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Eco-Efficiency and Sustainability of Jowar Production in Karnataka State, India

JAMES KOFI BLAY AND H. LOKESHA
Department of Agricultural Economics, College of Agriculture, UAS, GKVK, Bangalore - 560 065
e-Mail : jameskofiblay@gmail.com

AUTHORS CONTRIBUTION

JAMES KOFI BLAY : Data collection, compilation, data analysis and write-up of the manuscript;
H. LOKESHA : Suggestions, curation and editing of the manuscript.

Corresponding Author :
JAMES KOFI BLAY
Department of Agricultural Economics, College of Agriculture, UAS, GKVK, Bengaluru

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ABSTRACT

The present study was conducted to evaluate carbon footprint and environmental efficiency and sustainability of jowar production in Karnataka state. The results illustrated that the total input energies in jowar production for the period under study increased from 7310.27 MJ ha^{-1} in 2009 to 17487.08 MJ ha^{-1} in 2018 at an increasing rate of 4.2 per cent. Machinery energy, chemical fertilizer, diesel consumption and irrigation energy were main drivers of energy consumption and emission in jowar production in the study region. The total average CO_2 emission was calculated as 3180.9 kg CO_2 eq ha^{-1} with an average carbon footprint of 4.4 CO_2 eq ha^{-1}. Sustainability of the jowar production in general was characterized by negative growth rate for the study period. With regard to farming system, non-irrigated farms were more sustainable (1.31), large farms had the highest sustainability index (3.37) as compared to other farms. Jowar production in southern transitional zone was more sustainable (1.75) with the least carbon footprint of 3.01 CO_2 eq ha^{-1} as compared to central dry zone with the lowest sustainability index (0.65) and highest carbon footprint (7.62 CO_2 eq ha^{-1}). The production process of jowar was eco-inefficient with diverse decoupling elasticities implying more efforts are required to improve the sustainability. Therefore, we recommend that mitigation strategies should be diversified across zones and also should be geared towards by improving the efficiency of resources and provision of more energy efficient farm machinery with less energy consumption in mitigating carbon footprint in the region.

Keywords : Carbon footprint, Eco-efficiency, GHG emission, Jowar production, Sustainability

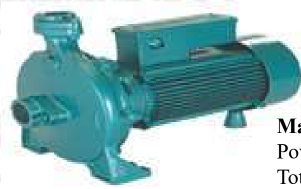
AGRO-ECOLOGICAL system in India has undergone drastic changes after the inception of green revolution. Although the revolution resulted in increasing food production by the use of high yielding seeds, but came at a cost of high utilization of agrochemicals along with other inputs such as diesel fuel and electricity power in the production process (Hatirli *et al,*. 2005; Yousefi *et al.,* 2016 and Benbi, 2018). Moreover, with the advancement of industrialization and urbanization resulting in contraction of agriculture land along with the increasing pressure for agricultural commodities to be intensively managed to sustain economic activities significantly influence the ecosystem resulting in environmental imbalances and instability leading to loss of biodiversity, pollution and eutrophication of aquatic habitats and toxification of soil (Blay and Lokesha, 2022). However, the traditional assessment of resource use efficiency in evaluating the performance of production system does not account for the problems of environmental degradation and excessive consumption of resources in the actual process of agricultural development. With increasing pollution levels in Indian agrarian sector (Jaiswal and Agrawal, 2020) ranking India as the third-largest emitter of greenhouse gases after China and the United States, the need to address the challenges for meeting food production in India while controlling and reducing the GHG emissions becomes paramount. Given the deepening concerns of global ecological degradation due to food production system, green productivity and efficient use of resources has become an indispensable prerequisite for assessing the sustainability of agricultural production. Therefore, environmental labelling of agricultural production systems through environment modelling and carbon footprint assessment becomes relevant and powerful tool to evaluate the potential impact of production system on ecological systems. Although myriad of studies has been conducted to evaluate the energy consumption and their GHG emissions in agro ecosystems in India (Singh *et al.*, 1999; Singh, 2002; Chhabra *et al.*, 2013; Vetter *et al.*, 2017; Benbi, 2018, Sah & Devakumar, 2018 and Jaiswal & Agrawal, 2020) but much has not been studied if any on jowar production being one of the intensively cultivated principal food crop in the study area. Hence, the main objectives of this study were to analyze the energy flow, sustainability, evaluate the carbon footprint and the eco-efficiency and productivity change in jowar production systems in Karnataka state for effective sustainable management action.

MATERIAL AND METHODS

The study focused on microlevel analysis and thus, cross-sectional plot level data on production inputs in jowar (sorghum) was obtained from the surveyed data of cost of cultivation scheme with the ultimate unit of data collection being the farmers household from 2009 to 2018 production season. In order to calculate input–output ratios and other energy indicators, the inputs were converted into their energy equivalents using equivalent energy values (Table 1) for each input. Electricity, quantity of water, diesel consumption as well as indirect energy consumed for irrigation were computed as given in each respective equation.

