2.22 million tons annually. The government needs to facilitate farmers in rice-producing centres with biochar processing units using appropriate technology on a proper scale.

1 Introduction

Rice is the main staple food for Indonesian people. Therefore, the government tries to increase rice production to meet rice needs. The “Green Revolution” has succeeded in boosting rice production. However, the long-term use of chemical inputs has detrimental environmental effects. It degrades soil fertility and reduces crop yield [1], mainly due to degraded C-organic and macronutrient content [2]. Previous studies have shown that the C-

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organic content in rice fields is categorised as low (<2%) and very low (<1%) [2–4], whereas in fact, C-organic >2.5% is needed to obtain optimal yield. This condition strongly suggests that rice fields need additional organic materials. On the other hand, as a country with a tropical wet climate, Indonesia has a very abundant source of organic materials that can be used to fertilise and support sustainable agricultural land. These organic materials can be livestock waste, agricultural waste, urban waste, and so on. However, these materials have not been utilised optimally.

Biochar has been used to improve energy, environment, and agriculture sustainability. In agriculture, biochar is globally recognised as a way to enhance soil fertility and reduce the impact of climate change through soil amendment. It has great potential to improve soil properties and promote eco-friendly agriculture residue management [6–10]. Using biochar is a prospective agricultural waste management effort to encourage optimising degraded and suboptimal rice fields.

Indonesia has abundant biomass that could serve as feedstocks of biochar in the form of agricultural waste. It is estimated that approximately 10.7 million tons of this feedstock are available each year [11]. Rice straw and husk (hull) are common crop residues and biomass feedstocks. They are composed of lignocellulosic biomass, are renewable and carbon neutral, and can be recycled into different environmentally friendly and value-added products, such as adsorbents, bioenergy, and soil amendments [12]. Their utilisation of biochar, which serves as a soil amendment, provides a closed-loop circular economy when used in rice fields.

Despite their abundant availability, this rice biomass has not been utilised optimally. In 2015, Indonesia had 8.09 million hectares of rice fields dedicated to rice cultivation [13]. Irrigated rice fields accounted for 4.75 million hectares (58.75%), while non-irrigated rice fields covered 3.34 million hectares (41.25%). The rice harvest area will reach 10.45 million hectares in 2022, with a 5.24 tons per hectare yield producing 54.75 million tons of dry unhusked grain (GKG) [14]. The large amount of rice production generates a significant quantity of rice husk and straw as primary residues or byproducts [12,15,16], which needs proper management.

Among the valorisation options for rice biomass, such as biochar production, energy generation, composting, and other activities, biochar production is the optimal valorisation strategy for managing rice biomass [17]. Recycling rice husk and straw as soil amendments in rice fields is an effective rice waste management method [18]. Until now, no study has assessed the potential use of rice husk and straw for biochar and its potential application in rice farming in Indonesia. Understanding the potential utilisation of biochar from rice biomass to increase rice yield is important, especially with the threat of rice field conversion and the demand for increased production due to population growth. Converting rice biomass to biochar and developing rice biomass biochar-based farming can solve rice production and residue management issues. Furthermore, it has the potential to support food security.

This paper aims to assess the potential of utilising rice biomass for biochar to support the sustainable development of rice farming in Indonesia. The results of the study are expected to provide valuable insights to the government to support rice biomass biochar utilisation for sustainable agriculture and promote a circular economy while also mitigating the impact of climate change.

2 Methodology

A literature review method was applied in this paper. This technique gathers, distils, and evaluates expert opinions presented in the text [19]. Four steps were conducted in the literature review, i.e., (1) choosing the topic to be reviewed, (2) tracking and selecting relevant articles, (3) conducting literature analysis and synthesis, and (4) organising the writing of the review [20]. A synthesis matrix was used to organise sources and create a

cohesive interpretation for literature analysis and synthesis. The review was organised into three parts: an introduction, the main body, and conclusions.

This study explored relevant papers published in journals, proceedings, books, and theses within the last ten years to assess the potential of biochar generated from rice biomass and the impacts of its application, primarily on land quality, crop yield, and sustainability. In addition, this study relied heavily on the data from BPS-Statistics Indonesia on rice harvest area, productivity, and production to estimate the potential of rice biomass that can be utilised for biochar.

3 Results and discussion

3.1 Rice biomass potential in Indonesia

According to BPS-Statistics Indonesia [14,21], the average rice harvest area in 2018–2022 was 10.72 million hectares, with a productivity of 5.18 tons per hectare. This produced 54.52 million tons of dry unhusked grain.

