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Case Study on Carbon Emissions form Irrigation Methods in Bonsucro and Non-Bonsucro Sugarcane Farming Systems

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Abstract

Sugarcane is an important cash crop for Pakistan's economy, which is a sustainable source of rural livelihoods and raw material for various sectors, but its cultivation is at risk due to its high irrigation demand and the environmental impact created by irrigation practices. The extraction of groundwater through tubewell turbines consumes a higher amount of diesel fuel, which ultimately becomes a source of CO_2 emissions, thus threatening the sustainability standards. This study compares two sugarcane farming systems that are sources of carbon footprint: one is Bonsucro (following sustainability standards), and the other is a non-Bonsucro farmer (following conventional standards). Data was collected by questionnaires and field surveys. The number of emissions was calculated based on irrigation sources like canal water, solar system and diesel turbine systems. The findings indicated that Bonsucro-certified farmers not only relied on green energy but also adopted mulching practices and irrigation scheduling, which reduced a significant number of irrigations and emissions as compared to other conventional farmers. When only tubewell turbines were used, Bonsucro irrigation practices caused a reduction of 15%. However, the integration of solar solar-powered system further improved it up to 18%. This comparative analysis presents the significance of sustainable irrigation sources in sugarcane farming, which lowered the carbon footprint and supported climate-resilient agriculture.

Keywords: Bonsucro, sustainable development, renewable energy, carbon footprint.

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Introduction

Sugarcane is grown in more than 120 countries of the world (Kumar et al., 2018) and 2nd most important crop of Pakistan contributing 0.6% in GDP. The country's sugarcane production is an impressive 70.35 tons per hectare, yielding a crop of 88,615,674 tons (PSMA, 2022). This important crop plays multiple roles in Pakistani agriculture being an important raw material for sugar and sweeteners, providing employment and other benefits to about 09 million farmers, such as green top used as feed and mill by-products in the chipboard and paper industries (Afghan et al., 2023). It has gained the favor of farmers due to the prices set by the government, especially considering falling prices of other agricultural commodities. Pakistan agriculture, domestic and industrial sector majorly depends upon groundwater use therefore it holds as a source of strategic importance. Indus basin where irrigated agriculture faces challenges due to high temperature and salinity ground water has emerged as a water resource of exceptional importance in Pakistan (Bhutta and Smedema, 2007). The world's energy consumption has been increasing due to several factors, especially that of an increase in global population reported at the rate of 1.14% per year (Powell and Arts, 2001). The latest technology has become more reachable due to which more people have installed pumping station, unsystematic water source utilization contributes little to biomass production but results in increased evaporation into the atmosphere and percolation back into the aquifer (Karimi et al., 2012). Groundwater irrigation requires pumps which consume fuel or electricity thus using fossil fuels which are the primary contributor of carbon emissions into the atmosphere (Shah et al., 2003). Pakistan is 3rd largest user of ground water globally with 1.4 million tube wells extracting 60% of groundwater. Five major crops of wheat, cotton, sugarcane, rice, and maize consume 85% of total water but, contribute less than 5% in GDP **(Hasan and Fatima, 2025).** Major cash crop requires additional water which cannot only be filled with canal or solar water. Thus, it needed to use groundwater to meet the requirement. The average cost of irrigating land with groundwater cost 30 times higher than that of surface irrigation (Qureshi et al., 2010). Today, natural resources are being depleted at a very fast pace; to conserve this resource the world is moving toward sustainability. Sustainable agriculture comprises management procedures that work with natural processes to conserve all resources, minimize waste and environmental impact, prevent problems and promote agroecosystem resilience, self-regulation, evolution and sustained production for the nourishment and fulfillment of all (Hassan et al., 2022), A standard was needed for sustainable sugarcane production keeping in view a nonprofit organization named Bonsucro which specifically focused on sustainable production of sugar and ethanol from sugarcane was introduced (Rein, 2012). Following Bonsucro standards of sustainable sugarcane production, a certified farmer keeps in mind triple bottom line and plan accordingly and keep himself adherent to Bonsucro protocols. The present study offers a comparative assessment of irrigation practices that are associated with carbon emissions in two types of farmers: one who sticks to sustainable ethical considerations and another with conventional practices in a sugarcane farming scenario. The focus is the emission comparison, which is caused by water extracted from the ground by using diesel turbines, contributing 73%,

which is a fairly common practice among farmers from shallow groundwater (Siyal and Gerbens-Leenes, 2022). In comparison with Bonsucro farmers, who are increasingly adapting irrigation sources like canal water and solar-powered systems, which reduce energy consumption as well as emissions reduction up to 0.02 tons/ha (Hussan et al., 2023). The study was designed to fill the gap in local context by giving empirical data on sustainable irrigation strategies. Ultimately the study gives the practical implications to guide the transition toward low-emission and sustainable agriculture practices.

