Energy-carbon-water footprint of sugarcane bioenergy
A district-level life cycle assessment in the state of Maharashtra, India

Hiloidhari, Moonmoon; Vijay, Vandit; Banerjee, Rangan; Baruah, D. C.; Rao, Anand B.

DOI
10.1016/j.rser.2021.111583

Publication date
2021

Document Version
Final published version

Published in
Renewable and Sustainable Energy Reviews

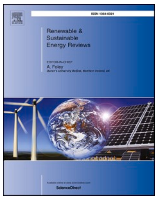
Citation (APA)
Hiloidhari, M., Vijay, V., Banerjee, R., Baruah, D. C., & Rao, A. B. (2021). Energy-carbon-water footprint of sugarcane bioenergy: A district-level life cycle assessment in the state of Maharashtra, India. *Renewable and Sustainable Energy Reviews*, *151*, Article 111583. https://doi.org/10.1016/j.rser.2021.111583

Renewable and Sustainable Energy Reviews 151 (2021) 111583

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Energy-carbon-water footprint of sugarcane bioenergy: A district-level life cycle assessment in the state of Maharashtra, India

Moonmoon Hiloidhari [a,b,*], Vandit Vijay [c,d], Rangan Banerjee [a,e], D.C. Baruah [f], Anand B. Rao [a,g,**]

[a] IDP in Climate Studies, Indian Institute of Technology Bombay, Mumbai, 400076, India
[b] Green Story, Social Ventures Zone (KHS42), Ryerson University, 40 Gould Street, Toronto, Canada
[c] Climate Institute, Delft University of Technology, Delft, the Netherlands
[d] Centre for Rural Development and Technology, Indian Institute of Technology Delhi, New Delhi, 110016, India
[e] Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Mumbai, 400076, India
[f] Department of Energy, Tezpur University, Tezpur, 784038, Assam, India
[g] Centre for Technology Alternatives for Rural Areas (CTARA), Indian Institute of Technology Bombay, Mumbai, 400076, India

ARTICLE INFO

Keywords:
Sugarcane
Bagasse
Bioenergy
Cogeneration
Life cycle assessment
Energy-carbon-water footprint

ABSTRACT

Sugarcane bagasse-based cogeneration contributes significantly to bioenergy conversion in India and therefore, appropriate performance analysis is required considering the regional factors. Further increase of sugarcane bioenergy is expected in India with the Government's mandate to enhance the share of renewable energy by 2030. Herein this study, district-wise sugarcane bagasse cogeneration potential is assessed in the state Maharashtra, India. Variations in energy, carbon and water footprint of energy generated from bagasse-based cogeneration plants are also assessed for all the districts considering farm to gate attributional life cycle assessment (ALCA). Avoided product function (also called as System expansion) of simaPro 9.2 LCA software is used to assess the environmental benefits of sugarcane waste or by-products (leaves and tops, press-mud and bagasse ash). The annual bagasse production potential in Maharashtra is 19 million tonne, equivalent to 8206 GWh of cogenerated electricity. The potential varies markedly among the districts (2–1500 GWh). Nearly 81 % of cogeneration potential is concentrated in 6 districts alone. The life cycle carbon footprint (0.075–0.2 kg CO_2e/kWh), the energy footprint (0.75–2.12 MJ/kWh) and the water footprint (206–516 L/kWh)-all the three estimated on the life cycle basis- differ considerably among the districts. The nexus among water, energy, and carbon footprint for sugarcane bioenergy is also analyzed to understand the complex interconnectivities among these individual resources. Cultivating high yielding varieties, use of renewable energy-based micro-irrigation, and installing modern cogeneration technology can lower the estimated carbon, energy and water footprint by up to 50 %. Such measures will help enhance farmers' income while addressing the sustainability issues in India.

Abbreviations: °C, Degree Celsius; BOD, Biological Oxygen Demand; BECCS, Bioenergy with Carbon Capture and Storage; BP, Back Pressure; CH_4, Methane; COD, Chemical Oxygen Demand; CO_2, Carbon dioxide; CO_2e, Carbon dioxide equivalents; CED, Cumulative Energy Demand; CF, Carbon footprint; DEC, Double Extracting Condensing; EF, Energy footprint; EROI, Energy Return on Investment; ET, Evapotranspiration; $FeSO_4$, ferrous sulfate; FU, Functional unit; GIS, Geographical Information System; GHG, Greenhouse gas; GWh, Gigawatt hour; GWP, Global warming potential; h, Hour; ha, hectare; hp, horsepower; HP, High pressure; ISO, International Standards Organization; K, Potassium; kg, kilogram; kWh, Kilowatt hour; kt, kilotonne; L, Litre; LCA, Life Cycle Assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; LP, Low pressure; m^3, Metre cube; MCS, Monte Carlo Simulation; mg, milligram; MJ, Megajoule; $MnSO_4$, Manganese(II) sulfate; mt, million tonne; MW, Megawatt; N, Nitrogen; N_2O, Nitrous oxide; OMC, Oil Marketing Companies; P, Phosphorus; PM, Particulate Matter; S, Scenario; SDG, Sustainable Development Goal; t, tonnes; TCD, tonne crushed per day; TPH, tonne per hour; TWh, Terawatt hour; US EPA, United States Environmental Protection Agency; WCP, Water Consumption Potential; WF, Water footprint; $ZnSO_4$, Zinc sulfate.

* Corresponding author. IDP in Climate Studies, Indian Institute of Technology Bombay, Mumbai, 400076, India.
** Corresponding author. Centre for Technology Alternatives for Rural Areas (CTARA), Indian Institute of Technology Bombay, Mumbai, 400076, India.
E-mail addresses: moonmoon@iitb.ac.in (M. Hiloidhari), a.b.rao@iitb.ac.in (A.B. Rao).

https://doi.org/10.1016/j.rser.2021.111583
Received 26 October 2020; Received in revised form 1 July 2021; Accepted 7 August 2021
Available online 16 August 2021

1. Introduction

Renewable energy is vital to meet the temperature reduction target of the Paris Agreement and also to meet the Sustainable Development Goal 7 (SDG 7: Affordable and Clean Energy) of the United Nations [1]. Among renewables, biomass is currently the most noteworthy contributor to energy supply, providing ~10 % of global primary energy demand [2]. The global biomass electricity generation has grown from 132 TWh in 2000 to 589 TWh in 2019 and could provide 1168 TWh of electricity by 2030 [2]. Sugarcane cultivation expansion is a global trend due to its interventions in food, energy, and economic development agendas of several nations. Agrarian countries like India, China can particularly take advantage of agro-residue based bioenergy from sugarcane to improve rural energy scenario and also to decrease the greenhouse (GHG) emissions from its energy sector.

Sugarcane bagasse is commonly used to produce renewable heat and electricity via cogeneration process throughout the world. The annual bagasse electricity potential of the world is reported to be 135,029 GWh [3]. Notable examples of successful implementation of bagasse cogeneration include India [4], Brazil [5] and Cuba [6]. India ranks second for sugarcane production in the world. About 7547 MW bagasse cogeneration has been installed in India as of 2020, i.e., 70 % of the total installed biomass power capacity of the country. The major share of installed cogeneration capacity is contributed by Maharashtra (2351 MW), Uttar Pradesh (1929 MW), Karnataka (1730 MW), Tamil Nadu (750 MW), and Andhra Pradesh (207 MW) [7]. There is further scope to increase the cogeneration potential in India through precise resource assessment, integrating cogeneration facilities in every sugar mill and replacing conventional low pressure boiler with modern high pressure (HP) boiler. In traditional sugar factories, low pressure (LP) boiler (<40 bar) is used for heat and electricity generation to meet the internal energy requirement of the sugar factories only. Cogeneration with HP boiler requires lesser amount of bagasse input, resulting in more number of operation days and surplus production of electricity which can be exported to the centralized grid [8]. With increasing awareness and demand for clean energy generation, Government mandates and incentives, sugar factories in India have been gradually shifting towards modern efficient cogeneration technology.

Biomass cultivation, processing, and its supply chain logistics are spatially interlinked. Therefore, the environmental impact of biomass cultivation and bioenergy varies spatially. Life cycle assessment (LCA) can be successfully applied to assess the environmental performance of a product or system over its lifetime. There has been successful application of LCA in bagasse cogeneration studies in different countries, for example, Brazil [9], Mauritius [10], South Africa [11], Thailand [12], Iran [13], Cuba [14], Mexico [15], Jamaica [16] and Australia [17]. Although the studies vary in terms of the system boundary, inventory and impact assessment method, all suggest that GHG emission from bagasse electricity is much less than fossil electricity.