Water and Energy Consumption for Irrigation

Water for irrigation was assumed to be pumped from well using electrically operated pumps (Fig. 1) as used by majority of farmers in India with the given manufacturer specification. However, the quantity of



Manufacture Specification
Power Range = HP
Total Dynamic Head = 60 m
Maximum flow rate = 18 lps (64.8 $m^3 h^{-1}$)

Fig. 1 : ACM pump series

TABLE 1

Energy Equivalent Coefficient of Inputs

Inputs	Units	Energy Equivalent Coefficient (MJ $unit^{-1}$)	Reference
Machine	kg yr^{-1}		Kitani (1999)
Tractor and self-propelled	kg yr^{-1}	9 – 10	Kitani (1999)
Stationary Equipment	kg yr^{-1}	8 – 10	Kitani (1999)
Implement and Machinery		6 – 8	Kitani (1999)
Human labour	Hr	1.96	Kitani (1999)
Animal labour - a. cattle	Kg	5.05	Hatirli et al (2005)
Diesel	L	47.5	Kitani (1999)
Nitrogen (N)	kg	66.14	Omid et al (2011)
Phosphate (P_2O_5)	kg	12.44	Omid et al (2011)
Potassium (K_2O)	kg	11.15	Omid et al (2011)
FYM	kg	0.3	Ozkan et al (2004)
Water for Irrigation	m^3	1.02	Omid et al (2011)
Electricity	kWh	11.93	Singh et al (1999)
Seed	kg	15.2	Maheswarappaet al (2011)
Jowar product (output)	kg	14.7	Kitani (1999)

TABLE 2
Irrigation Efficiency

Soil class	Irrigation efficiency (%)
Sandy	60
Sandy loam	65
Loam	70
Clay loam	75
Heavy clay	80

Source : Ramachandra and Kamakshi (2005)

water pumped for irrigation depends on irrigation efficiency. To compensate for this, the irrigation efficiency (Table 2) of the agroclimatic zones was taking into consideration by matching the dominant soil characteristics of the zones. Thus, total quantity of water (Q) was evaluated using the expression

$$Q = \text{flow rate} \times \text{hours used} \times \text{pump efficiency} \times \text{irrigation efficiency} \quad .....(1)$$

The indirect energy consumed for pumping the quantity of water as estimated in eqn (1) was evaluated following Khoshnevisan *et al.* (2013) expressed in equation (2) as

$$IDE = \frac{\gamma hgHQ}{\varepsilon_p \, \varepsilon_q} \quad ....(2)$$

IDE = Indirect Energy (MJ/ha), g = acceleration due to gravity (ms^{-2}), H = total dynamic head (m) of the pump (Fig.1), Q=volume of water calculated ($m^3 ha^1$), γ = density of water ($kg\ m^{-3}$), ε_p = pump efficiency (80 %), ε_q = total power conversion efficiency (19 %), h = the dept of the well from which the water was pumped and was assummed to be the water table level of a given geographical area. For the purpose of this study, water table for each zone was estimated by agregating the maximum water table level of the districts that constitute each zone for the months May 2016, August 2016, November 2016 and January 2017.

Electricity Consumption for Irrigation (E)

The total quantity of electricity consumed for pumping the water was evaluated as

$$E = \text{power } (HP) \times \text{total hours of irrigation} \times \varepsilon_p \quad ......(3)$$

1 HP = 746 Watt = 0.746 kW. The horse power of the pumping machine was determined using the manufacturer specification of the considered pump illustrated above (Fig. 1).

Diesel Consumption (DC)

The consumption of diesel for farm operation was assumed to be under conventional tillage where the basic implement used by farmer were cultivator and disc harrow. Following Goyal *et al.* (2010), maximum fuel consumption of tractor with these implement attached was estimated as 4.1 L/hr. Thus, direct consumption of of diesel (DC) was calculated as

$$DC = 4.1 \times \text{total machine labour used} \quad ......(4)$$

Energy of Carbon-based Inputs

Total Fertilizer based inputs energies were computed as

$$\sum_{l=1}^{n} fert\,(N, P, K)_i \times C_f \quad .... (5)$$

Where N, P, K are the quantity used by the farmers, C_f = Energy equivalent co-efficient (see appendix for the co-efficients) (Table 1).

Mechanical Energy

The machinery energy was calculated by using the formula following Hatirli *et al.* (2005) as expressed as

$$ME = \frac{EG}{TC_a} \quad ....(6)$$

Where G is the weight of the machine (kg), E is the production energy of machine ($MJ\ kg^{-1}\ yr^{-1}$) T is the economic use (hrs) of machinery, C_a is the effective field capacity ($ha\ h^{-1}$) calcualted as

$$C_a = \left(\frac{S \times W \times E_f}{10}\right) \quad ....(7)$$

S is the working speed (km/h), W is the working width, E_f is the the field efficiency was estimated following the methodology of Hancock *et al.* (1991) as expressed in equations 8.

$$E_f = \frac{\text{Effective field capacity (EFC)}}{\text{Theoritical field capacity (TFC)}} \quad ....(8)$$

These calculations were done by assuming a single axle tractor (1745 kg) and standard mould board plough and disc harrow for conventional tillage practices. Following Canacki *et al.* (2005) and Hatirli *et al.* (2005) the following equations were adopted for the estimations of the energy input output relationships

a. $$\text{Energy Ratio} = \frac{\text{Total Energy output (MJ)}}{\text{Total Energy input (MJ)}} \quad ....(9)$$

b. $$\text{Energy Productivity} = \frac{\text{Grain Yield (kg)}}{\text{Total Energy output (MJ)}} \quad ....(10)$$

c. $$\text{Specific Energy} = \frac{\text{Total Energy input (MJ)}}{\text{Grain Yield (kg)}} \quad ....(11)$$

Sustainability Index

Sustainability indices for each year was computed (Lal, 2004) as per the Eqn. 12

$$C_s = \frac{(C_o - C_i - \text{GHG emission})}{C_i} \quad ....(12)$$

Where C_o and C_i are the carbon content of output and input, respectively. The carbon-based output includes operations that involved harvesting, threshing of jowar grain and the management of crop residues whereas the carbon-based inputs included farm operation management practices such as fertilizer application, irrigation and tillage operation.