Groundwater Irrigation and CO_2 Emissions

Groundwater has a legacy in the irrigated agriculture system of Punjab. Before the 1960s, traditional methods such as ropes, buckets, and hand pumps were used, but after the 1960 transformation occurred with the initiation of salinity control and reclamation projects (SCARPs), which aimed to extract groundwater by using tube wells (Bhutta and Smedema, 2007). An essential feature of agriculture is groundwater irrigation, especially in areas with harsh climates with high temperatures and salt-affected soil. However, carbon dioxide emissions have a major negative influence on the environment. Diesel-powered pumps, which are used in many groundwater extraction systems, emit carbon dioxide into the atmosphere. About 2.7 kg of carbon may be released for every liter of diesel oil consumed in these pumps (Kainou, 2014). It is impossible to ignore the part that groundwater irrigation plays in adding to carbon emissions as the world's concern about rising greenhouse gas concentrations in the atmosphere grows. There is a dire need to investigate alternate irrigation techniques and energy sources in agriculture to address sustainability and lessen the negative environmental effects of rising emissions. More than 20,000 wells have been installed as part of SCARPs and drainage projects covering 0.22 million hectares of tile-drained land (Aslam et al., 2006). The total dynamic head based on water lift, pipe friction, system pressure, water flow rate, and pumping system efficiency all determines how much energy is needed to pump water (Whiffen, 1991). Increasing groundwater extraction will directly increase carbon emissions, as diesel oil releases 2.7 kg of CO_2 in one liter (Mickūnaitis et al., 2007). Rising atmospheric and greenhouse gas concentrations in the atmosphere are the cause of global warming. According to an estimate, increased fuel consumption, deforestation, and industrial activities projected a 30% increase in CO_2 concentration since the 18th century (Zhao and Li, 2015).

Environmental Impact Assessment

The Environmental Impact Assessment (EIA) is a systematic, comprehensive process aimed at

evaluating, realizing, and minimizing adverse impacts that result from actions carried out in an environment. In this case, actions are different irrigation techniques that are adopted by different farmers in sugarcane farming. The overall purpose of an EIA is to provide the policymakers as well as sugarcane farmers with information on the effects of these practices on the environment. Regarding the evaluation of the energy requirement for various irrigation systems. EIA has focused seriously on the diversification of reliance on fossil energy and the transition to renewable energy sources (Pandey et al., 2020). It assesses efficiency and compares different irrigation methods as well as provides outcomes of using limited water supplies in irrigation (Abid et al., 2021). The

EIA carefully tracks greenhouse emissions from the assumed irrigation activities like carbon monoxide and methane. It also discusses how these emissions can be reduced or offset (Lefebvre et al., 2020). Using the EIA framework, there are measures that are established on the impact of irrigation practices on the environment. Therefore, soil health is determined in terms of the effects that different methods of irrigation have caused on certain attributes such as salinity, conservation of biodiversity, and nutrient status (Heynen, 2021). Getting an understanding of the three main components of sustainability, EIA must be a strategic tool for the sustainable development of sugarcane farming; this is not an obligatory legal requirement. It is also important to assist farmers to make better sustainable choices. Environmental impact assessment basically entails making assessments regarding impacts that are least for implementation in the improvement of irrigation techniques. Since EIAs provide information on environmental impacts of various practices that may be associated with the adoption of fiscal incentives in future government policies on irrigation, then government incentives and policies conducive to encouraging the adoption of environmentally friendly systems of irrigation cannot be dismissed. Thus, it helps to have a more environmentally friendly and sustainable sugarcane industry as decision-makers make informed decisions (Rivera, 2022).