Literature on district-level bioenergy potential assessment is limited in India. A district is an administrative division of states in India. District-level bioenergy potential indicates the energy generation potential available from various biomass resources (e.g., agricultural residues, livestock manure, municipal solid waste, forestry, and horticultural waste) within a particular district administrative boundary. Spatially explicit biomass databases are important to support the decision makers and bioenergy industry sector at local scale [18]. The lack of local biomass information, for example in smallholder farming systems, hampers the development and dissemination of bioenergy technologies suitable for decentralized applications [19]. The use of local inventory is helpful to enhance biomass mapping accuracy and aid carbon emission reduction programs and policymaking [20]. Similarly, district-level LCA studies of bioenergy are also limited in India. The outcomes of LCA studies could vary significantly with local agro-climatic conditions, agricultural practices (e.g., differences in application of fertilizer, pesticide, and irrigation), crop productivity, and land-use change effects [21]. Using regional or national values to plan for district-level bioenergy programs may significantly under/over-estimate the resource potential and environmental consequence of bioenergy.

Given the above discussions, the present research is conducted in the state of Maharashtra, India at district-level for each 26 sugarcane producing districts. Administrative district is chosen because the district administration is primarily responsible for implementing central and state government policies. The objectives are (i) Estimation of bagasse production and electricity cogeneration potential, (ii) Evaluation of life cycle energy, carbon and water footprint of bagasse cogeneration, and (iii) Assessing the energy-carbon-water nexus of sugarcane bioenergy.

2. Materials and method

2.1. *Sugarcane cultivation and cogeneration in Maharashtra*

Maharashtra ranks second in sugarcane production in India with annual sugar production of 11 million tonnes (mt), 33 % of national output [22]. Sugarcane is cultivated in nearly 0.9 million ha of land in the state [23]. Out of the 36 districts, sugarcane is cultivated in 26 districts. Sugarcane yield varies from district to district, and ranges from 41 to 117 t/ha with a state average of 85 t/ha [23]. Nearly 80 % of Maharashtra's sugarcane production is contributed by six districts alone (Kolhapur, Pune, Solapur, Ahmednagar, Sangli, and Satara) as shown in Table 1.

Four different seasons for sugarcane cultivation *viz.* adsali, ratoon, preseasonal, and suru prevail in Maharashtra [22,24]. Adsali is the longest duration crop (17 months). Due to the extended maturity time, productivity is high (112 t/ha), but water, fertilizer, and other resources inputs are high. Therefore, districts with low rainfall do not cultivate adsali sugarcane in Maharashtra. Preseasonal sugarcane takes about 14 months for maturity, and productivity is 84 t/ha. Suru is a 12 months duration crop with a productivity of 67 t/ha. Ratoon is a cultivation practice where the bottom part of the plant sugarcane is left in the field after harvesting for regeneration. Its cropping cycle is about 10–12 months with a productivity of 61 t/ha.

There are 241 sugar factories in Maharashtra with a total installed sugarcane crushing capacity of 0.8 million TCD (tonne crushed per day) as shown in Fig. 1 [22]. It should be noted that, in 2018, only 188 sugar factories were operational out of the total. Of the non-operational 53 sugar factories, 47 were also not operational in the previous sugarcane season, primarily due to low sugarcane production and financial crisis. There are 117 sugar factories that have electricity exportable cogeneration facilities with a total installed exportable capacity of 2232 MW, as shown in Fig. 2 [25]. Sugar factory-wise installed cogeneration capacity ranges from 1.5 to 44 MW. Generally, all the sugar factories meet their internal heat and electricity demand through bagasse cogeneration, but all of them are not able to export surplus electricity to the public grid due to the use of traditional low-pressure boilers for cogeneration.

2.2. *Estimation of bagasse cogeneration potential*

District-wise bagasse electricity cogeneration potential is estimated as below:

$$E_{cogen,\ i=}\frac{S_i \times SA_i \times BR_i \times BA_i}{SBC} \tag{1}$$

$E_{cogen,i}$ is annual exportable electricity cogeneration potential in *i*th district, kWh; S_i is annual sugarcane production in *i*th district, kg; SA_i is sugarcane availability factor in *i*th district, fraction; BR_i is bagasse recovery rate in *i*th district, fraction; BA_i is bagasse availability rate in *i*th district, fraction and *SBC* is specific bagasse consumption for cogeneration, kg/kWh.

District-wise sugarcane production (S_i) data is given in Table 1. A small amount of sugarcane is used in traditional jaggery (*khandsari*)

Table 1
District-wise sugarcane and cogeneration statistics in Maharashtra, India.

District[a]	Cultivation area[b], ha	Productivity, t/ha	Production, kt	Total sugar factories	Sugar factories operational in 2018	Electricity exporting sugar factories	Total installed exportable cogeneration capacity, MW
Ahmednagar	102115	85	8700	23	22	13	298.90
Akola	42	71	3	0	0	0	0
Amravati	310	45	14	1	0	0	0
Aurangabad	15954	60	964	10	6	2	17.75
Bhandara	3897	69	268	2	1	0	0
Beed	33608	46	1531	10	7	4	83
Buldhana	298	60	18	3	0	0	0
Chandrapur	55	73	4	0	0	0	0
Dhule	4522	82	370	2	0	0	0
Gondia	919	54	50	0	0	0	0
Hingoli	8520	50	430	4	4	1	18.90
Jalgaon	9619	80	770	7	3	2	13.50
Jalna	20184	53	1069	5	5	3	44
Kolhapur	140667	98	13798	23	22	15	348.15
Latur	35680	53	1891	12	8	4	60.30
Nagpur	3473	57	199	2	2	1	24.45
Nanded	17460	58	1004	8	5	0	0
Nandurbar	11748	79	930	3	3	0	0
Nashik	15976	83	1331	9	5	2	32
Osmanabad	35680	41	1477	16	10	5	108.50
Parbhani	25000	55	1369	6	5	3	65.50
Pune	119829	109	13085	18	17	14	251
Sangli	74727	107	8004	18	15	8	137.70
Satara	65255	103	6703	15	14	10	172
Sindhudurg	961	81	78	0	0	0	0
Solapur	135290	84	11347	38	31	29	540.75
Wardha	2917	63	183	2	1	1	15
Washim	162	43	7	0	0	0	0
Yavatmal	10964	63	687	4	2	0	0
Maharashtra	895833	85	76282	241	188	116	2232

[a] Akola, Chandrapur, and Washim districts are not considered for further analysis in this study because sugarcane cultivation is negligible in these districts.
[b] Sugarcane cultivation area and production are weighted average five years (2014–2018) data [23].

production units. Fresh sugarcane is also used as a nutritional drink. Such uses could not be determined district-wise. Therefore, a uniform value of 10 % sugarcane use for other applications and 90 % available for sugar factories (SA_i) are considered for all the districts. The bagasse recovery rate (BR_i, 27–31 % among the districts), is determined based on a database available from Vasantdada Sugar Institute as shown in Table 2 [22]. Although bagasse is also used for paper manufacturing [26], no export of bagasse to paper plants is observed in Maharashtra [22]. Some amount of bagasse is used in ancillary units by the sugar factories, and a portion is sold as bale or loose (Table 2). Such uses are subtracted from the total bagasse production to determine the district-wise net bagasse availability for cogeneration (BA_i).

The cogeneration potential is estimated considering HP boiler (87 bar/515 °C), which is common among the electricity exporting sugar factories of Maharashtra (Table 3). The specific bagasse consumption (SBC) of a HP boiler is 2.33 kg/kWh. The value is determined from the values of steam to bagasse ratio (2.42 kg/kg) [27,28] and steam to electricity ratio (5.65 kg/kWh). The steam to electricity ratio (can also be termed as specific steam consumption) is determined based on the data acquired from selected sugar factories in Maharashtra having boilers in the range of 86–88 bar (Table 3). The steam to electricity ratio for the selected boilers varies from 5.3 to 5.8 kg/kWh, and therefore their average (5.65 kg/kWh) is taken. With increasing boiler pressure, steam to electricity ratio and thus bagasse requirement per unit of cogenerated electricity should reduce. However, a number of factors influence overall efficiency such as variety of sugarcane crop, quality of bagasse in terms of heating value, moisture content, and efficiency of furnace, boiler and turbine. Except for moisture condition, which varies from 46 to 51 % among the districts [22], other variations could not be determined.

The estimated district-wise cogeneration potentials are fed into the Geographical Information System (GIS) to geo-locate and spatially visualize the outcomes.

2.3. *Life cycle assessment (LCA)*

The LCA is carried out using SimaPro 9 software as per the ISO 14040 and 14044 standards (ISO, 2006; ISO, 2018) [29,30]. The LCA is farm to factory gate attributional type however, avoided product function of the LCA software is also used to assess the beneficial uses of sugarcane trash (leaves and tops), press mud, and bagasse ash.

