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A synergetic integration of bioenergy and rice production in rice farms

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ABSTRACT

Lack of energy for powering irrigation pumps limits off-season production of rice in Malawi. This paper reviews a 10-year historical rice production data from rice farms in Karonga district in Malawi to assess the impact on rice yields and availability of straws and husks for on-site bioenergy production in small scale gasifiers, to power irrigation pumping during off season over a projected period of 15 years. Annual production of rice straw and husks has been estimated using residues to product ratio while taking into account collectable amounts and allocations to competing uses. The heating values obtained from literature and validated by analytical Gross Calorific Values of straws and husks have been used to estimate the bioenergy potential. Irrigation pump capacity and pumping rate calculated from daily water demand, and carbon emissions savings determined from the differences between emissions generated by fossil diesel and bioenergy powered irrigation have been used for calculating environmental benefits. The sales of excess rice provided estimates for financial gains. In the base year, generation of straws and husks of about 44117 and 6703 t and collectable portions of 40% and 65%, respectively, are estimated, providing a total bioenergy potential of 16.64 GWh. With onsite-generated bioenergy, irrigated land can increase from 2367 to 13362 ha while rice and bioenergy production increases from 34703 to 59970 t and 15.34–87.72 GWh, respectively, by the 10th cycle. Cumulative revenue of US $354.60 million from sales of excess rice and net carbon emissions saving of 285.33 kilotonnes can be achieved by using electricity generated for irrigation pumping. Investment costs in electricity generation can breakeven by 8th year if sold at US0.166/kWh. Therefore, on-site generated bioenergy targeting irrigation pumping for off-season rice production is an enabler for promoting positive and sustainable fuel /food nexus in rice farming communities through intensive farming.

1. Introduction

Irrigation pumping is an energy limiting productive unit operation in rice farming in Karonga district in northern Malawi. The lack of energy in the agricultural sector in the district that can be used for irrigation, has confined irrigated rice production to rice schemes with gravity-fed irrigation systems [1–3]. Synergetic integration of bioenergy and rice (food crop) production in rural rice farming communities presents the opportunity to simultaneously meet energy and food demands without requiring extra land resources.

Rice is one of the four main staple food crops grown in Malawi, after maize (corn), cassava and potatoes. Significant quantities of rice straws and husks are produced annually in rice farms and processing mills but they are economically underutilised [4]. The straws and husks can be converted to other forms of energy, besides burning to supply modern forms of energy such as electricity [5–8]. In most rice producing regions, some of the straws and husks are used by the households for cooking and water heating [6,9–13], while large proportions are burnt in open fires in the field as part of land clearing and preparation for next planting season [14] or at the rice processing plants as a means of disposal. Therefore, the energy contained in the straws and husks is wasted when the straws and husks are burnt in the open fires. Bioenergy from the straws and husks could provide potential substitute for fossil fuels that is required to power irrigation pumps and other unit operations in rice production.

Fossil fuels have intensively been used in rice production for powering upstream as well as downstream processes, thus, cultivation, agro processing, packaging and transport to markets [15] but have remained the central component and a limiting factor of agricultural productivity in developing economies. The volatility of the global market of fossil fuels negatively affects the security, availability and reliability of fuel supply in countries like Malawi that largely depend on imported petroleum products. Over dependence on fossil fuels in crop production has resulted in high carbon footprint per unit mass of the crops, variations in costs of crop production overtime and food prices as a result of the frequent variations in fossil fuel prices [16–20].

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On-site production of electricity at the farms that can be supplied to crop production provides potential alternative clean and sustainable source of energy [21], which can be reliable and affordable compared to fossil diesel and electricity from the main grid. In case of rice production, the electricity generated from biomass can contribute to reducing carbon footprint per unit mass of rice and offset the cost of fossil fuels and grid electricity. As a result, holding other factors constant, rice production is likely to increase, thus enhancing food security. The extent to which on-site electricity production can increase rice production, and reduce greenhouse gas emissions overtime and the cost implications on the associated unit operations and the economics of the farming, has not been assessed.

The rice straws and husks that are left at the farming site and rice processing plants, respectively, go through a gradual biodegradation process that releases methane (CH_4) into the atmosphere. Methane is 21 times more potent greenhouse gas than carbon dioxide (CO_2) [22]. Therefore, bioenergy production from the straws and husks has the potential to reduce the methane gas emissions besides contributing to a secure energy supply [23].

Previous studies have reported on potential conversion routes that allow production of diverse forms of energy [4,5] or intermediary energy carriers and co products from rice straws and husks. For example, the physical and chemical characteristics of rice straws and husks [7] provide the opportunity to convert them to heat and electricity in a cogeneration mode or only heat or electricity in a single form of energy generation mode [23–27]. Rice straws and husks can be converted to bio char, bio oils and product gas through pyrolysis and gasification [28–30]. The high content of cellulose and hemicelluloses in the rice straws provides opportunity for conversion of rice straws and husks through biochemical processes of hydrolytic to fermentable sugars for production of bioethanol [5,31–34]. The volatile matter and the fixed carbon in rice husks can be converted to biogas in anaerobic digestion [35–37]. The biogas could be used for cooking in gas stoves or for generation of electricity in spark ignition engines coupled to generators [24].