Technology and Innovation in Sustainable Irrigation

Technology and innovation are crucial for sustainable sugarcane farming, especially in the field of irrigation. Precision irrigation systems, also known as drip irrigation, are one of the revolutionary technologies in sustainable irrigation. Such systems accurately apply the right amount of water at the right time and the right place with the aid of working with live data from meteorological predictions, moisture sensors, and crop growth models (Bolten et al., 2009). In addition to maximizing water use, this also lowers energy consumption because pumps and irrigation systems run more effectively (Tarjuelo et al., 2015). Thus, precision irrigation systems play a vital role in minimizing the carbon footprint in the farming of sugarcane crops. There is, however, another factor that is enhancing the effective farming of sugarcane; this is automation. Other types of irrigation can be controlled according to the current conditions to adjust the quantity of water applied, for example, the type of soil and climatic conditions obtainable by the crop plants (Gutiérrez et al., 2013). These systems can result in significant water and energy savings by minimizing human error and making sure water is only used, when necessary, thereby lowering the carbon footprint (Omer, 2008). However, data drives decision making in irrigation system requires training, integrated management systems specially in the context of site specific variable rate irrigation (Evans et al., 2013). This ensures water safety. Management of irrigation systems has the potential to reduce emissions and save a lot of energy (Koech and Langat, 2018). Drones equipped with sensors and remote sensing technologies have revolutionised sugarcane farming (Som-Ard et al., 2021). They can provide information about moisture level, crop health and other crucial parameters in high-resolution images and data (Sankaran et al., 2015). Farmers can make the right decisions on matters related to irrigation to be efficient and to minimize the negative impacts on the environment. Renewable energy resources such as solar and wind energy in

the operation are an important innovation for utilization in irrigation processes. By this way greenhouse gases emissions can be reduced (Chel and Kaushik, 2011). The technological advancements in big data analytics and IoT are useful in processing, harvesting, and analyzing big data on sugarcane farming and irrigation (Gopikrishnan et al., 2022). Farmers will be able to see a global picture of irrigation, the condition of the soil, as well as the performance of crops if they resort to the use of IoT devices and big data (Ayaz et al., 2019). Irrigation that follows this knowledge would therefore be more precise and friendly to the environment. With the help of innovation and technology, there is a new way of efficient irrigation in sugarcane farming. These have the impact of reducing energy and water consumption and carbon emissions and improving resource utilization. This will give both the Bonsucro and the non-Bonsucro sugarcane farmers a chance to improve the industry and make it more environmentally and economically friendly.

Sustainable Agriculture and Bonsucro Standards

Resource conservation methods, when combined with modern technology, can reduce farmers' dependency on hazardous methods to increase yield, which can be beneficial both environmentally and financially, and can increase yield up to 79%. (Reganold et al., 1990; Pretty et al., 2006). The first principle is environmental stewardship, which emphasizes conservation and enhancement of natural resources while limiting pollution and waste. Soil health should be maintained by using sustainable practices such as crop rotation, cover cropping, and reduced tillage. Efficient water uses and conservation is another pivotal principle, which involves drip irrigation, rainwater harvesting, and proper drainage to optimize water utilization. Biodiversity and ecosystems help in the preservation of natural habitats. Crop diversity and integrated pest management are strategies that are used to reduce dependencies on harmful chemicals (Villalobos and Fereres, 2016). Bonsucro offers two types of certifications, focusing on different aspects of the supply chain, one on the production end and the other on the trading end. This certification ensures sustainable production of sugarcane. The implementation of the Bonsucro environmental standard would result in a reduction of sugarcane production area by 24%, water use for irrigation by up to 65%, and greenhouse gas emissions by up to 51% (Nicolas Viart, 2008; Smith et al., 2019). Economic, social, and environmental considerations are all included in the triple bottom line strategy adopted by certified farmers who follow Bonsucro guidelines. Economically, they boost productivity, make use of cutting-edge technologies, and optimize resource consumption, resulting in increased profitability and long-term stability. For a resilient agricultural future, this all-encompassing approach assures a sustainable balance between economic success, social justice, and environmental well-being.