2.3.1. *Goal and scope*

The goal is to estimate the energy, carbon, and water footprint of bagasse cogeneration electricity at district-level in Maharashtra, India. The functional unit (FU) is the production of kilowatt-hour (1 kWh) electricity. The system boundary is displayed in Fig. 3. The processes associated with the manufacturing of farm machinery, transportation medium, and cogeneration unit are not considered. These processes don't have a significant impact on the LCA results [31].

2.3.1.1. Allocation. Allocation is done at two stages, i.e., sugarcane milling and cogeneration. Energy allocation is used in both the stages. Sugar is the primary product and molasses and bagasse are the co-products of the sugarcane milling stage. Information on recovery rate and energy value of sugar, molasses and bagasse are required for energy allocation. District-wise bagasse recovery rate is given in Table 2. Recovery rate for sugar and molasses is given in the Supplementary file. The lower heating value (LHV) of sugar, bagasse and molasses are considered as 16.5 MJ/kg, 7.4 MJ/kg and 10.0 MJ/kg, respectively [32–34]. Based on these, allocation percentage is determined, which varies among the districts as 38–45 % for sugar, 9–12 % for molasses, and 46–52 % for bagasse (full list is given in Supplementary file).

Sugar factories having HP boilers in the study region use either a backpressure turbine or a double extracting condensing turbine, however, the latter is more common (Table 3). Some factories use both types of turbines to generate cogeneration electricity. Steam produced

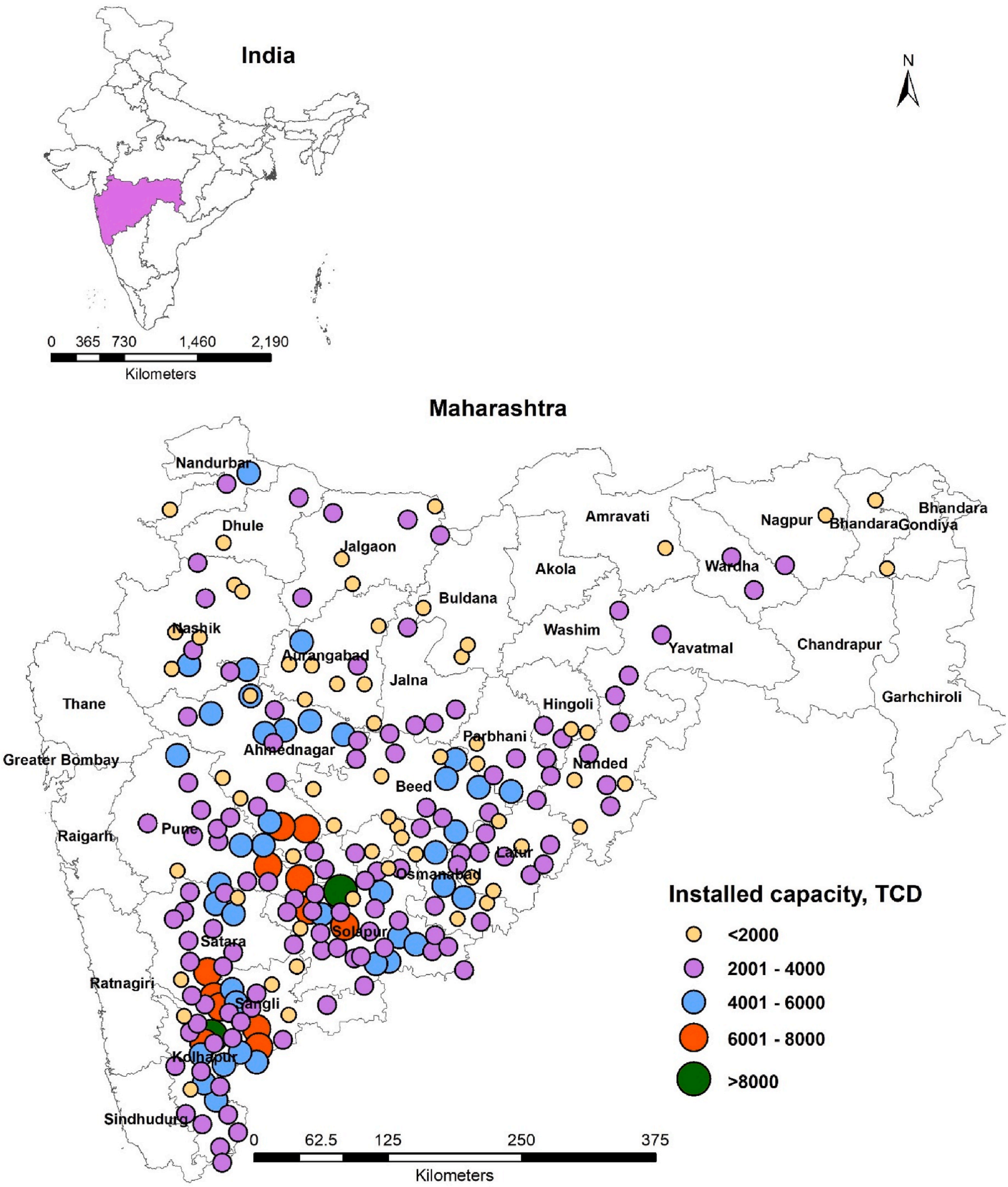


Fig. 1. District-wise spatial distribution of sugar factories in Maharashtra, India with daily sugarcane crushing capacity (TCD-tonne crushed per day).

through bagasse cogeneration is used to meet the internal process heat (low pressure and temperature) and electrical energy demand of a sugar factory. The surplus or additional electricity is supplied to the public grid at government-defined tariff. As discussed in Section 2.2, the steam to bagasse ratio is 2.43 kg/kg. Specific steam consumption of a HP boiler is estimated to be 5.65 kg/kWh, based on collected data from selected sugar factories of Maharashtra (Table 3). Allocation at the cogeneration stage is based on literature values [9,10,13,33]. Bagasse cogeneration LCA studies in Mauritius, Brazil, and Iran reported that about 67–76 % of the total steam generated is expended in the sugar mill to fulfill *in-situ* heat and electricity requirements, and the remaining 24–33 % is used utilized in the production of surplus electricity for export [9,10,13,33]. Based on the average values of the three studies and information generated in Section 2.3, it is determined that about 71 % of the total steam is required to meet internal process heat and electricity of a sugar mill and the remaining 29 % is utilized to produce additional electricity for supply to the state or central electricity grid.

2.3.2. *Avoided product (system expansion of ALCA)*

The SimaPro 9 LCA software has an option called avoided product which enables users to expand the existing ALCA study. It is used in the present study to investigate the alternative application of waste such as sugarcane trash, press mud (also known as filter cake), and bagasse ash.

Sugarcane trash, generated in the farming/cultivation stage has potential application as organic fertilizer. Around 100 kg of trash can be produced from a tonne of sugarcane produced [35]. Soil application of 1

