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Energy efficiency and water use indices for sweet potato (*Ipomoea batatas* L.) production under subtropical climatic conditions of Bangladesh

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ABSTRACT

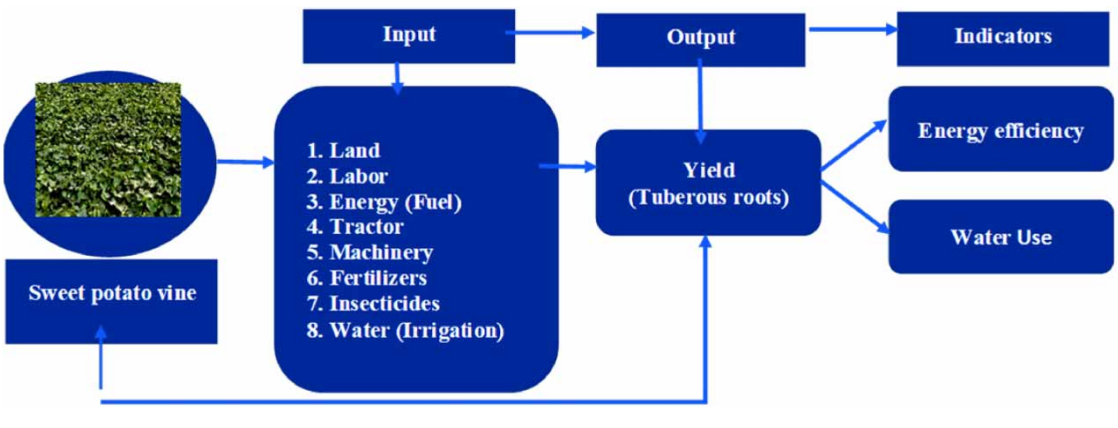
To estimate energy use efficiency for sweet potato production in Bangladesh under subtropical climatic conditions, a study was conducted with 60 individuals (12 producers for each sweet potato variety) by using a structural questionnaire. The results revealed that the majority of the energy input was consumed by the pre-harvest activities (22,313.55 MJ ha^{-1} or 90.85%), of which fertilizer application (36.84%) and irrigation (35.24%) consumed the most energy input, with only 9.15% (2,248.42 MJ ha^{-1}) consumed by the post-harvest activity for sweet potato production. The energy input involved in the production system was similar to the direct (12,149.76 MJ ha^{-1} or 49.47%) and indirect (12,412.21 MJ ha^{-1} or 50.53%) sources, while it was much higher in non-renewable sources (22,884.21 MJ ha^{-1} or 93.17%) with a minimum (1,677.76 MJ ha^{-1} or 6.83%) from renewable sources. The average energy use efficiency, energy productivity, specific energy, net energy, energy profitability and water-energy productivity of orange-fleshed sweet potato (OFSP) varieties 4.36, 1.22 kg MJ^{-1}, 0.83 MJ kg^{-1}, 82,511.73 MJ ha^{-1}, 3.36 and 1.32 g m^{-3} MJ^{-1}, respectively. The OFSP varieties showed better performance in respect of all the energy and water use indicators.

Key words: energy input, energy output, sweet potato, water indicators

HIGHLIGHTS

- Farmers generally grow crops in riverbank areas which need low irrigation; for example, sweet potato.
- The estimation of energy and water use indicators are important for sweet potato, since this crop needs minimal water.
- The study estimated energy and water use indicators for the production of sweet potato.
- The orange-fleshed sweet potatoes showed better performance in respect of energy and water use indicators.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Sweet potato (*Ipomoea batatas* L.) is one of the most important root crops and considered the seventh most important food crop globally and are grown all over the world. Sweet potatoes are now considered a super food as they contain many important vitamins, minerals, fermented sugars (glucose, fructose, sucrose) dietary fiber, a small amount of protein, lipids, antioxidants and other functional components (Ferrari *et al.* 2013; Wang *et al.* 2016). Likewise, sweet potato is an ideal food in terms of energy (Bovell-Benjamin 2007; Rumbaoa *et al.* 2009). Moreover, sweet potato is a dependable source of Vitamin A, Vitamin B, Iron, Copper and Manganese (Szalay 2017). The antioxidants present in sweet potatoes are long-lasting in the human body and can be beneficial in preventing deadly diseases like diabetes and cancer (Islam *et al.* 2002; Rumbaoa *et al.* 2009). In addition to starch, flour, sugar, alcohol and other industrial products, sweet potatoes are currently considered a significant source of feedstock for organic ethanol production (Lee *et al.* 2006; Adenuga 2010). About 12.5% bioethanol is obtained from fresh sweet potatoes (Qiu *et al.* 2010). Like other biofuels, bioethanol produced from sweet potatoes can play an important role as an environmentally friendly source of net energy (Flores *et al.* 2016).

In Bangladesh, sweet potato is grown in the riverbank areas. Currently, about 23,571 tons of sweet potato are being produced from an area of 23,014 hectares of land with an average yield of 10.25 t ha^{-1} (FAOSTAT 2021). Sweet potato cultivable area and total production in Bangladesh are oscillating. The total production of sweet potatoes increased by 3.16% from 2014 to 2016 and the area increased by 1.94% (FAOSTAT 2015, 2017). Conversely, from 2016 to 2019, it decreased the cultivable area by 11% and also reduced production by 10% (BBS 2020). According to the report of FAOSTAT (2021), the total cultivable area of sweet potatoes in Bangladesh has decreased by 26% and production by 23% in the last decade due to the lower availability of the planting materials (vine) at the farm level, high crop competition, less storability, higher production cost and difficult marketing channels.

Children in Bangladesh are at substantial risk for vitamin-A deficiency-induced night blindness (Mahmud *et al.* 2021a, 2021b). To combat the vitamin-A deficiency; the Bangladesh Agricultural Research Institute (BARI) has developed several high-yielding vitamin-A enriched sweet potato varieties that will play a significant role in increasing the sweet potato yield and improving the nutrition of the Bangladeshi people.

Energy is an important component to evaluate and optimize agricultural products (Mohammadi *et al.* 2008; Stolarski *et al.* 2019). In developing countries like Bangladesh, it is necessary to increase agricultural productivity by using limited resources to feed the ever-increasing population. On the other hand, limited arable land has increased the intensive use of energy and natural resources in agriculture (Flores *et al.* 2016).

Often, farmers do not know how to utilize their resources, and due to low cost and availability, they use their resources excessively and inefficiently. So, increasing input power is required to obtain maximum yield but farmers may not get higher profits despite increased input power due to increased production costs (Erdal *et al.* 2007). Effective use of energy in agriculture is one of the conditions for sustainable agricultural production as it helps in financial savings, conservation of fossil fuels, resource conservation and reduction of air pollution (Ozkan *et al.* 2004, 2007; Singh *et al.* 2004), and also prevents the destruction of natural resources and improves sustainable agriculture (Rafiee *et al.* 2010; Zhang *et al.* 2021). Input and output energy are the two crucial factors for energy analysis and environmental efficiency in crop production. Energy analysis is important to ensure efficient and environmentally-friendly production systems (Schroll 1994; Ozkan *et al.* 2004). The key to sustainable energy management is the improvement of energy efficiency. Efforts need to be made to produce and conserve input energy without affecting the output (production) (Singh *et al.* 2004). Several studies have focused on energy use for agricultural production in different crops (Kallivroussis *et al.* 2002; Ozkan *et al.* 2004, 2007, 2011; Canakci *et al.* 2005; Hatirli *et al.* 2005; Sartori *et al.* 2005; Shahin *et al.* 2008; Beheshti Tabar *et al.* 2010; Mobtaker *et al.* 2010; Mousavi-Avval *et al.* 2010; Flores *et al.* 2016; Nabavi-Pelesaraei *et al.* 2016; Tang *et al.* 2022). Therefore, sustainable agriculture requires efficient use of energy to increase production and productivity (Ozkan *et al.* 2004, 2007). Unfortunately, no studies have been conducted on the energy and water use indicators of sweet potato production in Bangladesh. In that case, it is necessary to assess the existing energy to increase energy efficiency in sweet potato production.