Greenhouse Gas (GHG) Emission Estimation

The estimation of GHG emission in the present study only considered emission level at farm gate (cardle-gate). Moreover, we emphasize primarily on CO_2 emission and GHG will be used from here onwards to connotes CO_2 emission. Greenhouse emission was estimated according to internationally accepted method of accounting for GHG emission (Tier 1of IPPC methodology).

Carbon Emission from Burning of Residues

The total biomass produced during the production process was computed using the relationship

$$\text{Total Biomas} = \frac{\text{Economic Yield (Agronomic Yield)}}{\text{Harvest Index (HI)}} \quad ....(13)$$

The value HI of 0.4 for course cereal was adopted from Maheswarappa *et al*. (2011). The emission released from burning of remaing straw generated from the biomass produced was estimated using the formula (IPCC, 2007).

$$CE = \text{Total Biomass} \times \text{Average Dry Matter Fraction} \times \text{Fraction Actually Burnt} \times \text{Fraction Oxidised} \times \text{Carbon Fraction} \times E_f \quad ....(14)$$

CE is the carbon equivalent produced, Dry matter fraction = 0.4, Carbon Fraction = 0.4709, Fraction of oxidation = 0.90, Fraction actually burnt = 0.10 (10%), Carbon emission factor (E_f) = 11.7 g/kg = 0.0117 kg / kg.

The carbon footprint of the production process was evaluated as

$$\frac{Total\ emission\ (kg\ CO_2\ eq\ ha^{-1})}{Total\ agronomic\ yield\ (kg)} \quad ....(15)$$

Environmental Efficiency and Productivity Measurement

During production process, individual decision-making unit (DMUs) produces desirable (jowar grain) along with undesirable outputs (CO_2) which is harmful to environmental sustainability. To incorporate undesirable outputs in the production process, the study adopt Envronmental Production Technology (EPT) that models the joint of outputs differently to estimate potential of energy saving and emission reduction as developed by Fare *et al*. (2005) as illustrated in the diagram (Fig. 2).

The environmental production technology is then defined as

$$T = \{ (x,y,b) \mid x \text{ can produce } (y,b) \} \quad ....(16)$$

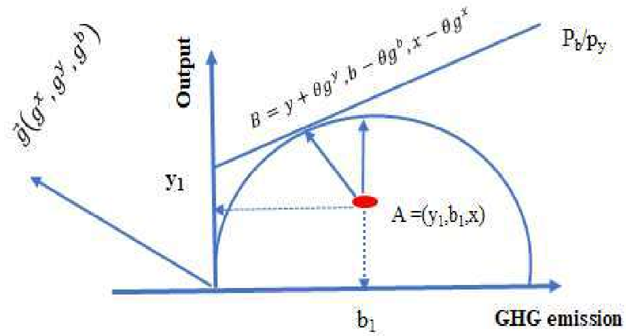


Fig. 2: Environmental production technological set

In order to ensure appropraite modelling of the technological function, strong disposability of inputs and desirable outputs expressed as

$$(x, y, b) \in T, x' \geq x \; or \; y' \leq y$$
$$\Rightarrow (x', y, b) \in T \; or \; (x, y', b) \in T;$$

Weak disposability of undesirable outputs expressed as

$$(x, y, b) \in T, 0 \leq \theta \leq 1 \Rightarrow (x, \theta y, \theta b) \in T;$$

Null-jointness of desirable and undesirable outputs expressed as

$$(x, y, b) \in T, b = 0 \Rightarrow y = 0$$

were assumed. Given the above technological set, the desirable undesirable directional distance function that seeks to maximize the production of desirable output was constructed as

$$\overrightarrow{D_T}(x, y, b, g^x, g^y, g^b) = \sup\{\theta | x - \theta g^x, y + \theta g^y, b - \theta g^b) \in T\} \quad ....(17)$$

Where (g^x, g^y, g^b) ε R_+^{m+s+q} is the directonal vector. Following Hampf and Krüger (2015), the optimization problem below was solved to the compute the eco-efficiency value (θ).

$$\min_{\theta, \alpha_y \alpha_b} \theta$$
$$\text{S.t. } X_i \geq \lambda X$$
$$y_i + \theta \alpha_y \odot y_i \leq \lambda Y$$
$$b_i - \theta \alpha_b \odot b_i = \lambda b$$
$$1' \theta \alpha_y + 1' \theta \alpha_b = 1$$
$$\theta \alpha_y, \theta \alpha_b, \lambda \geq 0$$

where '$\odot$' denotes the direct (Hadamard) product with θ and λ maximizing the objective function towards the distance frontier function. In this study, we employ a panel data (x_{it}, y_{it}), $t = 1, ..., T$ and assume that E (x_i, y_i) is constant over time at least by approximation. Thus, we calculate the differences from the mean as,

$$x_{it} - \bar{x}_i, y_{it} - \bar{y}_i$$

where

$$\bar{x}_i = \sum_{t=1}^{T} x_{it}, \bar{y}_i = \sum_{t=1}^{T} y_{it}$$

The sample variance was evaluated as

$$\sigma_x^2(g^x) = \frac{1}{T}\sum_{t-1}^{T}(x_{it} - \bar{x}_i)^2 \quad \sigma_y^2(g^y) = \frac{1}{T}\sum_{t-1}^{T}(y_{it} - \bar{y}_i)^2$$
$$\text{and} \quad \sigma_b^2(g^b) = \frac{1}{T}\sum_{t-1}^{T}\left(b_{it} - \bar{b}_i\right)^2$$