The mature rice grain is harvested as rough rice or paddy rice, with a tough siliceous husk enclosing the brown rice. Rice straw is generated when the rice grain is harvested, leaving stem and leaf as residues. Meanwhile, rice husk is produced during the initial stage of rice milling, when the rice grain is husked. The weight of husks is approximately 20% of the weight of rough rice, ranging from 16% to 28% [22]. Based on data from BPS-Statistics Indonesia, on average, 1.04 tons per hectare or approximately 11.10 million tons of rice husk are produced annually with this assumption. Meanwhile, if the weight ratio of dry rice straw to rice grain is 1.5 [18,23], the national dry rice straw production would be 7.77 tons per hectare or approximately 83.29 million tons annually. Hence, the total amount of these residues generated during rice production would be 8.81 tons per hectare or approximately 94.39 million tons annually in Indonesia. These figures show that rice biomass is an abundant renewable resource for producing biochar and other value-added products.

Rice straw and husks contain cellulose, hemicellulose, lignin, silica, and minor components [16]. The proximate and ultimate compositions of rice husk and straw are similar, with only slight differences in their ash, nitrogen, and sulphur contents. Rice husk has a slightly higher ash content than rice straw, by approximately 3% on a dry basis [12]. This indicates that rice straw is slightly more combustible than rice husk.

Rice straw in Indonesia has not been optimally utilised as raw materials or substitutes in producing goods [24]. According to Santoso [25], 31% of this biomass is usually used as animal feed, 7% is used for industrial purposes, and the remaining 62% is burned in rice fields. Burning rice straw is cheaper and easier for farmers to manage rice waste. However, it causes air pollution, increased greenhouse gas emissions, and nutrient loss. Hence, environmental contamination is made worse by the conventional practice of direct burning. Rice husk also experiences a similar case, but its potential uses are more diverse [16]. Biochar production from crop residue has economic, environmental, and sustainability advantages [26], decreasing greenhouse gas emissions from agricultural soils [27].

The biochar yielded from rice husk is approximately 35% of its feedstock material [15,28]. Therefore, the amount of rice husk biochar that could be produced annually in Indonesia is 3.89 million tons. Using the same conversion rate, the amount of rice straw biochar that could be produced is 29.15 million tons. The total potential biochar produced from rice husk and rice straw in Indonesia is approximately 33.04 million tons annually. These figures show the enormous potential of biochar that can be made from rice straw and rice husk to be applied to rice fields, both irrigated and non-irrigated.

3.2 Impacts of biochar on land quality, crop productivity, and sustainability

Biochar is a substance created through gasification or pyrolysis of organic materials at 300–600 °C while excluding oxygen [29–33]. It differs from charcoal because it is specifically used as a soil amendment [34]. Rice husk biochar contains 50% cellulose, 25–30% lignin, 15–20% silica, and 10–15% moisture [35]. The quality of biochar produced highly depends on the type of feedstock material, pyrolysis device, pyrolysis temperature, and pyrolysis duration [11].

Biochar application in rice fields can improve soil physicochemical and biological properties [36]. It can improve soil chemical properties (total N, soil organic carbon, cation exchange capacity (CEC), pH, available P, and exchangeable Al) and soil physical properties (water holding capacity, porosity, and bulk density) [11,37,38]. Additionally, biochar enhances the functional activity of soil microorganisms, increases biodiversity, and positively alters the community structure, improving soil biological properties [38,39]. Numerous studies have demonstrated that biochar improves soil quality by increasing microbial biomass, altering community composition, and enhancing diversity [40].

The improvement in soil physical and chemical properties impacted nutrient and water availability through nutrient and water retention. Thus, adding biochar improves land quality, allowing for higher crop productivity [15,35]. Biochar application can improve soil fertility by providing carbon-rich material from organic feedstock pyrolysed in anaerobic conditions [34]. It increases pH and CEC, leading to improvements in soil quality and phosphorus availability [41]. Rice husk biochar can improve fertiliser effectiveness because of its nutrient retention capacity and high silica content [15]. Rice straw biochar is an alkaline soil amendment that neutralises acidity in waterlogged rice fields [42] and retains C in acidic soils [43].