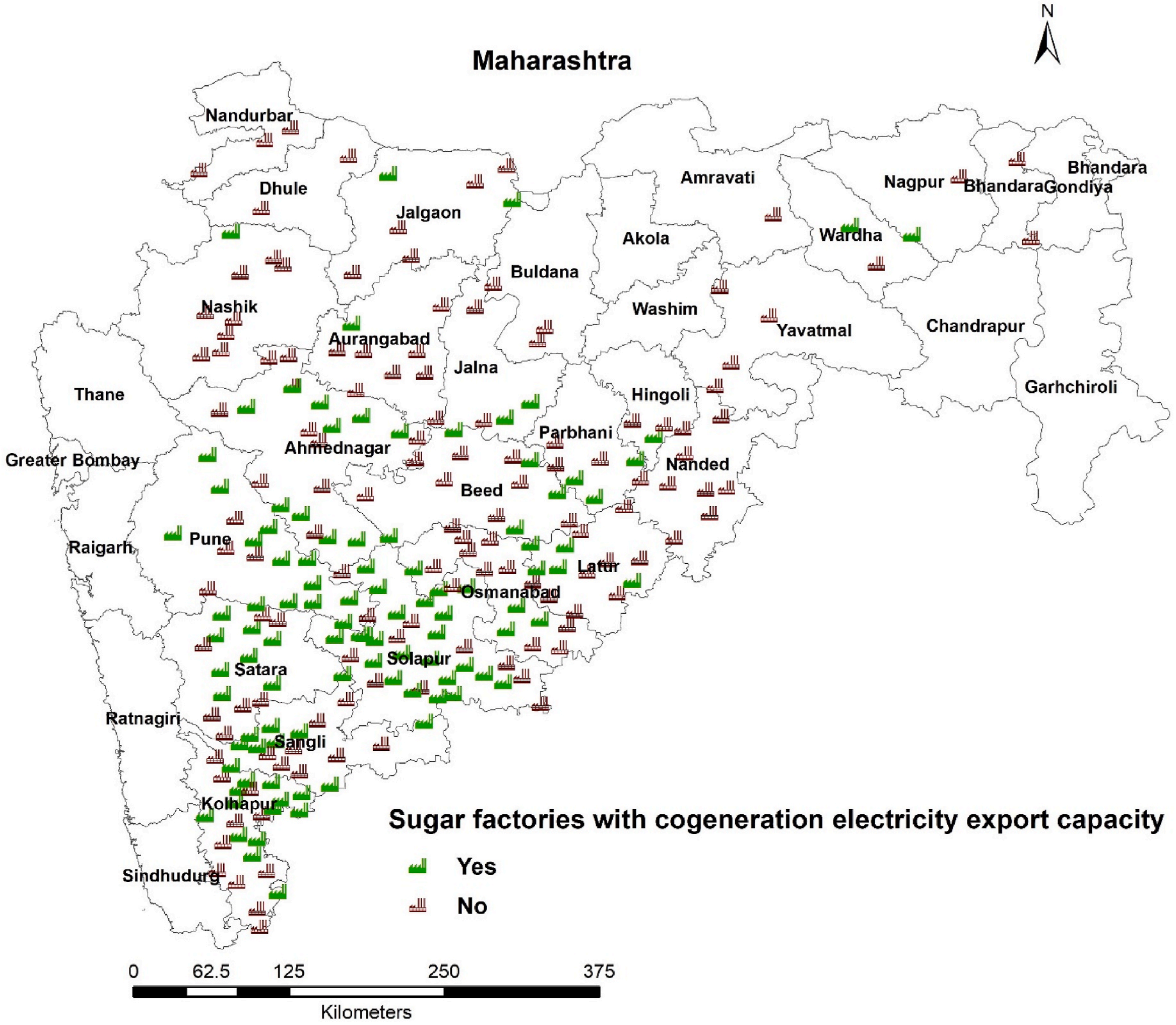


Fig. 2. District-wise distribution of sugar factories with exportable cogeneration electricity status in Maharashtra, India.

tonne of trash adds 3.8 kg of N, 1.6 kg of P, and 6.6 kg of K besides adding 375 kg organic carbon [36]. Therefore, it is assumed that application of one kg sugarcane trash will replace 3.75×10^{-3} kg N, 1.63×10^{-3} kg P, and 6.63×10^{-3} kg K inorganic fertilizer.

Press mud is produced during the sugar production stage at an average rate of 30 kg/t of sugarcane processed [37]. There is variation (3–4 %) in press mud recovery rate among the districts of Maharashtra (see Supplementary file). Press mud as soil nutrients could harm the soil biota due to the presence of toxic compounds [38]. Nevertheless, press mud is a good substrate for the production of biogas, which can be further purified and upgraded to BioCNG having a heating value equivalent to natural gas [39]. Around 80 m^3 of biogas is available from a tonne of press mud [37]. The production of BioCNG from press mud is considered, assuming biogas methane fraction as 65 %, methane purification efficiency, and leakage as 97 % and 2 % [40].

The present study considers bagasse ash as a substituent to cement material. The combustion of 1 tonne bagasse produces 15 kg ash [41]. Due to the inadequate amount of nutrients present in the ash, it cannot be used as a soil fertilizer [42]. Nevertheless, it has proven application as a cement material due to the high presence of silica [43]. A ratio of 20:80 bagasse ash:ordinary Portland cement is considered optimal [44].

2.3.3. *Life cycle inventory (LCI)*

The LCI is prepared per FU, *i.e.*, 1 kWh of surplus electricity, for each of the 26 studied districts separately. The background and foreground processes are based on Ecoinvent v3.5 inventory available with the SimaPro 9.0 software [45]), published literature [13,22,24,36,46–57], data available from sugar factories, sugarcane institutions, and interviews with experts as discussed below.

2.3.3.1. Estimation of district-wise input per FU. Procedure to determine district-wise amount of inputs per FU (1 kWh electricity):

(i) Determine steam demand per unit of electricity cogeneration, which is 5.65 kg/kWh.
(ii) Estimate steam production per unit of bagasse, which is 2.42 kg/kg for a HP boiler
(iii) Based on (i) and (ii), estimate bagasse demand, which is 2.34 kg/kWh.
(iv) Determine sugarcane demand to produce 2.34 kg bagasse. It depends upon the bagasse recovery rate (27–31 % among the district, Table 2). The higher the bagasse recovery, the lower the sugarcane demand.
(v) Assess the amount of land and other inputs (e.g., electricity, diesel, fertilizer) required to meet the sugarcane demand of step (iv). The higher the sugarcane productivity (varies from 41 to 109 t/ha among the districts), lower the input demand. District-wise sugarcane productivity is given in Supplementary Material.
(vi) Apply allocation (energy and mass) to allocate the input/output flows among sugarcane outputs. District-wise allocation percentage is given in Supplementary Material.

Table 2
District-wise bagasse recovery rate, availability factor and uses (other than cogeneration) and bagasse sold in market in Maharashtra, India.

District	Bagasse recovery rate, %	Bagasse availability factor, %	Bagasse used in ancillary unit, %	Bagasse sold as bale or loose, %
Ahmednagar	26.95	95	3.50	1.50
Amravati	28.51	96	1	3
Aurangabad	24.74	98	0	2
Bhandara	31.32	96	1	3
Beed	28.02	98	1.50	0.50
Buldhana	28.51	96	1	3
Dhule	28.51	96	1	3
Gondia	28.51	96	1	3
Hingoli	28.74	99	0	1
Jalgaon	29.60	99.50	0	0.50
Jalna	27.17	98	0	2
Kolhapur	28.20	94	1	4
Latur	27.98	92	2.50	5.50
Nagpur	30.48	96	1	3
Nanded	29.31	93	2	5
Nandurbar	29.06	92	1	7
Nashik	27.59	99.50	0	0.50
Osmanabad	30.01	94	0	6
Parbhani	28.38	99.50	0	0.50
Pune	27.61	92.50	5	2.50
Sangli	28.14	93	2	5
Satara	27.86	94	2.50	3.50
Sindhudurg	28.51	96	1	3
Solapur	28.06	96.50	2.50	1
Wardha	30.11	96	1	3
Yavatmal	29.39	98	1	1

Note: Data of bagasse used in ancillary units and bagasse sold as bale or loose for Amravati, Bhandara, Buldhana, Dhule, Gondia, Nagpur, Sindhudurg, and Warda districts could not be collected. Therefore, the average of other districts' values are used for them.

The LCI is further discussed life cycle stage-wise.

2.3.3.2. LCI at sugarcane farming/cultivation stage. Activities involved at sugarcane farming/cultivation stage include soil preparation, plantation, irrigation, fertilizer and pesticide applications, and harvest, collection & transportation. Land, electricity, water, fertilizer, pesticide, diesel, and lubricant are the inputs at the cultivation stage. The amount of inputs per unit of sugarcane area not only vary district-wise but also sugarcane season-wise (there are four sugarcane seasons in Maharashtra namely, preseasonal, adsali, suru and ratoon). The districts of south and central zones practice all four seasons, but the districts of northeast zone do not cultivate adsali sugarcane. District-level season-wise sugarcane area could not be collected, therefore zone-level data is used to represent the districts.

Data for irrigation water, organic and inorganic fertilizer, micronutrient ($ZnSO_4$, $FeSO_4$, Borax, $MnSO_4$), and pesticide (insecticide, fungicide, herbicide) are collected from Refs. [24,36] (see Supplementary file for detail).

In India, about 78 % and 22 % of irrigation is done through electricity-driven and diesel-based pumps, respectively [46]. Groundwater-based irrigation is common in Maharashtra [47]. Groundwater table depth affects the energy requirement for water lifting. District-wise groundwater depth is estimated from the data available from Central Ground Water Board, India [48]. Electricity and diesel requirement for irrigation is assessed separately (see Supplementary file for estimation method).

The source of electricity influences the GHGs emissions and other environmental effects. The state electricity mix of Maharashtra is coal-dominated (82 %), followed by nuclear (8 %), natural gas (6 %) and hydro (4 %) [49]. The demand for electricity is assessed source-wise.

Diesel requirement for farm operation is assessed according to Ref. [50]. A 35 hp (26.1 kWh) tractor is considered for land preparation with a specific diesel demand of 0.28 L/kWh, field preparation duration of 11 h/ha, and tractor load factor for field preparation of 0.8. In India, 35–40 hp tractor is common for agricultural farm operation (see Supplementary file for estimation method).