Thus, we employed the directions vector of

$$\vec{g} = (-\sigma_x^2(g^x), \; \sigma_y^2(g^y), \; -\sigma_b^2(g^b))$$

for the inputs, desirable and undesirable outputs respectively as the study aimed at improvement in energy conservation, reducing undesirable output without jeopardizing the economic output. To evaluate productivity change that incorporate the undesirable output, Malmquist–Luenberger index (MLI) that employs directional distance function through the framework of DEA was adopted. The MLI was expressed as

$$\text{MLI} = \left[\frac{\left(1 + D_0^t(X^t, y^t. b^t; y^t, -b^t)\right)}{\left(1 + D_0^{t+1}(X^{t+1}, y^{t+1}. b^{t+1}; y^{t+1}, -b^{t+1})\right)} \times \frac{\left(1 + D_0^{t+1}(X^t, y^t. b^t; y^t, -b^t)\right)}{\left(1 + D_0^t(X^{t+1}, y^{t+1}. b^{t+1}; y^{t+1}, -b^{t+1})\right)}\right]^{1/2} ......(18)$$

where t=1…,T denotes periods of study and $D_o^t(X^t, y^t. b^t; y^t, -b^t)$ is the distance function for frontier in period t+1 while assessing a DMU from period t. However, to explore the relationship between production and greenhouse gas (GHG) emissions in the jowar production for effective policy, decoupling elasticities for the period 2009–2018 period was calculated as

$$elasticity = \frac{\%\Delta Emission}{\%\Delta Agronomic\ yeild} = \left[\frac{\left(\frac{Emssion_{\ 2018} - Emission_{2009}}{Emission_{2009}}\right)}{\left(\frac{Yield_{\ 2018} - Yield_{2009}}{Yield_{2009}}\right)}\right] \quad ......(19)$$

RESULTS AND DISCUSSION

Energy Utilization Pattern in Jowar Production in Karnataka State

Comprehensive summary of input and output energies consumption in jowar production are presented in Table 3. The estimated average input energy consumption increased from 7310.27 MJ ha^{-1} in 2009 to 17487.08 ha^{-1} in 2018 at significant annual growth rate of 4.2 per cent. However, the estimated result revealed significant fluctuation in energy consumption during the study period as evident by the sharp decline in energy consumption between 2015 and 2016 due to failure of fertilizer subsidy policy of government resulting in high price of chemical fertilizer and thus impacted the input use and hence reduction in energy consumption (Himanshu, 2015). This result is similar to studies conducted by Sah & Devakumar (2018) and Benbi (2018) who reported similar trends of input energy usage in Indian agrarian system. Further analysis on the form of energy used in the production process revealed that the farmers used inputs that indirectly emit and release emission into the environment as indicated by highest energy from the indirect and non-renewable sources of energy (Fig. 3) at an exponential rate 3 and 3.6 per cent, respectively implying a change in energy use dynamics and over reliance on fossil fuel, mechanical energy

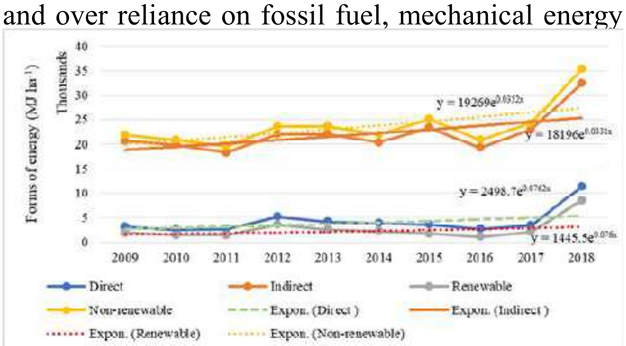


Fig. 3 : Forms of energy used in Jowar production

and the use of old electric water pumps with low power conversion efficiency as revealed by the energy composition that 23 per cent of total input energy consumed was direct energy dissipated as a result of the use of farm machinery during seed bed preparation. Chemical fertilizer consumption (N, P_2O_2, K_2O) accounted for 26 per cent (22,885.94 MJ) followed by diesel consumption presenting 19 per cent energy consumed and indirect energy from irrigation accounted for 17 per cent of total input energies during the study period. This higher energy from irrigation is due to the dropping levels of ground water resources and pumping machines with low power conversion efficiency hence, higher amount of irrigation energy is required to lift the quantity of water sufficient for crop growth. The energy indicators derived from the input and output energies showed that energy consumed to produce 1 kg of jowar during the period increased from approximately 31 MJ kg^{-1} in 2009 to 50 MJ kg^{-1} in 2018 production season at an annual growth rate of 4.8 MJ kg^{-1} signifying divergence in energy consumption. During the same period, energy use efficiency decreased from 2.61 in 2009 to 2.26 in 2018 at an annual growth rate of 1.6 percent with cyclical pattern as well as energy productivity also decreased from 0.06 kg MJ^{-1} to 0.05 kg MJ^{-1} in the same period implying energy-used inefficiency. Comparison of input energy consumption based on the system of farming (irrigated and non-irrigated) presented in Table 4 revealed a significant difference in input energies usage between the farming systems with an average of 21708.14 MJ ha^{-1} for irrigated farming system as compared to 6817.14 MJ ha^{-1} in non-irrigated farming system The results revealed that chemical fertilizer consumption accounting for 14.2 per cent in irrigated farming systems as compared to 31.9 per cent in non-irrigated farming system. Higher energy from fertilizer in rainfed agriculture was expected because they typically tend to increase the productivity of piece of land through high consumption inputs.