Groundwater Utilization in Sugarcane Farming

Groundwater plays a crucial role in sustainable agriculture (Gleeson et al., 2020). Water tables are viewed as potential water source for crops. Reduced irrigation lowers the risk of water logging conditions. Despite this, freshwater table can be beneficial for crop water requirements. Grimes et al. (1984) advocated the use of plant-based water measurements to adjust scheduling in areas where shallow water tables occur. Pakistan stands third-largest consumer of groundwater globally

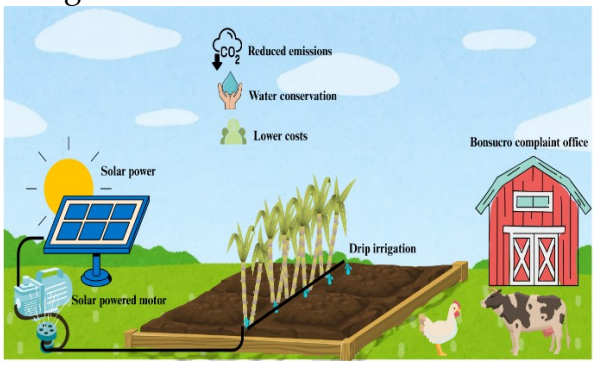
(Giordano, 2009). Water requirements for sugarcane are based on multiple factors, which include climate, soil structure, agricultural practices, and variety of sugarcane (Luo et al., 2016). In sugarcane growing regions shallow water tables are common features. Using groundwater in sugarcane farming has been crucial to supplying the crops' high-water requirements, especially in areas like Punjab and Sindh, where the climate is suitable for sugarcane production. Irrigation was formerly accomplished using conventional, less energy-intensive techniques, including ropes, buckets, and manual pumps, before the 1960s. But the sector saw a radical shift when initiatives like the Salinity Control and Reclamation Projects (SCARPs) were launched. The use of tube wells to draw groundwater became commonplace, greatly increasing agricultural output. However, because groundwater extraction commonly uses diesel-powered pumps, which increase carbon emissions, this shift has an impact on the environment. Concerns about climate change and sustainability are becoming more widespread; thus, it's imperative to look at a more environmentally friendly system. The reliance on groundwater is increasing because of stress factors such as drought prevalence also can cause an increase in irrigation costs ranging from 1.51 to 9.28 USD per hectare in groundwater-dependent irrigation regions (Feinerman and Knapp, 1983; Pretty et al., 2006). As population increases, demand for food is also increasing, which demands more utilization of water to grow food (Fukase and Martin, 2020). Groundwater provides a reliable source to bridge the gap between water demand and supply. Government policies have also played a role in excessive pumping of groundwater by subsidizing electricity and providing incentives for the installation of tube wells (Qureshi et al., 2010). Long-term sustainability can be ensured by implementing strict regulations on groundwater extraction and promoting sustainable groundwater recharge.

Alternative Irrigation Sources and Solutions

The annual food security of the country depends upon agricultural production, so it is important to increase production by adopting innovative technologies. Innovation in technology and methods is essential to increasing agricultural output and guaranteeing food security. The globe is embracing renewable energy sources, with solar energy leading the way, as a response to the urgent need for a sustainable and environmentally responsible strategy. Farm equipment and production facilities are always being improved in agriculture with the goal of lessening their impact on the environment and raising overall productivity. However, there is an increase in concern about environmental impacts due to the increased use of fossil fuels, which cause a lot of emissions. As a result, the world is moving to renewable resources of energy such as solar energy, which is causing agriculture farm machinery and production facilities to constantly improve (Choudhary and Singh, 2020). Numerous literature studies have emphasized the significance of integrating agriculture and renewable energy sources. They have been discussing various solar energy uses for drying crops and irrigation water pumps (Aroonsrimorakot et al., 2020; Choudhary and Singh, 2020). Groundwater irrigation, which is excessively dependent on fossil fuel engines, poses a major risk to the environment because of its high carbon emissions (Friedlingstein et al., 2010). These alternative irrigation solutions such as solar powered turbines should be looked

for reducing environmental harm and promoting agricultural sustainability. Water efficiency is also enhanced when groundwater pump connected to drip irrigation. It helped to reduce water losses, emission rates and boost yield making the environment clean and economically viable for sugarcane production as shown in figure 1. The reduction in emissions can be ensured by adopting the green energy sources that are available for free like windmills, solar panels, and canal water. Transitioning from burning fossil fuels to clean and green renewable energy sources forms an effective strategy for reducing carbon emissions and fostering an eco-friendlier and more sustainable agricultural sector (Parida et al., 2011).