Water is an essential element for agricultural production. Globally, agriculture will be the main user of water resources (de Fraiture *et al.* 2007). Hence, ensuring the supply and optimal use of water for agriculture has become a matter of high relevance for stakeholders and scientists worldwide (Prochnow *et al.* 2012). In addition to increasing population growth, climate change poses a threat to long-term environmental and economic sustainability (Koech & Langat 2018). Furthermore, irrigators are under pressure to ensure food security for a growing population. The current challenge is to ensure that agricultural water management is environmentally sustainable to make a reasonable profit and meet the needs of a growing population (Cosgrove & Loucks 2015; Rockström *et al.* 2017). Environmentalists, irrigators and policymakers have different views on what constitutes efficient use of water in agriculture and how to improve it. As a result, confusion arises regarding the interpretation of water use data for crop production (Perry 2011).

Irrigation is another major energy user in agricultural production (Smerdon & Hiler 1985; Khan *et al.* 2009). All other operations in agriculture can be several times more than just irrigation energy. Efficient use of water increases energy requirements in agricultural production. The need for energy in agricultural production increases with the effective use of water. Meanwhile, in developed countries, the conversion rate of energy gained to extracted water is about 20% but in many countries, it is close to 12.5% or less (Aked 2009). Thus, irrigation should be properly planned and managed to conserve both water and energy inputs to achieve sustainable agriculture. As there are no studies on energy efficiency and water use indices for sweet potato production in Bangladesh, consider that this study has been conducted.

2. MATERIALS AND METHODS

2.1. Site description and climatic condition

The energy efficiency and water use indices were estimated from a study which was conducted around Saghata (25.07–25° 10′N and 89.28–89°30′E) of Gaibandha district, Bangladesh (representing AEZ 2: Active Tista Floodplain agro-ecological zone of Bangladesh) (Figure 1). The area of experimentation was under a subtropical climate with a rainfall of 42–53 mm during the crop growing season (November–March). The monthly mean maximum and minimum temperature ranges from 26 to 34 °C and 12 to 18 °C in the respected area. The soil type was gray stratified sand and irregular patterns of silt, from strongly acidic to slightly acidic (pH: 3.8–6.4) with very low to low organic matter content. Zn and B contents with soil fertility levels are very low to moderate. A detailed overview of the site is also available in our previously published papers (Mahmud *et al.* 2021a, 2021b).

2.2. System boundary of sweet potato production

The production system of sweet potatoes at the farmer level is shown in Figure 2. Pre-harvest activities included land preparation, cutting and planting of sweet potato vines into the main field, fertilizer application, irrigation, weeding and earthing up, application of pesticides, etc. On the other hand, post-harvest activities included the removal of sweet potato vines, collection of roots, stacking, cleaning, sorting, bagging and transport from the field to the market for selling.

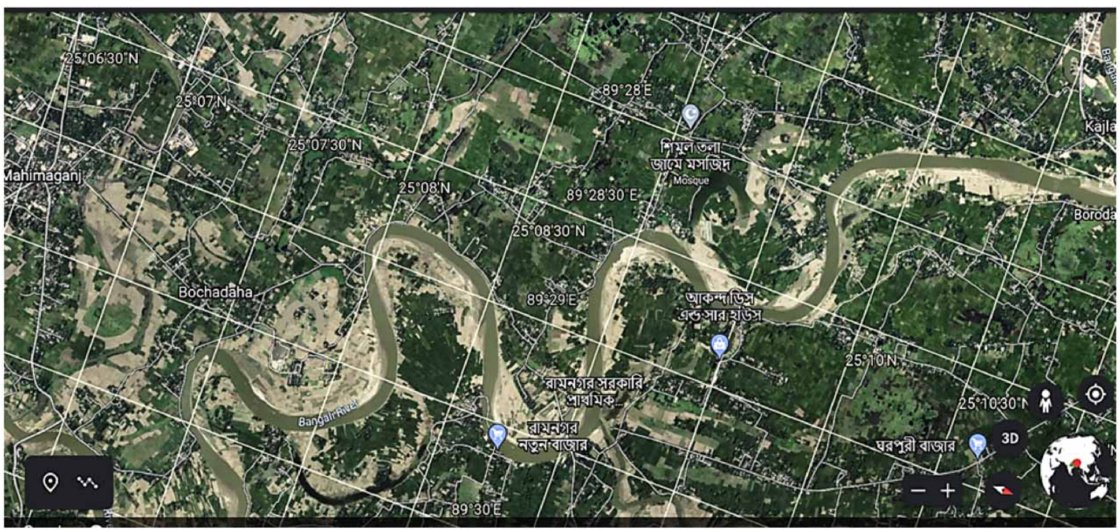


Figure 1 | Geographical location of the survey area under sweet potato production.

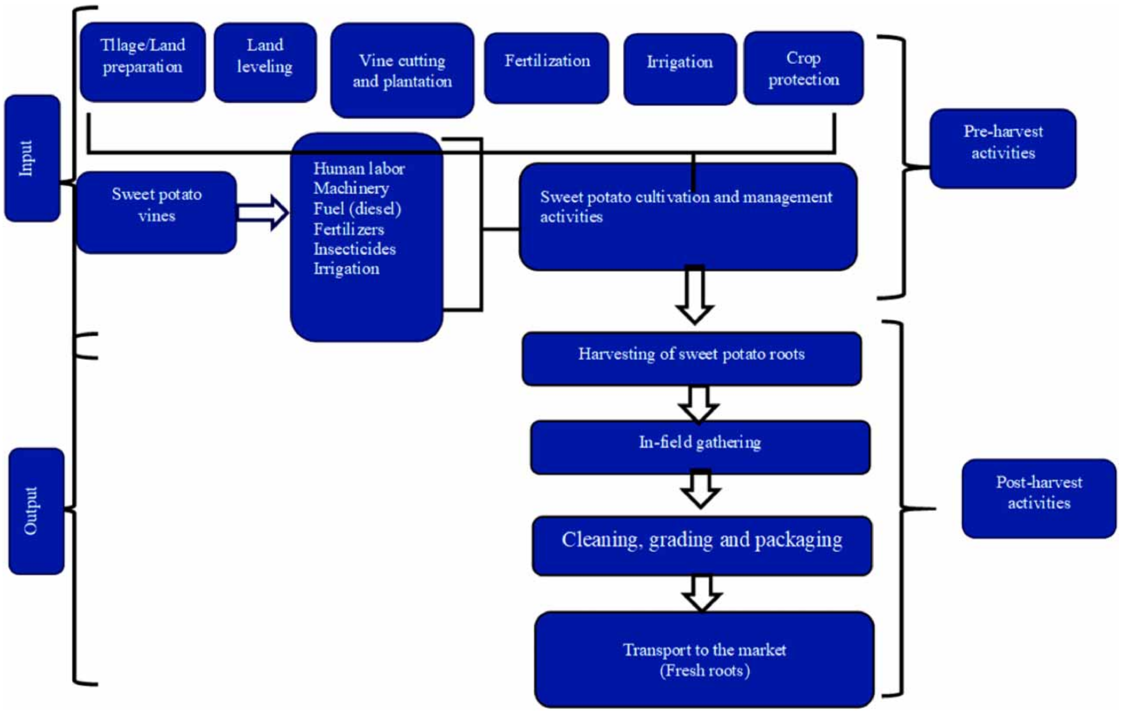


Figure 2 | The system boundary of sweet potato production used in the estimation.