Tractor-based biomass feedstock transportation prevails in India. Sugar factories have reported that about 70 % of the sugarcane is transported through tractors and 20 % and 10 % by trucks and bullock carts in Maharashtra. In this study, tractor-based transportation is considered. The average transport distance between sugarcane field and the sugar factory is 25 km. (See Supplementary file for estimation method).

Table 3
Cogeneration technology characteristics of selected sugar factories of Maharashtra, India.

Factory code[a]	Crushing capacity, TCD[b]	Captive/Cogen[c]		Boiler			Turbine capacity and type[e]			Steam Consumption[f]	Specific Steam consumption[g]	Electricity Consumption[h]
		Captive, MW	Cogen, MW	Capacity, TPH[d]	Pressure, kg/cm^2	Temp., °C	Capacity, MW	BP	DEC	On Cane %	Kg/kWh	kWh/t sugarcane
1	3500	12	6.6	40	45	490	12	✓		40.7	6.2	26
2	7000	1.2	6.3	80	67	485	12	✓		45.8	6.5	29.4
3	7500	10.5	10	70, 60	67	480, 520	21.5	✓	✓	36	6	24
4	7200	32	19	140, 50	86	515	32	✓	✓	47.7	5.3	28.3
5	7000	2	12	110	87	515	19.5	✓		45.8	5.6	29.4
6	6000	18	10	100	87	510	18		✓	33	6	33
7	5000	7	10.5	100	87	515	17.5		✓	42.4	5.7	26.3
8	5500	30	20	80	87	527	30	✓	✓	42.4	5.6	30.4
9	5000	10	16	140	87	515	26	✓		43	5.5	28.3
10	2500	–	15	85	87	510	15		✓	43.7	5.6	30.6
11	5000	20	13	115	87	520	22	✓	✓	42.9	5.8	35
12	3500	15	9.3	85	88	525	15		✓	40.7	5.8	26
13	4500	18.5	11.4	70, 40	100	520	21	✓	✓	45	5.2	22
14	2500	18	12.5	100	110	540	18		✓	38	5.5	20.7

[a] Names of the sugar factories are withheld.
[b] Installed sugarcane crushing capacity (TCD, tonne crushed per day).
[c] Captive implies installed capacity for the sugar factories for *in-situ* consumption, Cogen is the installed capacity for export to public grid.
[d] TPH is amount of steam generation, tonne per hour.
[e] BP is Back Pressure turbine, DEC is Double Extracting Condensing turbine.
[f] Steam consumption means steam consumed by the sugarcane processing unit (on sugarcane %).
[g] Specific steam consumption means amount of steam required per unit of exportable electricity cogeneration (kg/kWh).
[h] Power consumption means electricity consumed by the sugarcane processing unit (kWh/t sugarcane).

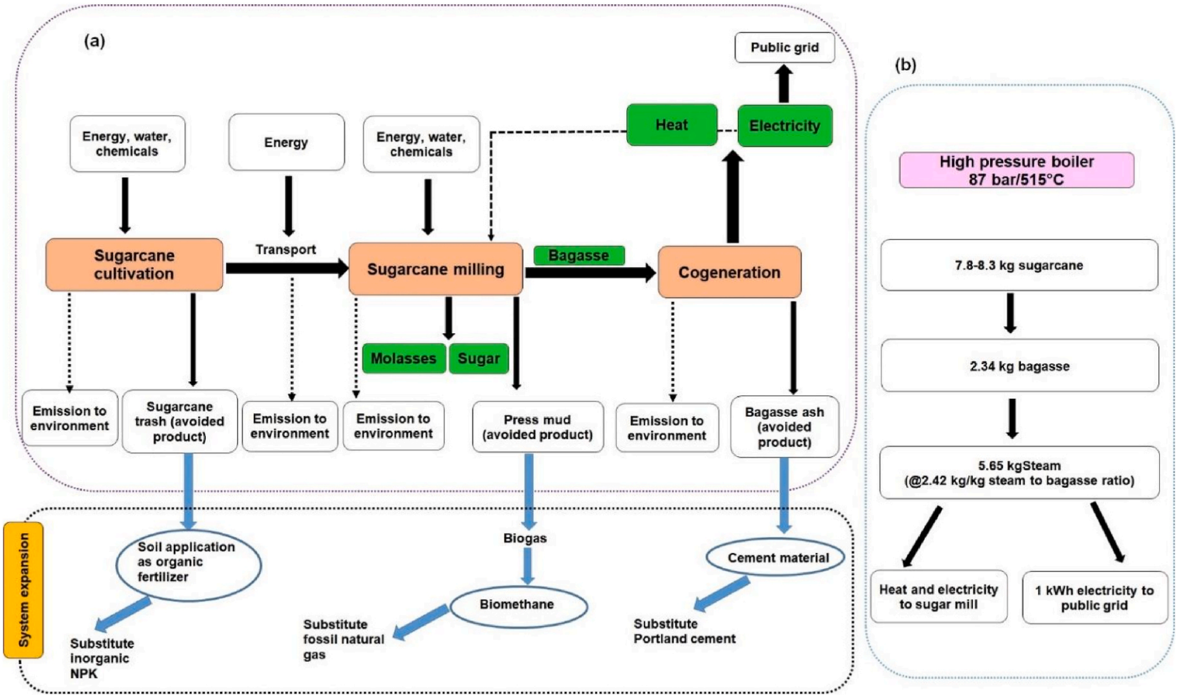


Fig. 3. (a) LCA system boundary, (b) fuel and steam balance of bagasse cogeneration in Maharashtra, India.

The inventory per FU at the sugarcane cultivation stage is summarized in Table 4. The inventory is prepared based on the data collected from standard sources as mentioned in the first paragraph of Section 2.3.3. The inventory is prepared for all 26 districts individually. However, an inventory list for all the districts could not be presented here due to the large volume of data. Therefore, the inventory is shown only for the two districts, Sangli and Osmanabad in Table 4 (and also in Tables 5 and 6). The two districts represent the lowest and highest input/output values, and the values for the other 24 districts lie within the range of these two districts.

Background processes and inventories associated with most of the inputs are derived from EcoInvent 3.5 database. For example, EcoInvent 3.5 provides India's state-wise and fuel type-wise electricity inventory. Thus, inventory for electricity is specific to Maharashtra state. If an inventory is not available from EcoInvent, it is collected from literature. For instance, emissions due to combustion of diesel and lubricant are derived from the US Environmental Protection Agency (US EPA) and the IPCC literature [52,53]. The GHG emission factors of CO_2, CH_4, and N_2O for lubricant combustion are considered as 2.8, $1.1 \times 10^{-4,}$ and 2.4×10^{-5} kg/L [52]. The emission factors of CO_2, CH_4, and N_2O for diesel combustion are 2.68, $3.6 \times 10^{-4,}$ and 2.2×10^{-5} kg/L, respectively [53].

The direct and indirect N_2O emission due to inorganic and organic (cattle dung) fertilizer application is assessed as per the IPCC tier-1 method [54]. The direct N_2O emission factor is 0.0125. The indirect emission is contributed by two processes: (i) volatilization/re-deposition and (ii) runoff/leaching. The indirect emission factor for volatilization/re-deposition is 0.010 and for runoff/leaching is 0.075. The fraction (of kg of N applied) that volatilized/re-deposited is 0.1 for inorganic and 0.2 for organic fertilizers, respectively. The fraction of N fertilizer loss through leaching/runoff is 0.3 (of kg N applied). Around 6.5 % of N fertilizer is leached as nitrate to water, and around 12.8 % phosphate is leached as run-off [13]. The application of urea as N-fertilizer also emits CO_2 that was fixed in the industrial production process [54]. The CO_2 emission factor for urea application is taken as 0.2 (kg/kg urea) as per the IPCC protocol [54].

2.3.3.3. LCI at sugarcane milling and bagasse cogeneration stages. Milling of sugarcane involves processes like washing, crushing, juice extraction & refining, sulphination of juice, boiling of syrup, centrifuging and finally production of sugar crystals. Consumption of electrical energy for various activities at the sugarcane milling stage varies from 21 to 33 kWh per tonne of sugarcane processed depending upon sugar mill configuration and energy-saving measures (Table 3). On average, about 30 kWh/t electricity and 300 kg/t low PT steam requirement are reported in literature [55]. The required electrical energy is produced through the cogeneration of bagasse.

The internal sugarcane water delivers 50–55 % of the water requirement of a sugar factory. The rest is met through freshwater collected from nearby water sources. On average, freshwater demand is 0.28 m^3/t of sugarcane treated [56]. Nearly 25 % of the freshwater is consumed in the sugar processing unit and 75 % in the bagasse cogeneration plant. Around 0.13 kWh/t electricity is needed to supply fresh water. The required electricity is derived from fossil energy sources.

The chemicals fed at the sugarcane milling stage are phosphoric acid, caustic soda, lime, and sulphur at the rate of 1.87, 1.8, 1.44, and 0.58 kg/t of sugarcane processed, respectively [22].