Using biochar to increase soil composition, texture, productivity, and nutrient sorption directly increases crop yields [44]. This method can benefit farmers by increasing their income and contributing to food security. Although biochar has benefits as a nutrient source for crops, it alone cannot meet all plant nutrient demands due to its low nutrient content [9,10]. It requires additional enrichment and modification to be effective in agriculture. It can also be combined with other management practices, particularly those that can improve grain weight and harvest index in rice production [45]. The addition of rice straw biochar (2.25 t/ha) to fertilisation practice treatments conducted by farmers (180.0 kg N/ha, 67.5 kg P₂O₅/ha, and 67.5 kg K₂O/ha) significantly improved rice yield [42]. This was primarily due to improvements in grains per panicle. The increase in production yield reached 33% compared to the treatment without added biochar. Singh et al. [35] showed that applying commercialised biofertiliser mixed with 10 t/ha of rice husk biochar increased the length of panicles, number of tillers, rice grain yield, and straw yield. However, applying 0.5 t/ha rice husk biochar with a recommended dose of fertilisers (RDF) had already impacted an increase in rice yield. Meanwhile, Sandhya et al. [46] suggested that applying 2 to 8 t/ha rice husk biochar was enough to promote wetland rice yield.

Biochar needs to be combined with other organic materials, such as compost, manure, and liquid organic fertiliser (POC), to increase macronutrients while maintaining the sustainability of agricultural land [47]. Rice husk biochar has been discovered to enhance nutrient retention not only in soil but also in compost. The addition of rice husk biochar to composted poultry manure results in an increase in nutrient content [48]. This is because rice husk biochar can delay poultry manure decomposition, thereby retaining nutrients for extended periods. Hadiawati et al. [49] revealed that adding 5 t/ha of cattle manure-biochar combination increased lowland rainfed rice yield by 11.55%. This increase was higher than the yield increase obtained from applying 5 t/ha of cattle manure alone (5.34%). With 200 kg/ha urea and 100 kg/ha NPK-Phonska, the control yield was 5.80 t/ha. Duarte et al. [50] suggested that incorporating biochar-compost or biochar with other organic matter into the

soil was considered a promising approach to support sustainable plant growth and sustainability of a farm.

Yang et al. [51] showed that applying rice straw biochar could increase rice yields by 16.7% and 24.3% by adding 20 t/ha and 40 t/ha rice straw biochar with controlled irrigation, respectively (average of two seasons). Combining biochar with controlled irrigation could be a suitable alternative for reducing greenhouse gas emissions while increasing soil fertility, irrigation water productivity, and rice yield. This combination can enable the sustainable utilisation of rice fields' soil and water resources.

Some studies on the long-term effects of biochar application on rice yield have suggested that the positive impact of applying biochar on rice yield and yield attributes depends on the application's duration and continuity [45,52,53]. Using 20 t/ha biochar combined with three doses of N fertiliser (0, 90, and 150 kg/ha) may negatively impact grain yield during the first three seasons. However, after 4–6 seasons of application, grain yield increased by 4–10% due to an increase in panicle size, number of panicles, or both [45]. Another study [52] showed that applying 10 t/ha rice husk biochar combined with RDF resulted in 21.9% and 20.0% higher rice grain yield over the control in the dry and wet seasons, respectively, after eight crop cycles.

Nan et al. [53] studied the impact of different biochar application methods on rice yields. They found that annual low-dose application (2.8 t/ha) impacted a higher rice yield increase (10.9%) than the high single dose (22.5 t/ha; 4.2%). The study investigated the impact of biochar application after eight crop cycles.

In summary, those studies worked on biochar application in rice fields, ranging from 2 to 40 t/ha, either with other nutrient sources (RDF [chemical and/or organic]) or not, with different biochar qualities, doses and frequencies of biochar application, rice varieties, application durations, soil types, and irrigation methods. They reported different rice yield increases, ranging from 4 to 33%. Furthermore, applying biochar with organic fertiliser gives a higher rice yield than chemical fertiliser alone.

Using a minimum of 2 t/ha rice biomass biochar combined with RDF can potentially increase rice yield in approximately 16.50 million hectares of rice fields. Taking a minimum 4% increase and using the average harvest area data from BPS-Statistics Indonesia in 2018–2022 (10.72 million hectares), the potential increase in rice production is at least 2.22 million tons annually. Assuming that only 50% of rice biomass is converted into biochar, it can still be sufficient to apply to approximately 8.25 million hectares of rice fields annually.

In addition to improving rice yield, biochar use promotes environmental sustainability. Long-term biochar application in rice fields of 20 t/ha combined with N (72 kg/ha), P₂O₅ (135 kg/ha), and K₂O (72 kg/ha) significantly reduced greenhouse gas emissions to 36.24% [38]. Likewise, a previous study in a short-term cycle found that biochar amendment in the first season lessened N₂O emissions and did not significantly reduce methane emissions. However, the application significantly decreased greenhouse gas emissions in the second season. On the other hand, the single amendment of biochar had a slightly temporary benefit, inclining N₂O emission only in the first and second seasons of fertile paddy soil [27]. In another study on upland rice, biochar could counterbalance the more efficient usage of N dose, leading to emission reduction [54]. Therefore, biochar application must concern the nutrient balance needed for rice farming.