2.3. Data collection

The yield data of four orange-fleshed sweet potatoes (OFSP)-BARI Mistialu-8 (BARI SP-8); BARI Mistialu-12 (BARI SP-12); BARI Mistialu-14 (BARI SP-14); BARI Mistialu-15 (BARI SP-15); with a white-bred local sweet potato variety were collected at the time of harvest from a unit area of 100 m^2. For the structural survey, questionnaires were developed for face-to-face interviews of the sweet potato producers and from these interviews, the energy efficiency and water use indices-related data (including all input costs like tillage, fertilizers, irrigation, crop protection, harvesting, cleaning, transport and marketing, etc.) were collected. The interview was conducted with 60 individuals (12 producers for each sweet potato variety) by a random selection method (Kizilaslan 2009). In all the cases, the averaged data were used for the calculation in respect of all the parameters.

2.4. Estimation of energy input and output of sweet potato production

Energy used in human labor, tractor and other machinery power, diesel as fuel, fertilizers, pesticides and irrigation were identified as inputs and sweet potato roots were considered as output. The amount of input energy used per hectare was multiplied by the energy coefficient equivalent referred to in Table 1.

2.5. Estimation of energy indicators of sweet potato

Energy indices were calculated based on input and output energy equivalents. The energy use efficiency, energy productivity, specific energy or energy intensity, net energy and energy profitability were calculated using the formula (Rafiee *et al.* 2010):

$$\text{Energy use efficiency} = \frac{\text{Total energy output (MJ ha}^{-1})}{\text{Total energy input (MJ ha}^{-1})} \tag{1}$$

$$\text{Energy productivity (kg MJ}^{-1}) = \frac{\text{Sweet potato root yield (kg ha}^{-1})}{\text{Total energy input (MJ ha}^{-1})} \tag{2}$$

$$\text{Specific energy or energy intensity (MJ kg}^{-1}) = \frac{\text{Total energy intput (MJ ha}^{-1})}{\text{Sweet potato root yield (kg ha}^{-1})} \tag{3}$$

Table 1 | Energy equivalent of inputs and output in sweet potato production

Input/output	Unit	Energy (MJ unit^{-1})	References
Inputs			
Human labor	h	1.96	Mohammadi *et al.* (2010); Rafiee *et al.* (2010)
Tractor	h	93.61	Canakci *et al.* (2005)
Machinery	h	62.70	Singh *et al.* (2002); Erdal *et al.* (2007); Singh (2002)
Diesel	L	47.80	Canakci *et al.* (2005)
Fertilizer			
Nitrogen (N)	kg	66.14	Rafiee *et al.* (2010); Yilmaz *et al.* (2005)
Phosphorus (P)	kg	12.44	Rafiee *et al.* (2010); Yilmaz *et al.* (2005)
Potassium (K)	kg	11.15	Rafiee *et al.* (2010)
Sulphur (S)	kg	1.12	Rafiee *et al.* (2010)
Zinc (Zn)	kg	8.4	Rafiee *et al.* (2010)
Boron (B)	kg	4.65	Jiménez-González *et al.* (2000)
Insecticides	kg	101.20	Ozkan *et al.* (2007)
Irrigation	m^3	0.63	Hatirli *et al.* (2005)
Output			
Sweet potato roots	kg	3.59	Oke & Workneh (2013)

$$\text{Net energy (MJ ha}^{-1}) = \text{Total energy output (MJ ha}^{-1}) - \text{Total energy input (MJ ha}^{-1}) \quad (4)$$

$$\text{Energy profitability} = \frac{\text{Net energy (MJ ha}^{-1})}{\text{Total energy input (MJ ha}^{-1})} \quad (5)$$

2.6. Estimation of water use indicators of sweet potato

The irrigation water use indicators in sweet potato production were calculated using the following formula (Khan *et al.* 2009):

$$\text{Water} - \text{energy use efficiency} = \frac{\text{Total energy output (MJ ha}^{-1})}{\text{Irrigation water energy input (MJ ha}^{-1})} \quad (6)$$

$$\text{Water productivity (kg m}^{-3}) = \frac{\text{Sweet potato root yield (kg ha}^{-1})}{\text{Total irrigation water applied (m}^3\text{ ha}^{-1})} \quad (7)$$

$$\text{Specific water or water intensity (m}^3\text{ kg}^{-1}) = \frac{\text{Total irrigation applied (m}^3\text{ ha}^{-1})}{\text{Sweet potato root yield (kg ha}^{-1})} \quad (8)$$

$$\text{Water} - \text{energy productivity (kg m}^{-3}\text{MJ}^{-1}) = \frac{\text{Sweet potato root yield (kg ha}^{-1})}{\text{Irrigation water applied (m}^3\text{ ha}^{-1}) \times \text{Water energy input (MJ ha}^{-1})} \quad (9)$$

3. RESULTS AND DISCUSSION

3.1. Root yield of sweet potato

The highest sweet potato root yield ranging from 25.65 to 38.70 t ha^{-1} was recorded from BARI SP-8 with an average of 31.90 t ha^{-1} followed by an average of 30.34 t ha^{-1} in BARI SP-12, slightly lower in BARI SP-14 (28.98 t ha^{-1}) like BARI SP-15 (28.08 t ha^{-1}). The lowest root yield of sweet potato ranged from 12.50 to 22.50 t ha^{-1} was observed in the local (Pingra) cultivar with an average value of 18.91 t ha^{-1} (Table 2). The details of the other statistical characteristics are presented in Table 2.

Table 2 | Statistical properties of the analyzed data of sweet potato

Items	BARI Mistialu-8	BARI Mistialu-12	BARI Mistialu-14	BARI Mistialu-15	Local
Mean	31.90	30.34	28.98	28.08	18.91
Standard Error	1.09	1.05	1.16	1.02	1.04
Median	31.06	30.03	29.12	28.20	20.28
Standard Deviation	3.77	3.64	4.02	3.52	3.61
Sample Variance	14.19	13.27	16.13	12.40	13.00
Coefficient of Variation	11.81	12.00	13.86	12.54	19.06
Kurtosis	−0.29	−0.20	−0.76	0.58	−0.81
Skewness	0.34	0.06	0.25	−0.31	−0.84
Range	13.05	12.07	12.90	12.71	10.00
Minimum	25.65	24.67	23.00	21.30	12.50
Maximum	38.70	36.74	35.90	34.01	22.50
Sum	382.77	364.13	347.77	336.96	226.97
Count	12.00	12.00	12.00	12.00	12.00
Confidence Level (95.0%)	2.39	2.31	2.55	2.24	2.29
Upper CI	34.29	32.66	31.53	30.32	21.21
Lower CI	29.50	28.03	26.43	25.84	16.62

The highest yield increased by 68.7% in BARI SP-8, next to BARI SP-12 (60.4%), BARI SP-14 (53.2%) and BARI SP-15 (48.5%) over the local sweet potato cultivar (Figure 3). Mahmud *et al.* (2021a) reported that the root yield of BARI SP-8 was 23.96–35.54 t ha^{-1} with an average of 29.57 t ha^{-1}, 22.50–37.67 t ha^{-1} in BARI SP-12 with an average of 30.24 t ha^{-1} and 21.72–30.85 t ha^{-1} with an average of 27.02 t ha^{-1} in BARI SP-14 across the different agro-ecological zones of Bangladesh mainly due to the different soil and agro-climatic conditions. They also reported that the average yield increase rate was 44.30–61.50% over the local sweet potato cultivar, similar to our study.