Despite the use of water to improve crop productivity in irrigated farms, the estimated energy use indicators in non-irrigated farms were significantly higher than irrigated farming system implying efficient conversion

TABLE 3

Forms of energy used in Jowar production

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	CAGR
A. Input Energy (MJ ha^{-1})											
Human labour	909.99	780.15	703.55	836.69	785.36	859.61	854.29	640.34	747.95	854.20	-0.71
Animal power	317.48	251.67	224.72	233.65	222.59	219.51	222.59	212.27	201.54	194.50	-3.81
Seed	111.62	120.48	117.47	134.92	144.83	122.98	396.96	137.84	125.58	152.86	4.33
Chemical fert	2236.57	1789.83	1532.05	2841.49	2048.64	2922.58	3099.08	1731.47	1622.84	3061.41	2.06
Machinery	1826.61	1790.06	1664.87	1901.62	1983.09	1727.64	1981.64	1736.11	2124.76	2922.29	3.47
Diesel	1368.28	1153.00	1311.81	1560.33	1682.54	1660.16	2178.53	1739.31	1369.05	2702.58	6.07
Irrigation water	511.80	287.79	422.50	2341.54	1341.36	1039.46	275.10	94.82	1013.19	7265.14	11.89
Electricity	27.94	23.18	19.01	170.14	86.46	55.21	14.09	9.18	66.36	334.10	11.62
Total input energy	7310.27	6196.16	5995.99	10020.38	8294.87	8607.15	9022.28	6301.34	7271.27	17487.08	4.20
B. Output Energy (MJ ha^{-1})											
Output Energy	46925.81	37830.62	33121.70	52432.45	44962.83	64205.48	47558.61	28967.00	36126.65	55937.17	0.40
Indicators											
SE (MJ kg^{-1})	30.96	43.58	35.35	40.82	36.86	26.84	38.53	68.42	46.68	49.87	4.70
ER	2.61	2.16	1.91	2.33	2.09	3.10	2.29	1.48	1.94	2.36	-1.56
EP (kg MJ^{-1})	0.06	0.05	0.04	0.05	0.05	0.07	0.05	0.03	0.04	0.05	-1.56
Sustainability index	1.61	1.16	0.91	1.33	1.09	2.10	1.29	0.48	0.94	1.36	-3.35

SE = Specific energy; ER = Energy ratio; EP = Energy productivity

TABLE 4

Energy use pattern in different farming system

Source of Energy	Irrigated system	Non-Irrigated System	Large farms (>4 ha)	Medium farms (<= 4 ha)	Small farms (<= 2 ha)
A. Input Energy (MJ ha^{-1})					
Human labour	973.37	777.00	472.95 ^{a}	551.48 ^{b}	871.18 ^{b}
Animal power	199.32	240.04	118.50 ^{a}	140.07 ^{b}	260.46 ^{b}
Seed	140.47	155.68	107.60 ^{a}	116.54 ^{a}	163.82 ^{a}
Chemical fertilizer	3091.32	2171.96	2157.06 ^{a}	1736.05 ^{ab}	2410.95 ^{b}
Machinery	2892.45	1831.70	3249.30 ^{a}	6755.94 ^{b}	2320.47 ^{b}
Diesel	1874.83	1640.74	1893.02 ^{a}	1560.07 ^{a}	1681.85 ^{a}
Irrigation water	11879.52	0.00	164.54 ^{a}	143.00 ^{ab}	1879.82 ^{b}
Electricity	656.87	0.00	7.40 ^{a}	6.87 ^{ab}	104.25 ^{b}
Total input energy	21708.14	6817.14	8,170.39 ^{a}	11,010.02 ^{b}	9,692.80 ^{b}
B. Output Energy (MJ ha^{-1})					
Output	55208.79	43308.99	36162.96 ^{a}	38387.60 ^{b}	4662.40 ^{ab}
C. Indicators					
SE (MJ kg^{-1})	52.13	39.82	23.55 ^{b}	24.45 ^{b}	45.99 ^{a}
ER	1.69	2.31	4.37 ^{a}	3.43 ^{b}	1.87 ^{c}
EP (kg MJ^{-1})	0.04	0.05	0.10 ^{a}	0.07 ^{b}	0.04 ^{c}
Sustainability Index	0.69	1.31	3.37 ^{a}	2.43 ^{b}	0.87 ^{c}

Note: SE = Specific Energy, ER = Energy Ratio, EP = Energy productivity. Different superscript letters show significant difference of means at $p < 0.05$ according to Duncan's multiple range test

of the inputs energies into higher output energy thus much more sustainable as 39.82 MJ of energy is required to produce 1 kg of jowar grain as compared to 52.13 in irrigated farming indicating mismanagement of resources and failure to convert water resources to enhance crop yields and consequently low output energy. From Table 4 , the comparison of input energy consumption based on the farm size showed that the average the consumption was higher in medium farms (11,010 MJ ha^{-1}) as compared to small farms (9,692.80 MJ ha^{-1}) and large farms (8,170 MJ ha^{-1}). This result is similar to study conducted by Prasannakumar (2016) who observed similar trend of energy consumption among large, medium and small-scale rice farmers in Karnataka state. The results demonstrated significant differences in average levels of total input energy utilization. Although, medium farms had the highest consumption of input energy, the analysis of the energy use indicators revealed that large farms had significantly higher sustainability index than the other farm size group which implies scale efficiency of energy use as 23.55 MJ of energy is required to produce 1 kg of jowar grain compared to medium and small farms of intensity factor of 24.45 and 45.99, respectively.