Further studies are needed to determine the optimal amount of rice biomass biochar application to rice fields. Likewise, the long-term impacts of biochar on soil quality and crop productivity, as well as environmental aspects, may require ongoing research and monitoring. However, it can be summarised that when used appropriately and in conjunction with good agricultural practices, biochar can potentially improve land quality, crop productivity, and sustainability in agriculture.

3.3 Development of biochar-based rice farming in Indonesia

In developing biochar-based rice farming, it is proposed that the biomass used for feedstock material is rice husk and rice straw, creating a closed-loop circular economy when applied to rice fields. The government needs to facilitate the construction of rice husk and straw biochar processing units in rice-producing centres using appropriate technology with a proper business scale. For this reason, it is necessary to conduct studies on the proper scale of the biochar processing unit based on field conditions and appropriate technology for biochar processing (e.g., pyrolysis temperature and biochar particle size) to produce good and standardised quality rice biomass biochar. The scale of processing units should meet economies of scale and require collective action from farmers. Thus, a solid farmer organisation is needed.

Considering that the application of biochar is less effective if used solely, it needs to be combined with other nutrient sources, i.e., chemical and/or organic fertiliser. Organic fertiliser is important to support sustainable agriculture. Thus, the development of biochar would be more advantageous if it is supported by the development of compost from livestock manure. To support integrated rice-livestock farming, farmers and farmer groups/unions need to be given access to livestock ownership through credit or other schemes, as well as organic fertiliser processing units (UPPOs). Farmers can obtain livestock manure from beef cattle or dairy farming centres if integrated rice-livestock farming cannot be conducted at these locations. In dairy farming centres in West Java, for example, livestock manure is generally underutilised, and some is discharged into the surroundings, causing environmental pollution [55,56]. The development of biochar-based rice farming offers a valuable tool for enhancing organic rice farming practices.

The dose of biochar used depends on the type of biochar raw material used, pyrolysis temperature, biochar particle size, soil type, and plant type. Therefore, it is necessary to study the optimal dose of rice husk and straw biochar in rice farming according to specific conditions in certain locations.

However, transitioning to biochar-based rice farming faces several hurdles. Farmers may find producing and applying biochar in rice fields challenging. This is mainly due to the bulky nature of biochar and the fact that a much higher dose is recommended than chemical fertilizers. Previous studies demonstrated that some farmers perceive organic farming, as more labour-intensive and time-consuming, leading to reluctance [57,58]. In addition, they may face resource limitations, including biochar and labour, and perceived risks associated with adopting a new method. Therefore, developing appropriate technology for applying biochar in rice fields is crucial.

For the success of biochar-based rice farming development, socialisation, training, and assistance of farmers/farmer groups should be carried out in processing rice biomass into biochar and its application in rice fields. Developing technical guidelines on good agricultural practices of biochar-based rice farming is necessary as guidance for extension workers, farmers, and other practitioners. It is recommended that participatory extension activities be utilised to improve the technology adoption processes of rice farmers. These activities should be provided in a series rather than one-time events, allowing farmers to accumulate knowledge over time at a pace and style matching their skills and education level [59]. Continuous monitoring and evaluation are also important to ensure its success and sustainability.

Furthermore, it is necessary to collaborate, coordinate, and synergise between the central and local governments, research institutions, colleges/universities, extension institutions, farmers/farmer groups/unions, the private sector, and other stakeholders. Each has a specific role in developing sustainable rice biomass biochar rice farming.

4 Conclusions and policy recommendations

Indonesia has abundant rice biomass that has excellent potential to be recycled back to rice fields in the form of biochar. Developing biochar for rice farming can be one solution to sustainably increase agricultural productivity and reduce the negative impacts of climate change. Applying biochar from rice husks and straw can improve nutrient status, microbial biomass, and rice productivity in degraded agricultural land, leading to sustainable rice farming. However, it should be remembered that the use of biochar must be adapted to local conditions and integrated into sustainable agricultural practices.

The government needs to facilitate farmers in rice-producing centres with biochar processing units using appropriate technology on a proper business scale. Integrated livestock-rice farming would be advantageous since livestock waste could be composted and applied to rice fields to add nutrients. Hence, government facilitation in the form of the organic fertiliser processing unit (UPPO) would be an advantage. Further research is needed to produce good and standardised rice biomass biochar and determine its optimal dose for rice farming, considering soil type, irrigation methods, and the combined use of organic and/or chemical fertilisers with biochar.

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