The amount of effluent discharged from a sugar factory is around 14 % of the total sugarcane processed [56]. The typical characteristic of sugar mill effluent include COD (3000 mg/L), BOD (500–1200 mg/L), total dissolved solids (1000–2000 mg/L), suspended solids (600 mg/L), and oil & grease (20–50 mg/L), temperature (30–45 °C) and pH (4–6.5) [57].

The inventory at the sugarcane milling stage is presented in Table 5. Most of the background processes and inventories are obtained from the EcoInvent 3.5 database.

The outputs of cogeneration stage are steam and electricity through bagasse combustion. Bagasse is used as boiler fuel to produce high PT steam. The steam drives the turbine to produce electricity. The low PT exhaust steam is recycled to the sugar processing unit to meet the heat demand. Any additional electricity produced is traded to the public grid. Inventory at cogeneration state is given in Table 6.

The particulate matter (PM and PM10) emissions, N_2O, and CH_4 due to bagasse combustion are calculated based on emission factors reported by the US EPA [52,57]. The emission factors for PM, PM10, CH_4, and N_2O are taken as 3.5×10^{-3}, 5.6×10^{-4}, 2×10^{-4}, and 3×10^{-5} kg/kg

Table 4
Input and output per FU (1 kWh electricity) at sugarcane cultivation stage.

Input/output	Unit	Amount per kWh electricity	
		Sangli district	Osmanabad district
Input from nature (Resources)			
Water	m^3	1.53	3.44
Land	m^2a	0.78	1.90
CO_2 air	kg	3.65	3.42
Input from technosphere (Materials/fuels)			
Cane seed	2-eyes bud	2	5
Diesel[a] (for irrigation, land preparation and transportation)	kg	0.04	0.05
Lubricant[b]	kg	8.6×10^{-4}	1.2×10^{-3}
Fertilizer			
Urea as N	kg	2.4×10^{-2}	5.3×10^{-2}
Single superphosphate as P	kg	1.1×10^{-2}	2.5×10^{-2}
Muriate of Potash as K	kg	1.1×10^{-2}	2.5×10^{-2}
Cattle manure	kg	1.7	4.1
Micronutrient			
FeSO4	kg	1.9×10^{-3}	4.7×10^{-3}
ZnSO4	kg	1.5×10^{-3}	3.8×10^{-3}
MnSO4	kg	7.8×10^{-4}	1.9×10^{-3}
Borax	kg	3.8×10^{-4}	9.5×10^{-4}
Pesticide			
Phorate 10G	kg	1.0×10^{-3}	2.6×10^{-3}
Atrazine	kg	1.4×10^{-4}	3.4×10^{-4}
Mancozeb 0.3 %	kg	1.1×10^{-4}	2.6×10^{-4}
Input from technosphere (Electricity/heat)			
Electricity, coal	kWh	8.1×10^{-2}	3.1×10^{-1}
Electricity, natural gas	kWh	6.0×10^{-3}	2.3×10^{-2}
Electricity, nuclear	kWh	8.0×10^{-3}	3.0×10^{-2}
Electricity, hydro	kWh	4.0×10^{-3}	1.5×10^{-2}
Output to technosphere (products)			
Sugarcane	kg	8.3	7.8
Output to technosphere (avoided products)			
N	kg	3.1×10^{-3}	2.9×10^{-3}
P	kg	1.35×10^{-3}	1.26×10^{-3}
K	kg	5.5×10^{-3}	5.2×10^{-3}
Emissions to air			
CO_2 (fossil)	kg	0.37	0.94
CH_4 (fossil)	kg	4.2×10^{-4}	1.1×10^{-3}
N_2O	kg	3.7×10^{-4}	9.6×10^{-4}
NOx	kg	4.8×10^{-4}	1.6×10^{-3}
Emissions to water			
Nitrate	kg	1×10^{-2}	2.6×10^{-2}
Phosphate	kg	1.7×10^{-3}	4.3×10^{-3}

[a] Diesel density is 0.85 kg/L.

[b] Lubricant demand is 2 % of diesel consumption [51]. Lubricant is density 0.95 kg/L.

Table 5
Input and output per FU (1 kWh electricity) at sugarcane milling stage (before allocation).

Input/output	Unit	Amount per kWh electricity	
		Sangli	Osmanabad
Input from nature (Resources)			
Water	m^3	6×10^{-4}	5×10^{-4}
Input from technosphere (Materials/fuels)			
Sugarcane	kg	8.3	7.8
Lime	kg	1.2×10^{-2}	1.1×10^{-2}
Sulphur	kg	4.8×10^{-3}	4.5×10^{-3}
Sodium hydroxide	kg	1.5×10^{-2}	1.4×10^{-2}
Phosphoric acid	kg	1.6×10^{-2}	1.5×10^{-2}
Lubricant	kg	8.0×10^{-4}	7.8×10^{-4}
Input from technosphere (Electricity/heat)			
Electricity, coal	kWh	2.2×10^{-4}	2.1×10^{-4}
Electricity, natural gas	kWh	1.6×10^{-5}	1.5×10^{-5}
Electricity, nuclear	kWh	2.2×10^{-5}	2.0×10^{-5}
Electricity, hydro	kWh	1.1×10^{-5}	1.0×10^{-5}
Bagasse cogeneration electricity	kWh	0.25	0.23
Low PT steam	kg	2.49	2.34
Output to technosphere (Products and co-products)			
Sugar	kg	1.02	0.77
Molasses	kg	0.37	0.34
Bagasse	kg	2.34	2.34
Output to technosphere (Avoided products)			
Natural gas	kg	1.0×10^{-2}	8.5×10^{-3}
Emissions to air			
CO_2 (fossil)	kg	2.2×10^{-2}	2.4×10^{-2}
Emissions to water			
Phosphate	kg	7×10^{-5}	8×10^{-5}
COD	kg	1.7×10^{-3}	1.8×10^{-3}
BOD5	kg	5×10^{-4}	5.3×10^{-4}
Suspended solids	kg	2.6×10^{-4}	3×10^{-4}
Waste water	kg	0.54	0.56

Note: Allocation factors for sugar, molasses, and bagasse are given in the supplementary file for all the 26 districts.

Table 6
Input and output per FU (1 kWh electricity) at cogeneration stage (before allocation).

Input/output	Unit	Amount per kWh electricity	
		Sangli	Osmanabad
Input from technosphere (Materials/fuels)			
Water	m^3	1.7×10^{-3}	1.6×10^{-3}
Bagasse	kg	2.34	2.34
Input from technosphere (Electricity/heat)			
Bagasse cogeneration electricity	kWh	0.11	0.11
Electricity, coal	kWh	6.6×10^{-4}	6.2×10^{-4}
Electricity, natural gas	kWh	4.9×10^{-5}	4.6×10^{-5}
Electricity, nuclear	kWh	6.5×10^{-5}	6.1×10^{-5}
Electricity, hydro	kWh	3.2×10^{-5}	3.0×10^{-5}
Output to technosphere (Products and co-products)[a]			
Electricity	kWh	1	1
Low PT steam	kg	3.67	3.67
Emissions to air[a]			
CO_2, biogenic	kg	0.6	0.6
CH_4, biogenic	kg	1.6×10^{-4}	1.6×10^{-4}
N_2O	kg	2×10^{-5}	2×10^{-5}
PM	kg	2.3×10^{-3}	2.3×10^{-3}
PM10	kg	3.8×10^{-4}	3.8×10^{-4}
NOx	kg	3×10^{-4}	3×10^{-4}

Allocation factors for steam and cogeneration electricity are 71 % and 29 %.

[a] Output to technosphere and emissions are same for all the districts because the same amount of bagasse (2.34 kg) is required to generate 1 kWh of electricity.

bagasse combusted.

2.3.3.4. LCIs for avoided product. As discussed in section 2.3.2, potential application of sugarcane by-products or wastes is evaluated under avoided product and system expansion. In LCA, the term avoided product indicates a substance or material which is being replaced by waste or by-product of the studied system. For example, biogas generated from press mud can be upgraded to biomethane, replacing fossil natural gas. System expansion is a part of consequential LCA, therefore, when it is applied to an ALCA, the resulting LCA is also termed as hybrid LCA.

The LCI for the system expansion phase of the current study is given below in Table 7.

2.3.4. *Life cycle impact assessment (LCIA)*

ReCiPe 2016 midpoint (H) method is used for the LCIA [58]. ReCiPe is the most widely used LCIA method [59]. Two midpoint indicators, global warming potential (GWP) and water consumption potential (WCP), are selected for the present analysis. The GWP and WCP are referred to as carbon footprint (CF) and water footprint (WF) in this study. The midpoint level characterization factor for water footprint is water consumption potential (WCP), expressed in m^3 water-eq. consumed [58]. The WCP represents irrigation or blue water footprint.