Furthermore, variability in energy consumption across the various agroclimatic zones (Table 5) revealed

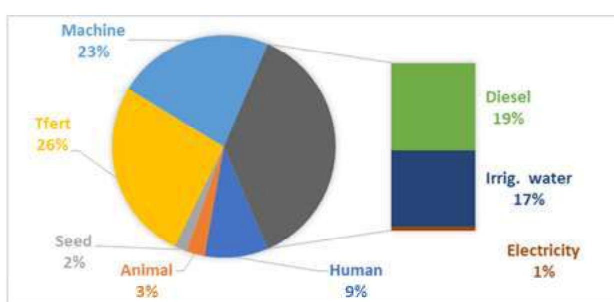


Fig. 4 : Contribution of inputs in total inputs energy in jowar production

TABLE 5

Sources of energy use in jowar production across agroclimatic zones in Karnataka

	Output Energy (MJ ha^{-1})	Input energy (MJ ha^{-1})	SE (MJ kg^{-1})	ER	EP (MJ kg^{-1})	Sustainability Index
CDZ	46300.16 ^{a}	8351.15 ^{a}	85.83	1.65	0.04	0.65
HZ	39497.55 ^{ab}	8809.41 ^{ab}	35.02	1.78	0.04	0.78
NDZ	46613.03 ^{b}	9897.75 ^{ab}	39.00	2.40	0.05	1.40
NEDZ	38650.03 ^{b}	6995.69 ^{ab}	38.44	2.14	0.05	1.14
NETZ	42235.85 ^{b}	5507.54 ^{ab}	35.13	2.21	0.05	1.21
NTZ	41441.53 ^{b}	7645.30 ^{ab}	51.16	1.81	0.04	0.81
SDZ	51693.75 ^{b}	6844.56 ^{b}	23.53	1.95	0.04	0.95
STZ	82824.70 ^{b}	10429.68 ^{b}	32.20	2.75	0.06	1.75

EP = Energy Productivity, SE = Specific Energy, ER = Energy Ratio

Note: Different superscript letters show significant difference of means at $p < 0.05$ according to Duncan's multiple range test

significant differences in the use of energy inputs across the zones. Southern Transitional Zone (STZ) differed significantly from the other zones with the highest (10,429.68 MJ ha^{-1}) consumption of energy with the least (8351.15 MJ ha^{-1}) observed in Central Dry Zone. The principal drivers of input energy consumption were chemical fertilizer, irrigation water energy, diesel and machinery. Among the zones highest consumption of water, electricity was observed in STZ with least observed in North Eastern Transition Zone (NETZ) and Northern Transition Zone (NTZ). This result was expected as the soil characteristics in STZ is dominated by sandy loam and thus, low irrigation efficiency whilst the soils in NETZ and NTZ are clay dominated and hence higher irrigation efficiency that result in low requirement of water. The production process in Hilly Zones and Southern Dry Zone was fertilizer and labour dependent. The high consumption of fertilizer in these zones could be due to the low fertility of the soil as the dominated soils is red sandy loam. The average energy efficiency for the zones were determined to be above one implying energy consumption across the zones was efficient whilst the lowest was observed in CDZ. The sustainability index for southern transitional zone was found to be relatively higher as compared to the other zones. On the other hand, central dry zones accounted for the lowest sustainability index with highest consumption of approximately 85.83 MJ of energy in producing 1 kg of jowar grains.

Greenhouse Gas (GHG) Emission Pattern in Jowar Production

GHG emission was investigated to determine the role of energy utilization in environmental condition of jowar production (Table 6). The total GHG emission

TABLE 6

Greenhouse emission pattern in jowar production

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	CAGR
Total GHG (kg CO_2 eq ha^{-1})	3018	2659	2428	3546	3169	3459	3116	2356	3032	5026	3.12*
CFP (kg CO_2 eq kg^{-1})	3.53	4.44	3.82	4.37	3.96	3.2	3.81	6.3	4.77	5.32	3.75**

NB : GHG = Greenhouse gas, CFP = Carbon footprint, *, **, indicates level of significance at 10 and 5 % probability level respectively of jowar production was approximately estimated at 3018 kg CO_2 eq ha^{-1}in 2009 production season to 5026 kg CO_2 eq ha^{-1} in 2018 at a compound annual growth rate of 3.12 per cent signifying increasing level of emission in jowar production. However, the result revealed that production of 1 kg jowar grain results in emission of 4.4 CO_2 eq ha^{-1}on average at an annual growth rate of 3.75 implying increase in carbon emission intensity and environmental pressure from the production system.

The detailed analysis revealed that maximum amount of CO_2 emission was due to machinery usage contributing approximately 44 per cent (3,957.67 kg CO_2 eq ha^{-1}) of the total emission during study period followed by chemical fertilizer contributing (8%) 2445.44 kg CO_2 eq ha^{-1} and dissipated emission from irrigation facilities contributed (4%) 1464.27 kg CO_2 eq ha^{-1}. Threshing and processing of the grain into seed constituted (36%) (11,314.33 kg CO_2 eq ha^{-1}) to total emission. These results are in line with the study conducted by Kashyap and Agarwal (2021) who reported similar drives of emission in wheat and rice production in Punjab State.