Figure 1: Solor powered motors being used in sugarcane fields for sustainable farming. The image was created using BioRender.



Case Study: Bonsucro vs. Non-Bonsucro Farmers

The groundwork for this case study was an irrigation approach used by two different farmers, one representing a unique method of sugarcane farming while adhering to sustainable standards and the other following conventional farming methods. Within the main group there are two types of subgroups, one that totally relies on diesel running turbines and other integration of solar plus diesel turbines. The main difference that standout Bonsucro farmers and others was the number of irrigations. With the help of soil sensors, he set the irrigation schedule and watered the crop when needed, which was according to the standard of sustainability. The sustainable farmers who followed Bonsucro criteria were the first group to stand out as models of ecologically responsible farming methods. Their selection of irrigation techniques demonstrated their dedication to sustainability. They reduced their carbon impact and preserved this valuable resource by using canal water. This decision is especially important in areas like Punjab and Sindh, where the overuse of groundwater resources results in higher carbon emissions from the consumption of fossil fuel-powered pumps. Investigation was started by visiting sugarcane farmers in the field and gathering information from a variety of farmers using questionnaires. The main goal was to compare two different farming groups to assess the carbon emissions resulting from different farming practices. The study's conclusions highlight the striking variations in how each affects the environment.

Table 1. Comparison of emissions method between two farming systems.

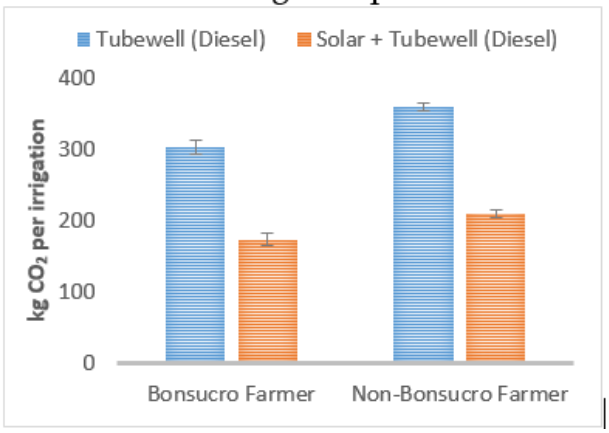
Aspects	Bonsucro Farming	Non-Bonsucro Farming
Irrigation source	Solar powered plus diesel powered tubewell, high efficiency electric monitoring systems	Diesel powered, low efficiency systems
Water use efficiency	Improved irrigation efficiency by reducing number of irrigations	High water consumption. no irrigation scheduling
Fertilizer use	Better nutrient management up to 11% reduced use	Injustice use of fertilizers enhancing N2O emissions

Emissions per hectare	Decrease emissions ranged ~15.7% to 17.5%	Low efficiency practices causing higher emission rate
Carbon footprint	Lowers footprint	Higher due to intensive practices
Yield	Increase in yield with low emission rates and better water mangemnet.	Yield increases with higher emission rates.

Farmers that are adhering to Bonsucro guidelines became leaders in sustainable farming. Their commitment to environmentally responsible practices by using canal water for irrigation is a well-known technique for using water resources sustainably and efficiently. Mulching practices are another sustainable source for lowering carbon emissions while also improve soil health (Hayat et al., 2024). Bonsucro protocols helped farmers to use canal water for irrigation, ensuring mulching techniques that showcase their commitment to optimize soil health. To reduce emissions count while irrigation they integrated solar energy with conventional diesel use, thus reducing emissions. In contrast, non-Bonsucro farmers mostly use diesel-powered engines without incorporating alternate energy sources, resulting in higher expenses. These findings highlight the considerable impact of sustainable practices, especially with Bonsucro standards for reducing carbon footprint and encouraging more sustainable farming methodologies within the sugarcane industry.