3.2. Energy input and output of sweet potato production

The input–output energy of sweet potato production has been presented in Table 3. The total input energy was 24,561.97 MJ ha^{-1} for all the sweet potato cultivars. The maximum energy output was observed from the BARI SP-8 (114,511.65

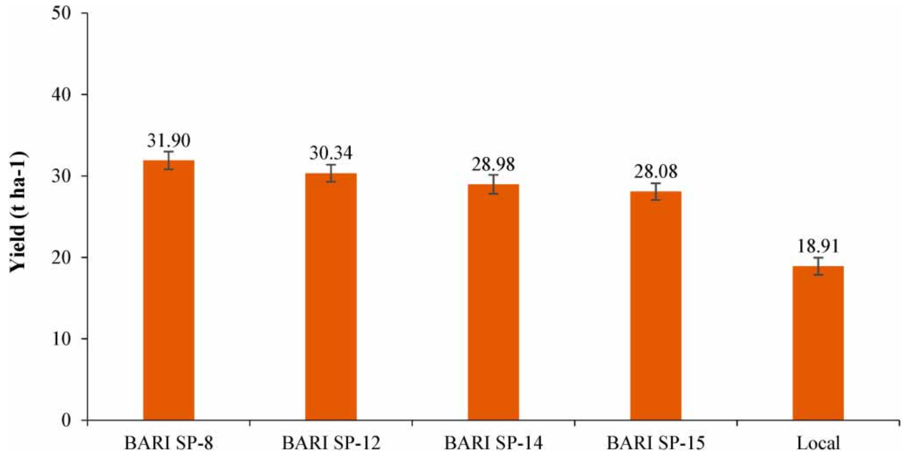


Figure 3 | Mean root yield (t ha^{-1}) of sweet potato varieties in the farmed fields in the study area (vertical bars indicate the standard error of the mean).

Table 3 | Energy input and output which were used in sweet potato production in the subtropical climate of Bangladesh

Input/output	Unit	Quantity (ha^{-1})	Total energy equivalent (MJ ha^{-1})
Inputs			
Human labor	h	856	1,677.76
Tractor	h	14	1,310.54
Other Machinery	h	30	1,881.00
Diesel	L	140	6,692.00
Fertilizer			9,018.27
Nitrogen (N)	kg	120	7,936.80
Phosphorus (P)	kg	30	373.20
Potassium (K)	kg	60	669.00
Sulphur (S)	kg	15	16.80
Zinc (Zn)	kg	2.11	17.72
Boron (B)	kg	1.02	4.74
Insecticides	kg	2	202.40
Irrigation	m^3	6,000	3,780.00
Total input			**24,561.97**
Output (Sweet potato roots)			
BARI SP-8	kg	31,897	114,511.65
BARI SP-12	kg	30,344	108,935.18
BARI SP-14	kg	28,981	104,040.78
BARI SP-15	kg	28,080	100,807.20
Local	kg	18,914	67,901.86

MJ ha^{-1}), followed by BARI SP-12 (108,935.18 MJ ha^{-1}), BARI SP-14 (104,040.78 MJ ha^{-1}) and BARI SP-15 (100,807.20 MJ ha^{-1}), respectively (Table 3).

However, the minimum energy output (67,901.86 MJ ha^{-1}) was recorded from the local sweet potato cultivar due to the lowest root yield (18.91 t ha^{-1}). The variation of output energy among the sweet potato varieties is mainly due to the variation of root yields. Flores *et al.* (2016) stated that the energy output from sweet potato was 53,885.90 MJ ha^{-1} in Tarlac, Philippines, which was half compared with our study. The reason for the lower energy output from sweet potato production in their study was mainly due to the lower root yield (15.01 t ha^{-1}) compared with our study (28.08–31.90 t ha^{-1}). Most of the total energy input was contributed by chemical fertilizers (36.72%), of which nitrogen fertilizers contributed a maximum of 32.31%, followed by diesel (27.25%) and irrigation by 15.39% (Figure 4). Similar results have been revealed for sweet potato (Flores *et al.* 2016), rice (Rahman *et al.* 2015), wheat (Singh *et al.* 2007; Devi *et al.* 2018), corn (Yousefi *et al.* 2014), Irish potato (Pishgar-Komleh *et al.* 2012), watermelon (Nabavi-Pelesaraei *et al.* 2016) and sugar beet (Asgharipour *et al.* 2012), where fertilizer, especially nitrogenous fertilizer, was the largest energy contributor to the total input energy of most crops, similar to our study. Total energy input and output amounts were variable depending on crop type and even varied from species to species.

3.3. Energy involved in each activity for sweet potato production

The energy spent on pre-harvest and post-harvest activity for sweet potato production is presented in Table 4.

The pre-harvest operation consumed the major energy input (22,313.55 MJ ha^{-1}), which is about 91% of the total energy input for sweet potato production (Figure 5). Conversely, about 2,248.42 MJ ha^{-1} energy input was from the post-harvest activity for sweet potato production, which contributed about 9% of the total energy input (Figure 5).

Among the pre-harvest activities, the most energy was consumed by fertilizer application (9,049.63 MJ ha^{-1} or 36.84%) followed by irrigation (8,654.44 MJ ha^{-1} or 35.24%) and land preparation (3,529.00 MJ ha^{-1} or 14.37%) of the total input

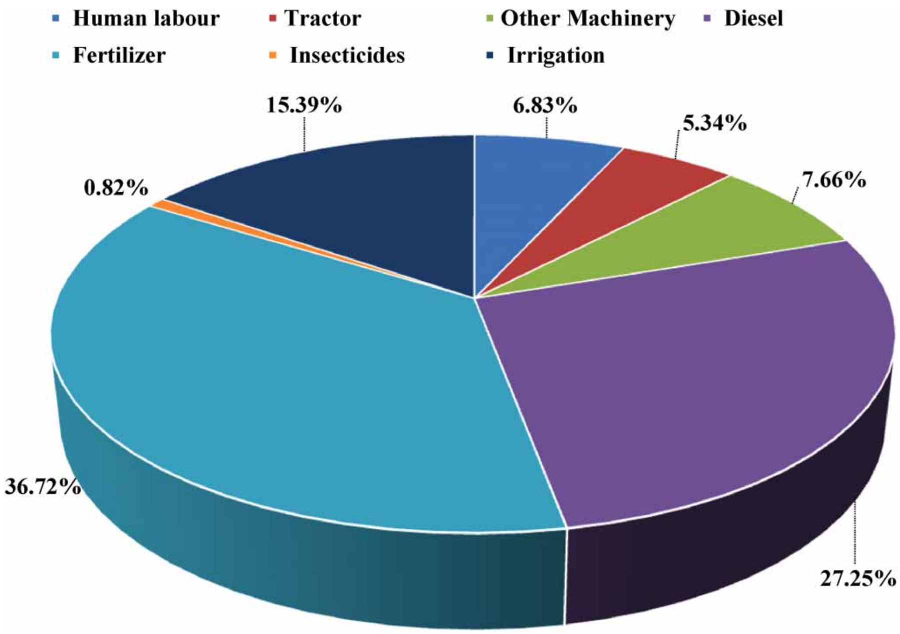


Figure 4 | Energy share (%) involvement in sweet potato production.