Carbon Footprint among Farming Systems, Farm Sizes and Across Agroclimatic Zones in Karnataka

The carbon footprint of both farming systems was found to be significantly different. On average, irrigated farming system emits 5879 kg CO_2 eq ha^{-1} with carbon intensity factor 6.08 CO_2 eq ha^{-1} as compared to non-irrigated farming with emission value and intensity factor of 2797 kg CO_2 eq ha^{-1} and 4.07 CO_2 eq ha^{-1}, respectively. CFP of the Central Dry Zone was found to be relatively higher, as compared to the other zones with Southern transitional zone accounted for the lowest carbon footprint (CFP). CFP pairwise comparison among different farms sizes (Table 6) was significantly different among the farms with the highest significant carbon intensity factor (4.71 kg CO_2 eq kg^{-1}) observed in smaller farms as compared to medium and large farms. However, no significant difference was found between among large and medium farms.

The estimates decoupling elasticities are presented in Table 6 . The elasticities revealed that the sub farming system in jowar production differ in terms of management. The elasticities show that in an irrigation farming system yield production decreased with an expansion of GHG emissions (strong negative decoupling) where as large farms, medium farms and CDZ, NDZ other zone exhibited weak decoupling of energy and emission implying that rate of agricultural production increased faster than GHG emissions in the production process which is desirable to ensure environmental sustainability and food security. In SDZ and STZ expansion in agricultural production results in significant reduction GHG emissions indicating improvement in farm practices. The differences in elasticities reflect the extent diverse farm management practices towards GHG emissions removal thus, providing insights for policy formulation and hence environmental policies related to farming systems that consider the heterogeneity would be more effective than lumpsum policy for region or state.

Environmental Efficiency and Green Factor Productivity

The results of the environmental productivity and efficiency is presented in Table 8. The estimated parameters illustrated that the overall average eco-efficiency score for jowar production was 0.92 for the study period implying the production process was environmental inefficient with a decline in average total environmental productivity of 8.6 per cent. During the study period, there was no improvement or change in use of inputs to produce more desirable output (jowar grains) and lesser undesired output (CO_2) as depicted by the constant technical efficiency change. The decline in the environmental productivity was purely due to lack of technological adoption as revealed by retrogression technological effects during the study period. Thus, improvement in environmental governance in the agricultural production focusing on adjustment in input use structure taking into account the diversity across agroclimatic zones, faming systems will result in emission reduction potential without huge investment in new technology.

TABLE 7

Greenhouse gas emission in jowar production across farming systems and agroclimatic zones in Karnataka

	Emission level (kg CO_2 eq ha^{-1})	Carbon Footprint (kg CO_2 eq kg^{-1})	% Δ Yield	% Δ GHG	Elasticity	Interpretation
Systems of farming						
Irrigated system	5878.81	6.08	-0.42	0.48	-1.14	Strong negative decoupling
Non-irrigated system	2796.78	4.07	0.24	0.16	0.70	Weak decoupling
Farming size						
Large farms	1465.93	2.37	0.13	0.07	0.56	Weak decoupling
Medium farms	1769.70	2.86	0.36	0.14	0.38	weak decoupling
Small farms	3576.04	4.71	0.14	0.55	3.97	Expansive decoupling
Agroclimatic zones						
CDZ	3970.35	7.62	4.63	0.50	9.35	Weak decoupling
HZ	3236.3	4.01	-0.11	-0.42	0.27	Weak negative decoupling
NDZ	3269.34	4.16	0.19	0.99	0.19	Weak decoupling
NEDZ	2892.31	4.26	0.22	0.53	0.42	Weak decoupling
NETZ	2738.9	3.88	0.09	-0.01	-15.66	Strong decoupling
NTZ	2999.78	4.82	0.11	0.17	0.61	Weak decoupling
SDZ	3408.8	3.83	0.08	-0.07	-0.82	Strong decoupling
STZ	5590.09	3.01	0.41	-0.07	-6.29	Strong decoupling

Source : Authors computation

TABLE 8

Efficiency and green factor productivity

Year	θ	ML	MLTEC	MLTC
2009	0.82	-	1	
2010	0.97	1.039	1	1.039
2011	0.84	0.795	1	0.795
2012	0.88	0.519	1	0.519
2013	0.94	1.161	1	1.161
2014	0.86	1.495	1	1.495
2015	1.00	0.817	1	0.817
2016	0.92	1.063	1	1.063
2017	1.00	0.543	1	0.543
2018	0.91	0.590	1	0.590
Average	0.92	0.89	1	0.891

Source : Author's computation

Carbon footprint and sustainability of jowar production was quantified for farming system, farm size and across agro-climatic zones of Karnataka state using survey data of cost of cultivation from 2009 to 2018. The following salient findings were discovered.

1. The results revealed a shift in production process in which the tradition renewable dependent production system has been replaced with higher consumption of non-renewable energy sources in the form of higher consumption of machinery power, chemical fertilizer, irrigation and electricity with overriding impact and implication on ground water extraction. Since machinery, irrigation and fertilizer consumption are principal drivers in the non-renewable energy consumption, development of eco-friendly machines with higher energy conversion efficiency for farm operations and application of fertilizers either in terms of slow

released or coated or fortified fertilizers depending upon crop nutrient requirement would be essential for improving energy conservation and emission.