The Figure 2, bar chart demonstrates the comparison between four farming groups based on their sources they used for irrigation pumping purpose. Within Bonsucro group there are two farmers, one that solely rely on diesel and the other has a hybrid system of solar plus diesel coupled with organized irrigation schedules aligning crop water requirements. On the other hand, non-Bonsucro farming group follow unregulated water practices leading higher emissions. Using kainou. (2014) emissions formula of release of 2.7kg emissions for consumption of every liter of diesel. We calculated emissions by both farming groups during the whole cropping period of sugarcane. Bonsucro standard has high potential in mitigating environmental impacts i.e. global compliance can reduce upto 65% irrigation water use, 51% greenhouse gas emissions and 34% reduction in nutrient loading when compared to conventional methods (Smith et al., 2019).

Figure 2: Comparison of Bonsucro and Non- Bonsucro irrigation practices



Challenges and Barriers

The implementation of sustainable agriculture, especially in sugarcane farming, has several hurdles, like heavy dependence on carbon-based fuels and machinery. One of the most difficult areas that several conventional farmers faced was the lack of awareness and capacity to put in place strict measures for sustainable agriculture. In other ways, Bonsucro benefits its certified farmers to help them understand the steps in the process of cutting emissions and advancing in the field of environmental stewardship. Thus, there remain poorly developed programs for non-certified farmers to facilitate their transition to sustainable agricultural

practices. Extension facilities and outreach programs are usually used to support sustainable farming practices, and donors need to ensure that there is adequate information flow in this regard. But there is always the problem of availability of these commodities and products. The farmers cannot get the information to put into practice the sustainable practices. This is due to a lack of previously developed research works, which results in the fact that farmers do not have the necessary information regarding sustainable practices in the field specific to their regions. Lack of such knowledge may limit their capacity to make proper decisions on sustainable agriculture. Apparently, domestic sugarcane growers deal with a problem of lack of availability of high-recovering, short-duration varieties of crops. This shall help in minimizing the time taken in the process of harvesting while improving efficiency. To achieve this kind of ideal, they found that identifying the right crop varieties is not a very easy task. Farming is gradual and dynamic since it cannot be restrained and must change when a new trend or customer preference surfaces. These requirements involve shifting the practices of farmers, which may at times be very difficult. The other factor that has to do with this is government policies and incentives that could also encourage the adoption of sustainable practices. Some of the issues of concern are emissions from carbon-based fuel produced in tractors and other farming machinery. Such practices have a great impact on carbon footprint and thus have a direct link with sustainable and environmentally friendly farming of sugarcane. To address these challenges effectively, policymakers and stakeholders in the agricultural sector should prioritize the implementation of education and extension programs, foster region-specific research, promote the development of short-term, high-yield crop varieties, and support farmers in diversifying their crops through the provision of seeds and resources. By overcoming these obstacles, farmers can more readily embrace and sustainably integrate innovative agricultural practices, ultimately contributing to a more sustainable and environmentally friendly farming sector.

POLICY IMPLICATIONS FOR LOW-CARBON FARMING

Conclusion

In conclusion, this study highlights the notable differences between sugarcane growers who have obtained Bonsucro certification and those who have not. This research's main finding emphasizes the critical role that sustainable agriculture plays in significantly lowering carbon dioxide emissions and eventually promoting an environmentally friendly and sustainable agricultural industry. Our results clearly highlight the beneficial effects of sustainable irrigation methods, particularly the utilization of solar energy and canal water, in reducing emissions and encouraging environmental responsibility in the agricultural sector. Furthermore, the use of mulching techniques has been shown to be revolutionary, improving soil health and moisture retention while also promoting the sustainability of farming. This study's implications go beyond environmental concerns and have significant commercial potential. Adopting sustainable farming practices not only lowers carbon emissions but also puts farmers in a position to receive financial incentives that can raise their standard of living and contribute to the development of the agricultural industry. Ultimately, this study is a strong call to action for both governments and farmers. It urges the quick adoption of sustainable agricultural

methods since they promise both financial and environmental benefits. The adoption of environmentally aware agricultural practices is not just a choice but a necessary step towards a more sustainable, profitable and environmentally friendly future considering the changing climatic challenges and growing sustainability imperatives.

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Declaration of Competing Interests

The authors declare no conflict of interest.

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Not applicable.

Availability of Data and Material

All data is published in this case study.

Informed Consent

Not applicable.

Consent for Publication

All authors have submitted consent to publish this article in the 'International Journal of Agriculture Innovation and Cutting-Edge Research'.

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