Table 4 | Activity-based energy input of sweet potato production in the Teesta Riverbank area of Bangladesh

Activities	Total energy equivalent (MJ ha^{-1})	% Energy share
Pre-harvest activities		
Tillage/Land preparation	3,529.00	14.37
Vine cutting and plantation in the main field	595.84	2.43
Fertilizer application	9,049.63	36.84
Irrigation	8,654.44	35.24
Insecticide application	249.44	1.02
Weeding and earthing up	235.20	0.96
Post-harvest activities		
Harvesting	470.4	1.92
Field gathering	47.04	0.19
Cleaning, grading and packaging	78.4	0.32
Transport to the market	1,652.58	6.73
Total input		

energy for sweet potato production (Table 4). In the case of post-harvest activity, about two-thirds of the energy input (1,652.58 MJ ha^{-1} or 6.73%) was consumed by the transportation of sweet potato from field to market for selling (Table 4). The remaining one-third of energy is consumed by harvesting (470.4 MJ ha^{-1} of 1.92%, field gathering (47.04 MJ ha^{-1} or 0.19%) and cleaning, grading, and packaging (78.4 MJ ha^{-1} or 0.32%). Flores *et al.* (2016) reported that the amount of input energy was 26,327.41 MJ ha^{-1} or 89.77% for pre-harvest and 2,999.45 MJ ha^{-1} or 10.23% for post-harvest operation for sweet potato production in the Philippines which is similar to our study.

3.4. Diverse energy forms of sweet potato production

The total energy inputs involved in sweet potato production can be categorized as direct, indirect, renewable and non-renewable energies (Figure 6). The amount of indirect energy (12,412.21 MJ ha^{-1}) was slightly more compared with the direct

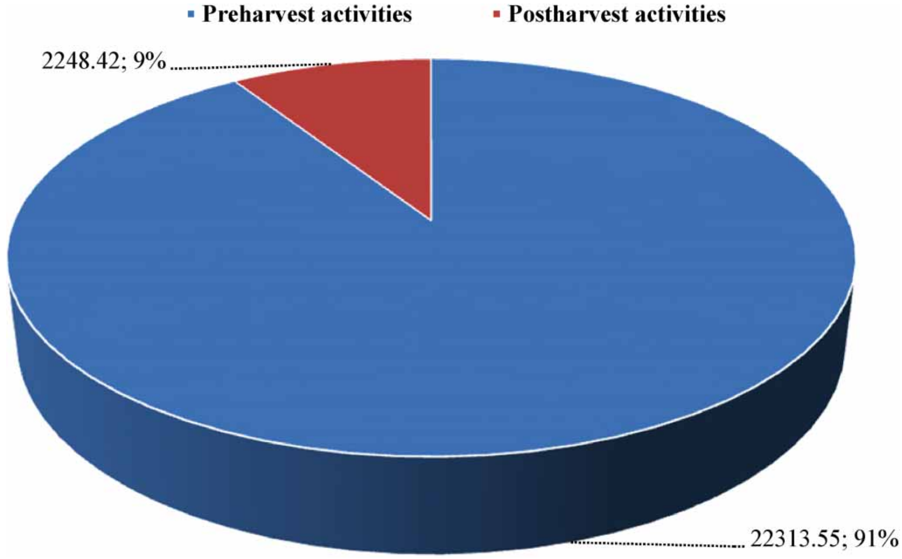


Figure 5 | Energy inputs (MJ ha^{-1}) and energy share (%) involved in the pre-harvest and post-harvest activities for sweet potato production.

energy (12,149.76 MJ ha^{-1}) for sweet potato production due to the energy inputs supplied by the fertilizers. Considering the energy share ratio, both the direct and indirect energy contributed similar trends (Figure 6). The reason for this was that more diesel was used especially for irrigation as well as human labor in direct energy, which was equated by the fertilizer and machinery functioned as indirect energy. Most of the total input energy share in this study (22,884.21 MJ ha^{-1} or 93%) was from non-renewable energy contributed by the fertilizers, machinery and diesel used in the production of sweet potatoes and the remainder (1,677.76 MJ ha^{-1} or 7%) from renewable energy (Figure 4). Flores *et al.* (2016) reported that the amount of direct, indirect, renewable and non-renewable energy involved in sweet potato production was 46.07, 53.93, 11.77 and 88.23%, respectively, similar to our study. Several studies reported that the use of non-renewable energy is more than renewable energy in sweet potato (Flores *et al.* 2016), soybean (Mousavi-Avval *et al.* 2010), wheat (Shahin *et al.* 2008; Devi *et al.* 2018) and winter tomato (Ozkan *et al.* 2011) production. Moreover, the use of low input energy in sustainable crop production is more efficient than conventional systems and much more efficient in organic farming instead of chemical inputs (Mendoza 2005).

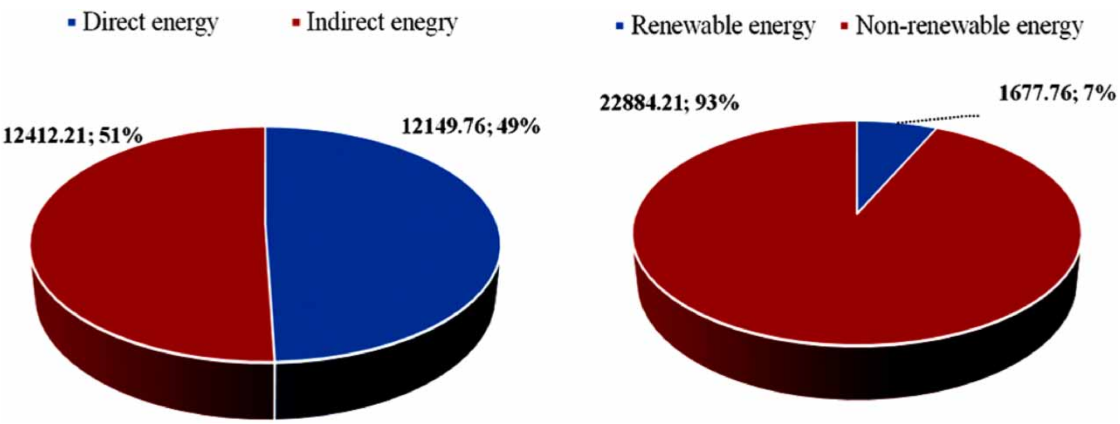


Figure 6 | Total energy input and energy share (%) involved in different categories for sweet potato production (direct energy includes human labor, diesel and irrigation water; indirect energy includes tractor, other machinery, fertilizer and insecticides, renewable energy includes human labor and non-renewable energy includes machinery, diesel, fertilizer and insecticides).