2. The ratio of carbon output to carbon input decreased over time period characterized by negative annual growth implying inability of farmers to convert input energy resources into economics output. Moreover, based on environmental assessment of the production process, the study found that the production process was environmentally inefficient characterized by retrogression of productivity and technological effect. Therefore, the government has a critical role to play by incentivizing adoption of existing technology along with spreading awareness on the technology through effective extension education.

3. Non-irrigated and large-scale farmers had higher sustainability index and lowest CFP. There was wider carbon footprint variability across agroclimatic zones. The Central Dry Zone had higher CF and low sustainability index as compared to other zones. Production process was more sustainable in Southern Transition Zone with lowest CF. Thus, government should reorient its programs by providing carbon incentives to encourage farmers to pursue climate-friendly activities by shifting to conservational tillage, reduced number of ploughings, intercropping with cover crops with high carbon absorption rate and use of renewable sources of energy such as the use of solar operated irrigation systems. However, given the wide variability in production performance across zones, farming system and size, farm management mitigation strategies to improve efficiency of resource and carbon reduction that consider agroclimatic diversity would be more effective than policies that focuses holistically at state or country level.

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References

Benbi, D. K., 2018, Carbon footprint and agricultural sustainability nexus in an intensively cultivated region of Indo-Gangetic Plains. *Sci. of the Total Env't.*, **644** : 611 - 623.

Blay, J. K. and Lokesha, H., 2022, Economic analysis of greenhouse gas emission reduction potential, energy-use and sustainability of maize production in Karnataka. *Economic Affairs*, **67**(3) : 239 - 250.

Chhabra, A., Manjunath, K. R., Panigrahy, S. and Parihar, J. S., 2013, Greenhouse gas emissions from Indian livestock. *Climatic Change*, **117** : 329 - 344.

Canakci, M., Topakci, M., Akinci, I. and Ozmezri, A., 2005, Energy use pattern of some field crops and vegetable production : Case study for Antalya region, Turkey. *Energy Conversion and Management,* **46** : 655 - 666.

Fare, R., Grosskopf, S., Noh, D. W. and Weber, W., 2005, Characteristics of a polluting technology : Theory and practice. *J. Econometrics,* **126** : 469 - 492.

Goyal, S. K., Samsher, K., Chandra, S., 2010, A study on fuel consumption and work performance of different tractors with tillage implements materials and methods. *Prog. Agric.* **10**(2) : 270 - 274.

Hancock, J. N., Swetnam, Larry, D. and Benson, F. J., 1991, *Calculating Farm machinery field capacities.* Agricultural Engineering Extension Publications. https://uknowledge.uky.edu/aen_reports/20.

Hampf, B. and Krüger, J. J., 2015, Optimal directions for directional distance functions : An exploration of potential reductions of greenhouse gases. *American J. Agric Econ.*, **97** : 920 - 938.

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

Himanshu, A., 2015, India's flawed fertilizer policy. *Mint publisher*. https://www.livemint.com/Opinion/XCCJwEzbzwiyWFYfK1wRdO/Indias-flawed-fertilizer-policy.html. Accessed 20/04/2022.

Inter Government Panel on Climate Change, 2007, Climate change 2007 : Mitigation contribution of working group III to the fourth assessment report of the inter government panel on climate chnage edited by Metz, O. R., Davidson, P. R., Bosch, R. D. and Meyer, L. A., cambridge University Press, Cambridge, UK.

Jaiswal, B., Agrawal, M., 2020, Carbon footprints of agriculture sector. S. S. Muthu(ed.), *Carbon Footprints*, Environmental footprints and eco-design of products and processes. https://doi.org/10.1007/978-981-13-7916-1_4.

Kashyap, D. and Agarwal, T., 2021, Carbon footprint and water footprint of rice and wheat production in Punjab, India. *Agricultural Systems*. **186** : 1 - 9. https://doi.org/10.1016/j.agsy.2020.102959.

Khoshnevisan, B., Rafiee, S., Omid, M. and Mousazadeh, H., 2013, Reduction of CO_2 emission by improving energy use efficiency of greenhouse cucumber production using DEA approach. *Energy*, **55** : 676 - 682.

Lal, R., 2004. Carbon emissions from farm operations. *Environ. Int*, **30**: 981–990.

Maheswarappa, H. P., Srinivasan, V., Lal, R., 2011, Carbon footprint and sustainability of agricultural production systems in India. *J. Crop Improvement*, **24** (4) : 303 - 322.

Prasannakumar, P. S., 2016, *Energy use in agriculture-An econometric analysis*. University of Agricultural Sciences. *Doctoral thesis* (unpublished).

Singh, S., Singh S., Pannu, C. J. S. and Singh, J., 1999, Energy input and yield relations for wheat indifferent agro-climatic zones of the Punjab. *Applied Energy*, **63**(4) : 287 - 298.

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**: 2275–2286.

Sah, D. and Devakumar, A. S., 2018, The carbon footprint of agricultural crop cultivation in India. *Carbon Management*, **9**(3): 213□225 .DOI: 10.1080/17583004.2018.1457908.

Vetter, S. H., Sapkota, T. B., Hillier, J., Stirling, C. M., Macdiarmid, J. I., Aleksandrowicz, L., Green, R., Joy, E. J. M., Dangour, A. D. and Smith, P., 2017, Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation. *Agriculture, Ecosystems and Environment*, **237** : 234 - 241.

Yousefi, M., Khoramivafa, M. and Damghani, A. M., 2016, Water footprint and carbon footprint of the energy consumption in sunflower agroecosystems. *Environ. Sci. Pollut. Res.* DOI 10.1007/s11356-017-9582-4.