Viable technology configurations for conversion of rice residues to electricity have been reported in Thailand [7,38], Malaysia [14], India [39] and Brazil [40], which include direct combustion (boiler → steam-turbine → generator) and gasification (gasifier → gas turbine → generator or gasifier → internal combustion engine). Electricity generation using downdraft biomass gasifiers, coupled with internal combustion engines, have shown favourable economies of scale of low capital cost per kilowatt-hour, unlike the biomass → boiler → steam turbine → generator configuration [41,42]. The downdraft gasifiers provide producer gas which has relatively low tar content with acceptable quality for use in internal combustion engines (ICE) for generation of electrify [40]. The restriction on scaling up downdraft gasifiers to a maximum plant capacity of 250 kW [41] provides opportunity for deploying small-scale modular systems in the rice farms in rural areas suffering the lack of electricity.

Rural electrification based on agricultural residues is evidently not a new phenomenon [7,27]. However, the implementation strategy of such bioenergy systems is not effective in promoting sustainable integration with food systems. Consequently, rural communities are expected to access the biomass generated electricity through the main electricity grid where they have very little control and participation. Therefore, the system is characterised by several loopholes that leak benefits directed to the communities. Furthermore, the benefits from the conventional rural electrification programmes to the rural communities are improperly accounted for by considering the number of connected communities rather than what the electricity was used for and the actual impact it made on their livelihoods.

This paper is presenting a closed-loop for integrated bioenergy and rice production system promoted by introduction of on-farm self-generated bioenergy for powering irrigation pumping on rice farms during off season. A case study of rice farms in Karonga district in the northern part of Malawi based on a10-year historical rice production data, is used to demonstrate how bioenergy generation (electricity) from rice straw and husks, if targeted to a specific energy limiting productive unit operation in rice production, can be used as an enabler for promoting positive fuel /food nexus. In this approach, the electricity generated from the rice straws and husks using a small-scale downdraft gasifier coupled with internal combustion engine (ICE) rated 250 kW_E, with capacity factor of 0.8, is specifically applied to power water pumps for irrigation of the rice farms during dry season.

The potential of such targeted bioenergy system to promote positive integration with food production with regards to food security, feedstock availability, financial returns and greenhouse gas emissions savings has been assessed. In the base year, the bioenergy generated from the rice straws and husks is initially used to power irrigation pumps to irrigate part of the rice farms during dry season. The increase in rice yields increases the availability of rice straws and husk as bioenergy feedstocks for the subsequent cycle. As the bioenergy production capacity increases, the portion of land that is irrigated during off season increases correspondingly.

The approach is considered holistic and strategic for allowing the rural communities to benefit from direct use of biomass generated electricity where it would make the most positive impact in their livelihood. In addition, the partial implementation of the off season irrigation allows communities to gradually adapt to the increase in rice production which might necessitates increasing capacity of downstream operations. The increase in capacity of the downstream operations can be strengthened by the resilience of the rice straws and husks supply chain overtime. The assessment of the potential for carbon and financial savings and revenue generated from increased rice production, when bioenergy from rice straws and husks is supplied to rice production, is done using fossil diesel and/ or conventional grid electricity as benchmarks.

2. Materials and methods

Data collection involved a field survey undertaken in Malawi with the stakeholders in agriculture (national and division levels), energy and the rural households in rice farms in Karonga district. Data collected using structured and semi structured questionnaires, formal group discussions and from literature captured historical rice production trends in a 10 year period and projected over a 15-year period.

2.1. Assessment of rice straws and husks production

Rice straws and husks produced in rice farms in Karonga district have been obtained from the10-year 2005–2014) historical data on rice production obtained from Ministry of Agriculture in Malawi. The quantities of rice straws and husks generated per annum have been estimated using residues to product ratios reported in literature [43–46]. The annual production of rice straws and husks have been using Eq. (1) reported in [46].

$$R_{CR}=(C\ x\ RPR) \tag{1}$$

where:

R_{CR} is the annual production of crop residues;
C is the annual rice production; and
RPR is the residues to product ratio of rice straws or husks

As a result of unrecorded data on the farms and at the government offices, the proportions of residues collected for competing uses to bioenergy, were estimated through interviews with the stakeholders and experts in the agriculture sector and the rice farmers. Bioenergy potential from the rice straws and husks was estimated using Eq. (2) and the heating value (HV) reported in [33,35,36], which were validated in an experiment using the Standard Test Method for Gross