3.5. Energy indices of sweet potato production

Energy indices have been presented in Table 5. Energy use efficiency is an indicator to assess the energy efficiency for crop production. Energy use efficiency is commonly used as an indicator to evaluate energy efficiency in crop production systems. The energy use efficiency or energy ratio of OFSP varieties ranged from 4.10 to 4.66 with an average of 4.36 which was 58% higher compared with the local sweet potato cultivar with a value of 2.76. This indicates that the energy used in sweet potato production has been replaced by 4.10–4.66 times the energy produced by the output energy from sweet potato roots. The higher the energy ratio, the more efficient use of energy in crop production will be achieved. Flores *et al.* (2016) stated the energy use efficiency of sweet potato was 1.84, lower than our study because of low output energy as well as consumption of high input energy. The higher energy use efficiency attains the efficient use of input energy to increase productivity, sustainability and competitiveness in agricultural production (Hatirli *et al.* 2005). The energy use efficiency varied from crop to crop and even from location to location. Several studies reported the energy use efficiency in potato was 0.95–1.71 (Mohammadi *et al.* 2008; Zangeneh *et al.* 2010; Pishgar-Komleh *et al.* 2012); 2.29 in soybean (Mousavi-Avval *et al.* 2010); 3.13 in wheat (Shahin *et al.* 2008); 0.8 in tomato (Ozkan *et al.* 2011) and 1.52 in watermelon (Nabavi-Pelesaraei *et al.* 2016). The energy productivity in the OFSP varieties was 1.14–1.30 kg MJ^{-1} with an average of 1.22 kg MJ^{-1} compared with the local sweet potato cultivar (0.77 kg MJ^{-1}), which implies that 1.14–1.30 kg of sweet potato root is produced from per unit input energy. In this study, the specific energy was 0.77–1.30 MJ kg^{-1}, indicating about 0.77–1.30 MJ input energy consumed for one kg of sweet potato root production. Flores *et al.* (2016) reported energy productivity of 0.51 kg MJ^{-1}, comparatively lower and specific energy of 1.95 MJ kg^{-1}, comparatively higher than our study for sweet potato production in the Philippines. The net energy of OFSP varieties ranged from 76,245.23 to 89,949.68 MJ ha^{-1} with an average of 82,511.77 MJ ha^{-1}, about 90% more compared with the local sweet potato cultivar (43,339.89 MJ ha^{-1}). Variation in net energy among sweet potato cultivars is mainly due to variation in output energy production from sweet potato roots while expending the same input energy. Energy profitability in OFSP ranged from 3.10 to 3.66 with an average of 3.36, almost double that of the local (1.76) sweet potato cultivar.

3.6. Water use indices of sweet potato production

The water use indices of sweet potato production have been presented in Table 6. The water use efficiency of OFSP ranged from 26.67 to 30.30 with an average of 28.33, about 58% higher compared with the local sweet potato cultivar (17.96), which indicates that an average increase of 1 MJ energy inputs leads to an extra growth in output energy by 28.33 MJ ha^{-1}. The water productivity of OFSP ranged from 4.68 to 5.32 kg m^{-3} with an average of 4.97 kg m^{-3}, revealing that the 4.68–5.32 kg root yield of sweet potato produced from per m^3 of irrigation water. However, the lowest water productivity showed in the local sweet potato cultivar due to the lowest root yield with the same irrigation (6,000 m^3) water. The water intensity of the OFSP variety ranged from 0.19 to 0.21 m^3 kg^{-1} when it was 0.32 m^3 kg^{-1} in the local sweet potato cultivar, specifying that 1 kg OFSP production required 0.19–0.21 m^3 irrigation water when it was 0.32 m^3 for the local cultivar of sweet potato. The water-energy productivity of OFSP ranged from 1.24 to 1.41 g m^{-3} MJ^{-1} with an average of 1.32 g m^{-3} MJ^{-1}, 59% higher than that of the local cultivar (0.83 g m^{-3} MJ^{-1}). This might be due to the higher output energy from sweet potato roots with a similar energy input of irrigation. The water-energy productivity was 0.02–0.07 g m^{-3} MJ^{-1}

Table 5 | Energy use indices involved in sweet potato production in the subtropical climate of Bangladesh

		Quantity				
Indicators	**Unit**	**BARI SP-8**	**BARI SP-12**	**BARI SP-14**	**BARI SP-15**	**Local**
Energy input	MJ ha^{-1}	24,561.97	24,561.97	24,561.97	24,561.97	24,561.97
Energy output	MJ ha^{-1}	114,521.00	108,920.60	104,038.20	100,807.20	67,886.90
Energy use efficiency	–	4.66	4.44	4.24	4.10	2.76
Energy productivity	kg MJ^{-1}	1.30	1.24	1.18	1.14	0.77
Specific energy	MJ kg^{-1}	0.77	0.81	0.85	0.87	1.30
Net energy	MJ ha^{-1}	89,949.68	84,373.21	79,478.81	76,245.23	43,339.89
Energy profitability	–	3.66	3.44	3.24	3.10	1.76

Table 6 | Water use indices for sweet potato production in the subtropical climate of Bangladesh

Indicators	Unit	Quantity				
		BARI SP-8	BARI SP-12	BARI SP-14	BARI SP-15	Local
Water energy use efficiency		30.30	28.81	27.52	26.67	17.96
Water productivity	$kg\ m^{-3}$	5.32	5.06	4.83	4.68	3.15
Water intensity	$m^3\ kg^{-1}$	0.19	0.20	0.21	0.21	0.32
Water-energy productivity	$g\ m^{-3}\ MJ^{-1}$	1.41	1.34	1.28	1.24	0.83

in soybean in different irrigation systems (Mousavi-Avval *et al.* 2010) and 0.03 $g\ m^{-3}\ MJ^{-1}$ in potato (Mohammadi *et al.* 2010) which is much lower compared with our study. This may be due to the higher input energy consumed for the irrigation of the crops compared with their study. The amount of irrigation required in sweet potato can vary depending on the soil type.

4. CONCLUSIONS AND RECOMMENDATIONS

A case study of energy and water inputs for sweet potato production in the subtropical climatic condition of Bangladesh has been presented in this study. The data collection was done by applying structural questionnaires in a random method. Energy and water indicators were measured based on the use of energy and water inputs from various sweet potato growers. The following conclusions were drawn:

- The OFSP produced total output energy ranging from 100,807.20 to 114,511.65 $MJ\ ha^{-1}$ with an average of 107,073.70 $MJ\ ha^{-1}$ using the same input energy (24,561.97 $MJ\ ha^{-1}$), which was 39,171.75 $MJ\ ha^{-1}$ more or 58% higher compared with the local sweet potato variety.
- Among the input energy, chemical fertilizers contributed the most (36.72%) followed by diesel (27.25%).
- The major share of energy input was consumed by pre-harvest activities (22,313.55 $MJ\ ha^{-1}$ or 90.85%), whereas only 9.15% (2,248.42 $MJ\ ha^{-1}$) was consumed by the post-harvest activity for sweet potato production.
- The total energy inputs involved in the direct and indirect sources were similar to a value of 12,149.76 $MJ\ ha^{-1}$ (49.47%) and 12,412.21 $MJ\ ha^{-1}$ (50.53%). Conversely, it was much higher from the non-renewable sources (22,884.21 $MJ\ ha^{-1}$ or 93.17%) than renewable sources (1,677.76 $MJ\ ha^{-1}$ or 6.83%).
- The OFSP varieties showed greater average energy use efficiency (4.36), energy productivity (1.22 $kg\ MJ^{-1}$), specific energy (0.83 $MJ\ kg^{-1}$) and net energy (82,511.73 $MJ\ ha^{-1}$) and energy profitability (3.36) compared with the local sweet potato cultivar.
- Similar trends were also observed in the OFSP varieties in terms of the average water use efficiency (28.33), water productivity (4.97 $kg\ m^{-3}$), water intensity (0.20 $m^3\ kg^{-1}$) and water-energy productivity (1.32 $g\ m^{-3}\ MJ^{-1}$). Finally, we can say the OFSP varieties showed better performance in the case of all energy and water use indicators.
- Re-examination of chemical inputs and use of non-renewable energy resources is needed to increase sweet potato productivity as well as sustainability. Besides, inclusions of leguminous crops may be considered in the crop rotation to reduce the use of more nitrogen fertilizers.
- In order to control the high rate of non-renewable energy use, the use of organic fertilizers or green manures should be considered instead of chemical fertilizers.
- The use of non-renewable energy (diesel) can be reduced for irrigation by using organic mulching materials.