The CED or Cumulative Energy Demand LCIA method is used to estimate the energy footprint (EF). The CED is the amount of total primary energy consumed (renewable, non-renewable) during the life cycle of the product. Energy Return on Investment (EROI) is estimated based on energy input (*i.e.*, CED) to produce bagasse electricity and energy output of bagasse electricity (3.6 MJ/kWh). Murphy and Hall, 2010 [60], defined EROI as “the ratio of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question.”

2.3.5. *Interpretation*

Interpretation is the final stage of LCA to assess the results of inventory and LCIA for decision making and recommendations. Uncertainty and sensitivity analysis are also part of this stage.

Table 7
LCIs of fertilizer production from sugarcane trash, biogas production from press mud, and bagasse ash for cement material per FU (1 kWh).

LCA stage	Waste or by-product and avoided product	Amount, kg		Note
		Osmanabad district	Sangli district	
Cultivation stage	Sugarcane trash production	0.78	0.83	Detailed discussions for the cultivation, production and cogeneration stages are available in section 2.3.3.
	-Potential amount of inorganic N fertilizer replacement via sugarcane trash	0.0029	0.003	
	-Potential amount of inorganic P fertilizer replacement via sugarcane trash	0.0012	0.0013	
	-Potential amount of inorganic K fertilizer replacement via sugarcane trash	0.005	0.0055	
Sugar production stage	Filter cake production	0.24	0.29	
	-Potential to replace fossil natural gas via filter cake	0.0085	0.01	
Cogeneration stage	Bagasse ash production	0.035	0.04	

2.3.6. *Uncertainty analysis and alternative scenario*

Monte Carlo Simulation (MCS) is done using ModelRisk software with 10000 iterations to determine uncertainty associated with some key variables (Table 8). The MCS is done for the sugarcane cultivation stage only since this phase accounts for about 90–95 % of the total life cycle impacts.

Two alternative scenarios (S1 and S2) are developed to assess scope of reducing environmental impact and tested for Sangli and Osmanabad districts. For Sangli in S1, sugarcane productivity is taken as 150 t/ha (current 107 t/ha), achievable under recommended cultivation practice [36]. For Osmanabad, productivity is taken as 61 t/ha (currently 41 t/ha), average productivity of the north-east zone.

S2 scenario is developed considering the following situations:

(i) High sugarcane productivity (similar to S1).
(ii) Drip irrigation instead of flood irrigation. Drip irrigation can save 26 % of water used for irrigation under the flood irrigation in Maharashtra [61].
(iii) Hydropower as a source of electricity for irrigation.
(iv) Higher cogeneration boiler capacity (105 bar). With higher boiler capacity, steam generation per unit of bagasse increases (from 2.42 kg/kg for 87 bar boiler to 2.56 kg/kg for 105 bar boiler) [27, 28], leading to more electricity generation.

3. Results and discussion

3.1. *Bagasse electricity cogeneration potential*

Annual bagasse availability in Maharashtra is estimated to be 19.2 mt, equivalent to 8206 GWh electricity. Bagasse potential varies markedly at district-level, from 4 kilo tonne (kt) in Amravati to 3502 kt in Kolhapur. Similarly, bagasse electricity potential varies from 2 GWh in Amravati to 1500 GWh in Kolhapur district (Fig. 4). Nearly 81 % potential is contributed by 6 districts alone, namely Kolhapur (1500 GWh), Pune (1394 GWh), Solapur (1229 GWh), Ahmednagar (897 GWh), Sangli (868 GWh), and Satara (719 GWh). They also contribute 80 % of Maharashtra’s sugarcane production. There are 135 sugar factories (out of total 241) and 94 cogeneration plants (out of total 117) are distributed within these 6 districts (Table 1).

Maharashtra is the economic and industrial hub of India but also faces electricity deficit. In 2019–2020, against the demand of 153540 GWh, supply was 148236 GWh, resulting in 3.5 % (5304 GWh) supply deficit [49]. The estimated bagasse electricity potential (8206 GWh) can fulfill 5.3 % of the state’s electricity demand.

3.2. *Carbon footprint (CF)*

The CF of bagasse electricity at the state level is 0.13 kg CO_2e/kWh. The CF varies significantly among the districts ranging from 0.075 kg CO_2e/kWh in Sangli to 0.2 kg CO_2e/kWh in Osmanabad (Fig. 5). The CF is less than 0.1 kg CO_2e/kWh in 5 districts. These districts belong to central and south zones. In 12 districts, the CF lies between 0.1 and 0.15 kg CO_2e/kWh, and they belong to the north-east zone except Solapur and Ahmednagar. For the remaining nine districts, the CF ranges from 0.15 to 0.2 kg CO_2e/kWh, and they also belong to the north-east zone.

Sugarcane cultivation stage accounted for 88–95 % of the total CF, followed by milling (4–8 %) and cogeneration (1–3 %) (Fig. 5). The key polluters at the cultivation stage include electricity derived from coal power plant for irrigation and the use of N-fertilizer application (inorganic and organic manure).

Potential for avoided GHG emissions (or emissions saving) through alternate uses of sugarcane wastes are illustrated district-wise in Fig. 5. The avoided GHG emission at the farming stage ranges from 7×10^{-3} to 9×10^{-3} kg CO_2e/kWh among the districts. Avoided GHG emission at the sugarcane milling stage (range from 1.6×10^{-3} to 2.0×10^{-3} kg CO_2e/kWh. At the cogeneration stage, avoided GHG emission is 9.5 ×

Table 8
Parameters for Monte Carlo simulation.

Parameter	Distribution	Unit	Value[a]		Note
			Sangli	Osmanabad	
Sugarcane productivity	Normal	t/ha	108, 8.16	39, 7.76	Based on five years of sugarcane data [23].
Bagasse recovery	Normal	%	28.14, 0.21	30.01, 2.26	Based on five years of bagasse data [22].
N-fertilizer application	Triangular	Kg/ha	250, 310, 400	250, 280, 350	Based on sugarcane season-wise data [36].
Water consumption	Triangular	Million L/ha	169, 196, 244	169, 181, 206	Based on sugarcane season-wise data [24].
Electricity for irrigation	Triangular	kWh/ha	816, 1273, 1632	1287, 2007, 2573	

[a] Normal distribution (mean, standard deviation), triangular distribution (min, mostly likely value, max).

10^{-3} kg CO_2e/kWh for all the districts.

Life cycle CF of sugarcane and sugar are also assessed (Fig. 6). About 0.8–1 kg sugar is produced (at sugarcane milling stage) during generation of 1 kWh electricity. The CF of sugarcane and sugar is assessed to be 0.11 kg CO_2e/kg and 0.43 kg CO_2e/kg, respectively at the state level. At district level, sugarcane CF varies from 0.06 to 0.16 kg CO_2e/kg. The sugar CF ranges from 0.24 to 0.65 kg CO_2e/kg among the districts.

Globally several studies have assessed the emissions of sugarcane and sugar production and reported them to be in the range of 0.1–0.2 kg CO_2e/kg and 0.2–2.0 kg CO_2e/kg, respectively [12,13,17,31,62]. The estimated CF for sugar is close to the author's previous study, where the CF of sugar was found to be 0.40 kg CO_2e/kg. Similarly CF of 0.55 kg CO_2e/kg in Thailand [63], 0.45 and 0.63 kg CO_2e/kg in two regions of Mexico [64], 0.60 kg CO_2e/kg in Pakistan [65], and about 2.0 CO_2e/kg for Iran [13] have been reported for sugar. The higher CF impacts in these studies are mainly due to the higher nitrogen fertilizers usage especially urea, which causes direct and indirect emissions of nitrous oxide, a potent GHG with significantly higher GWP_{100} of 265 [66]. The preference of impact allocation method (energy, economic, mass), system boundary, inventory, assumptions, LCIA methods, and local differences in cultivation methods also influence the outcome.

The life cycle CF of sugarcane bioenergy is less than coal or other fossil fuels. For instance, the estimated CF of bagasse cogeneration electricity (0.13 kg CO_2e/kWh) for Maharashtra is significantly lesser than the coal-based electricity having CO_2e emission factor of 0.983 kg CO_2e/kWh [66]. Similarly, a study in Brazil reported a CF of 0.227 kg CO_2e/kWh for bagasse-based electricity, much is lower than the CF of 1.060 kg CO_2e/kWh from diesel thermoelectric process [67]. Earlier investigations from Thailand and Mauritius reported the life cycle CF of bagasse cogeneration electricity as 0.038 and 0.037 CO_2e/kWh [41,68].