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ETHICAL STATEMENT

No living organism (human or animal) was involved in conducting the present experiments.

AUTHOR CONTRIBUTIONS

Conceptualization: M.J.A. and A.A.M.; methodology: M.J.A. and A.A.M.; formal analysis: M.J.A. and A.H.; data curation: M.J.A. and A.H.; statistical expertise: M.J.A. and A.H.; writing – original draft preparation: M.J.A. and A.A.M.; writing – review and editing: A.G, M.E., S.S. and A.H.; visualization: M.J.A. and A.A.M.; supervision: A.A.M.; funding acquisition: A.G, M.E., S.S. and A.H. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adenuga, W. 2010 Nutritional and sensory profiles of sweet potato potato-based infant weaning food fortified with cowpea and peanut. *Journal of Food Technology* **8** (5), 223–228.

Aked, L. G. 2009 Energy and irrigation in LDCs. *Food Policy* **8** (1), 84–85.

Asgharipour, M. R., Mondani, F. & Riahinia, S. 2012 Energy use efficiency and economic analysis of sugar beet production system in Iran: a case study in Khorasan Razavi province. *Energy* **44** (1), 1078–1084.

BBS 2020 *Bangladesh Bureau of Statistics, Yearbook of Agricultural Statistics-2019*. Statistics and Informatics Division (SID), Ministry of Planning, Government of the People's Republic of Bangladesh. Dhaka, Bangladesh. Available from: http://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/b2db8758_8497_412c_a9ec_6bb299f8b3ab/2021-08-11-04-54-154c14988ce53f65700592b03e05a0f8.pdf (accessed on 19 June 2022).

Beheshti Tabar, I., Keyhani, A. & Rafiee, S. 2010 Energy balance in Iran's agronomy (1990–2006). *Renewable and Sustainable Energy Reviews* **14** (2), 849–855.

Bovell-Benjamin, A. C. 2007 Sweet potato: a review of its past, present, and future role in human nutrition. *Advances in Food and Nutrition Research* **52**, 1–59.

Canakci, M., Topakci, M., Akinci, I. & Ozmerzi, A. 2005 Energy use pattern of some field crops and vegetable production: case study for Antalya Region, Turkey. *Energy Conversion and Management* **46** (4), 655–666.

Cosgrove, W. J. & Loucks, D. P. 2015 Water management: current and future challenges and research directions. *Water Resources Research* **51** (6), 4823–4839.

de Fraiture, C., Wichelns, D., Rockstrom, J., Kempt-Benedict, E., Eriyagama, N., Gordon, L. J., Hanjra, M. A., Hoogeveen, J., Huber-Lee, A. & Karlberg, L. 2007 Looking ahead to 2050: scenarios of alternative investment approaches. In: *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (Molden, D., ed.). Earthscan/IWMI, London, UK; Colombo, Sri Lanka, pp. 91–145.

Devi, S., Hooda, V. S. & Singh, J. 2018 Energy input-output analysis for production of wheat under different planting techniques and herbicide treatments. *International Journal of Current Microbiology and Applied Sciences* **7** (7), 749–760.

Erdal, G., Esengün, K., Erdal, H. & Gündüz, O. 2007 Energy use and economical analysis of sugar beet production in Tokat province of Turkey. *Energy* **32** (1), 35–41.

FAOSTAT 2015 *Food and Agriculture Data*. Food and Agriculture Organization of the United Nations, Rome, Italy. Available from: http://www.fao.org/faostat/en/#data/QC (accessed 19 June 2022).

FAOSTAT 2017 *Food and Agriculture Data*. Food and Agriculture Organization of the United Nations, Rome, Italy. Available from: http://www.fao.org/faostat/en/#data/QC (accessed 19 June 2022).

FAOSTAT 2021 *Food and Agriculture Data*. Food and Agriculture Organization of the United Nations, Rome, Italy. Available from: http://www.fao.org/faostat/en/#data/QC (accessed on 19 June 2022).

Ferrari, M. D., Guigou, M. & Lareo, C. 2013 Energy consumption evaluation of fuel bioethanol production from sweet potato. *Bioresource Technology* **136**, 377–384.

Flores, E. D., Dela Cruz, R. S. M. & Antolin, M. C. R. 2016 Energy use and CO_2 emissions of sweet potato production in Tarlac, Philippines. *Agricultural Engineering International: CIGR Journal* **18** (3), 127–135.

Hatirli, S. A., Ozkan, B. & Fert, C. 2005 An econometric analysis of input energy/output in Turkish agriculture. *Renewable and Sustainable Energy Reviews* **9** (6), 608–623.

Islam, M. S., Yoshimoto, M., Terahara, N. & Yamakawa, O. 2002 Anthocyanin compositions in sweet potato (*Ipomoea batatas* L.) leaves. *Bioscience, Biotechnology, and Biochemistry* **66**, 2483–2486.

Jiménez-González, C., Kim, S. & Overcash, M. 2000 Methodology for developing gate-to-gate life cycle inventory information. *The International Journal of Life Cycle Assessment* **5** (3), 153–159.

Kallivroussis, L., Natsis, A. & Papadakis, G. 2002 The energy balance of sunflower production for biodiesel in Greece. *Biosystems Engineering* **81** (3), 347–354.

Khan, S., Khan, M. A., Hanjra, M. A. & Mu, J. 2009 Pathways to reduce the environmental footprints of water and energy inputs in food production. *Food Policy* **34** (2), 141–149.

Kizilaslan, H. 2009 Input-output energy analysis of cherries production in Tokat Province of Turkey. *Applied Energy* **86** (78), 1354–1358.

Koech, R. & Langat, P. 2018 Improving irrigation water use efficiency: a review of advances, challenges and opportunities in the Australian context. *Water* **10** (12), 1771.

Lee, J. S., Kim, H. S., Chung, M. N., Ahn, Y. S., Jeong, B. C. & Bang, J. K. 2006 Various forms of utilization and breeding of sweet potato in Korea. *Acta Horticulturae* **703** (13), 125–132.

Mahmud, A. A., Alam, M. J., Heck, S., Grüneberg, W. J., Chanda, D., Rahaman, E. H. M. S., Molla, M. S. H., Anwar, M. M., Talukder, M. A. A. H., Ali, M. A., Amin, M. N., Alhomrani, M., Gaber, A. & Hossain, A. 2021a Assessing the productivity, quality and profitability of orange fleshed sweet potatoes grown in riverbank of the Tista floodplain agro-ecological zone of Bangladesh. *Agronomy* **11**, 2046. doi:10.3390/agronomy11102046.

Mahmud, A. A., Hassan, M. M., Alam, M. J., Molla, M. S. H., Ali, M. A., Mohanta, H. C., Alam, M. S., Islam, M. A., Talukder, M. A. H., Ferdous, M. Z., Amin, M. R., Hossain, M. F., Anwar, M. M., Islam, M. S., Dessoky, E. S. & Hossain, A. 2021b Farmers' preference, yield, and GGE-Biplot analysis-based evaluation of four sweet potato (*Ipomoea batatas* L.) varieties grown in multiple environments. *Sustainability* **13**, 3730. doi:10.3390/su13073730.

Mendoza, T. C. 2005 An energy analysis of organic, low external input sustainable agriculture (LEISA) and conventional rice production in the Philippines. *The Philippine Agricultural Scientist* **88** (3), 257–267.

Mobtaker, H. G., Keyhani, A., Mohammadi, A., Rafiee, S. & Akram, A. 2010 Sensitivity analysis of energy inputs for barley production in Hamedan Province of Iran. *Agriculture, Ecosystems & Environment* **137** (34), 367–372.

Mohammadi, A., Tabatabaeefar, A., Sashin, S., Rafiee, S. & Keyhani, A. 2008 Energy use and economical analysis of potato production in Iran a case study: Ardabil province. *Energy Conversion and Management* **49** (12), 3566–3570.

Mohammadi, A., Rafie, S., Mohtasebi, S. S. & Rafiee, H. 2010 Energy inputs-yield relationship and cost analysis of kiwifruit production in Iran. *Renewable Energy* **35**, 1071–1075.

Mousavi-Avval, S. H., Rafiee, S. & Jafari, A. 2010 A comparative study on energy and water use indicators for soybean production under different irrigation systems in Iran. *International Journal of Environmental Science* **1** (4), 419–428.

Nabavi-Pelesaraei, A., Abdi, R., Rafiee, S. & Bagheri, I. 2016 Determination of efficient and inefficient units for watermelon production – a case study: Guilan province of Iran. *Journal of the Saudi Society of Agricultural Sciences* **15** (2), 152–170.

Oke, M. O. & Workneh, T. S. 2013 A review on sweet potato postharvest processing and preservation technology. *African Journal of Agricultural Research* **8** (40), 4990–5003.

Ozkan, B., Akcaoz, H. & Fert, C. 2004 Input energy–output analysis in Turkish agriculture. *Renewable Energy* **29** (1), 39–51.

Ozkan, B., Fert, C. & Karadeniz, C. F. 2007 Energy and cost analysis for greenhouse and open-field grape production. *Energy* **32** (8), 1500–1504.

Ozkan, B., Ceylan, R. F. & Kizilay, H. 2011 Energy inputs and crop yield relationships in greenhouse winter crop tomato production. *Renewable Energy* **36**, 3217–3221.

Perry, C. 2011 Accounting for water use: terminology and implications for saving water and increasing production. *Agricultural Water Management* **98** (12), 1840–1846.

Pishgar-Komleh, S. H., Ghahderijani, M. & Sefeedpari, P. 2012 Energy consumption and CO_2 emissions analysis of potato production based on different farm size levels in Iran. *Journal of Cleaner Production* **33** (8), 183–191.

Prochnow, A., Drastig, K., Klauss, H. & Berg, W. 2012 Water use indicators at farm scale: methodology and case study. *Food and Energy Security* **1** (1), 29–46.

Qiu, H., Huang, J., Yang, J., Rozelle, S., Zang, Y., Zang, Y. & Zang, Y. 2010 Bioethanol development in China and the potential impacts on the agricultural economy. *Applied Energy* **87** (1), 76–83.

Rafiee, S., Mousavi, A. S. H. & Mohammadi, A. 2010 Modeling and sensitivity analysis of energy inputs for apple production in Iran. *Energy* **35** (8), 3301–3306.

Rahman, M., Halder, M., Hassan, N. & Haque, F. 2015 Energy input-output analysis of rice cultivation in the coastal region of Bangladesh. *Songklanakarin Journal of Science and Technology* **37** (4), 455–464.

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P. & de Fraiture, C. 2017 Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* **46** (1), 4–17.

Rumbaoa, R. G. O., Cornago, D. F. & Geronimo, I. M. 2009 Phenolic content and antioxidant capacity of Philippine sweet potato (*Ipomoea batatas*) varieties. *Food Chemistry* **113**, 1133–1138.

Sartori, L., Basso, B., Bertocco, M. & Oliviero, G. 2005 Energy use and economic evaluation of a three year crop rotation for conservation and organic farming in NE Italy. *Biosystems Engineering* **91** (2), 245–256.

Schroll, H. 1994 Energy-flow and ecological sustainability in Danish agriculture. *Agriculture, Ecosystems & Environment* **51** (3), 301–310.

Shahin, S., Jafari, A., Mobli, H., Rafiee, S. & Karimi, M. 2008 Effect of farm size on energy ratio for wheat production: a case study from Ardabil Province of Iran. *American-Eurasian Journal of Agricultural & Environmental Sciences* **3** (4), 604–608.

Singh, J. M. 2002 *On Farm Use Pattern in Different Cropping Systems in Haryana, India*. *Master of Science*, International Institute of Management, University of Flensburg, Germany.

Singh, H., Mishra, D. & Nahar, N. M. 2002 Energy use pattern in production agriculture of a typical village in Arid Zone India – Part I. *Energy Conversion and Management* **43** (16), 2275–2286.

Singh, G., Singh, S. & Singh, J. 2004 Optimization of energy inputs for wheat crop in Punjab. *Energy Conversion and Management* **45** (3), 453–465.

Singh, H., Singh, A. K., Kushwaha, H. I. & Singh, A. 2007 Energy consumption pattern of wheat production in India. *Energy* **32** (10), 1838–1854.

Smerdon, E. T. & Hiler, E. A. 1985 Energy in irrigation in developing countries. In: *Proceeding of the International Conference on Water and Water Policy in World Food Supplies*, May 26–30, 1985. Texas A & M University, USA.

Stolarski, M. J., Krzyaniak, M., Tworkowski, J., Zauski, D. & Szczukowski, S. 2019 Camelina and Crambe production – energy efficiency indices depending on nitrogen fertilizer application. *Industrial Crops and Products* **137**, 386–395.

Szalay, J. 2017 *Sweet Potatoes: Health Benefits, Risks & Nutrition Facts*. Live Science. Available from: https://www.livescience.com/45838-potato-nutrition.html (accessed 3 January 2022).

Tang, C., Lu, Y., Jiang, B., Chen, J., Mo, X., Yang, Y. & Wang, Z. 2022 Energy, economic, and environmental assessment of sweet potato production on plantations of various sizes in South China. *Agronomy* **12**, 1290. https://doi.org/10.3390/agronomy12061290.

Wang, S., Nie, S. & Zhu, F. 2016 Chemical constituents and health effects of sweet potato. *Food Research International* **89**, 90–116.

Yilmaz, I., Akcaoz, H. & Ozkan, B. 2005 An analysis of energy use and input costs for cotton production in Turkey. *Renewable Energy* **30**, 145–155.

Yousefi, M., Damghani, A. M. & Khoramivafa, M. 2014 Energy consumption, greenhouse gas emissions and assessment of sustainability index in corn agroecosystems of Iran. *Science of The Total Environment* **493**, 330–335.

Zangeneh, M., Omid, M. & Akram, A. 2010 Assessment of machinery energy ratio in potato production by means of artificial neural network. *African Journal of Agricultural Research* **5** (10), 993–998.

Zhang, W., Qian, C., Carlson, K. M., Ge, X., Wang, X. & Chen, X. 2021 Increasing farm size to improve energy use efficiency and sustainability in maize production. *Food and Energy Security* **10**, e271.

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