The CF obtained in the present study for different districts of Maharashtra is in the range reported for biomass combustion-based electricity (0.01–0.5 kg CO_2e/kWh) in different regions of the world [13,69,70]. High demand of energy and GHG emissions at sugarcane farming stage as observed in this study, are corroborated by findings previously reported for Brazil [71], Thailand [72], Iran [13], and Nepal [73]. Bagasse combustion-related CO_2 emission can be treated as carbon neutral because sugarcane is an annual crop, and the emitted CO_2 is absorbed by the next cropping cycle. Literature analysis also reveals carbon neutrality considerations for bagasse cogeneration LCA [9,41].

3.3. Energy footprint (EF)

The CED is expressed as EF in this study which details the life cycle energy demand for 1 kWh (equivalent to 3.6 MJ) bagasse electricity cogeneration. The EF varies from 0.75 to 2.12 MJ/kWh among the districts, with a state average of 1.21 MJ/kWh. The EROI, which is the ratio of energy output and input, ranges from 1.7 to 4.8 among the districts with a state average of 2.8. The lower the EF, higher the EROI. District-wise EF and EROI are shown in Fig. 7.

The EROI indicates if a product results in net energy gain or loss. EROI above 4 is witnessed for three districts, *viz.* Sangli (4.8), Pune (4.6) and Satara (4.5). EROI of 3–4 is observed for 9 districts, 2 to 3 for 13 districts. Three districts have an EROI less than 2.

Authors previously conducted a state-level study for Maharashtra considering 20 different scenarios with differences in sugarcane cultivation seasons and cogeneration boiler characteristics [74]. The results revealed that simultaneous production of sugar and surplus electricity provides high EROI compared to only sugar-producing units.

3.4. Water footprint (WF)

State level WF of cogenerated electricity is 334 L/kWh. However, it varies from 206 to 516 L/kWh at district level (Fig. 8). The WF of sugarcane and sugar at state level is 285 and 1097 L/kg, respectively. At district level, WF of sugarcane ranges from 181 to 444 L/kg. The WF of sugar at district-level varies from 674 to 1688 L/kg.

The estimated WF represents both direct and indirect water consumption. Examples of direct consumption include irrigation water for sugarcane cultivation and freshwater for sugar factories. The indirect water consumption represents water demand for production of materials and fuels (fertilizer, pesticide, diesel, lubricant), and electricity, used in different stages of the life cycle. The sugarcane cultivation stage accounts for 99.5 % water demand. The estimated WF can also be termed as blue water footprint, a term coined by Hoekstra et al., 2011 [75] because it represents irrigation and indirect water consumption.

A study assessed the green (rainfall), blue (irrigation), and grey (water pollution assimilation) WF of sugar for several countries and found it to be varying from 870 L/kg in Peru to 3340 L/kg in Cuba [76]. The same study also found WF of sugar for the major producing nations of Brazil and India as 1285 L/kg and 1570 L/kg, with the global average of 1500 L/kg. The WF of sugar at state level in this study is found to be 1097 L/kg (district variation: 674–1688 L/kg) lower than the values reported as the present study considered only blue water footprint.

Concerning irrigation water requirement for sugarcane cultivation (L/kg), similar observations are also reported for different states of India, like Maharashtra (293 L/kg), Madhya Pradesh (276 L/kg), Karnataka (266 L/kg), Andhra Pradesh (262 L/kg) and Gujarat (260 L/kg) [77]. In other states, the demand is low, for example, West Bengal (48 L/kg), Bihar (95 L/kg), Uttar Pradesh (99 L/kg), Kerala (67 L/kg), Punjab (135 L/kg) and Haryana (133 L/kg) [78]. Generally, the states lying in the northern sub-tropical parts of India, unlike Maharashtra, have higher precipitation, cooler winters and relatively shorter crop growing season, and hence irrigation water requirements are lower with a higher irrigation water productivity [79]. Water requirements for sugarcane cultivation across regions also vary with the crop duration period ranging from 10 to 17 months for different growing seasons.

Sugarcane cultivation in India consumes more water than the global average. The global average water footprint of irrigated sugarcane is 238 L/kg (comprising green 104 L/kg, blue 104 L/kg, and grey 14 L/kg) [77]. Brazilian sugarcane is rainfall dependent and therefore, irrigation water demand (WF_{blue} 38 L/kg) is less with WF_{green} 145 m^3/t, and WF_{grey} 18 m^3/t [80]. Similarly, a study from Thailand found sugarcane WF as 226 m^3/t, consisting of WF_{green} (146 m^3/t), WF_{blue} (31 m^3/t), and WF_{grey} (49 m^3/t) [21,37].

Variations in sugarcane WF in different regions can be attributed to the crop and soil types, agriculture management practices, climatic conditions, rate of nitrogen fertilizer application, and water use

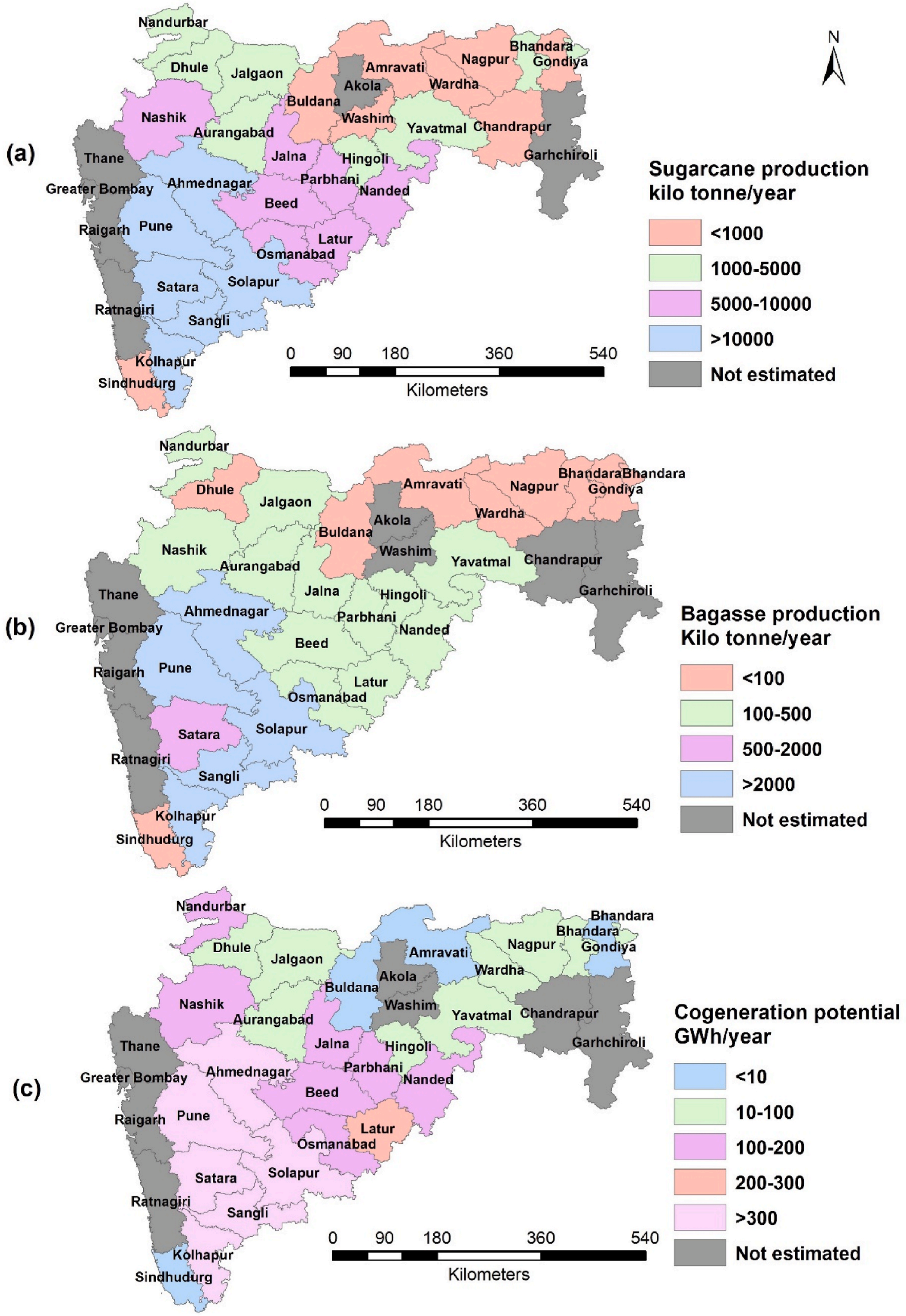


Fig. 4. District-wise (a) sugarcane production, (b) bagasse production, and (c) cogeneration potential in Maharashtra, India (districts with not estimated legend means they either don’t cultivate sugarcane or have cultivation area <1000 ha).

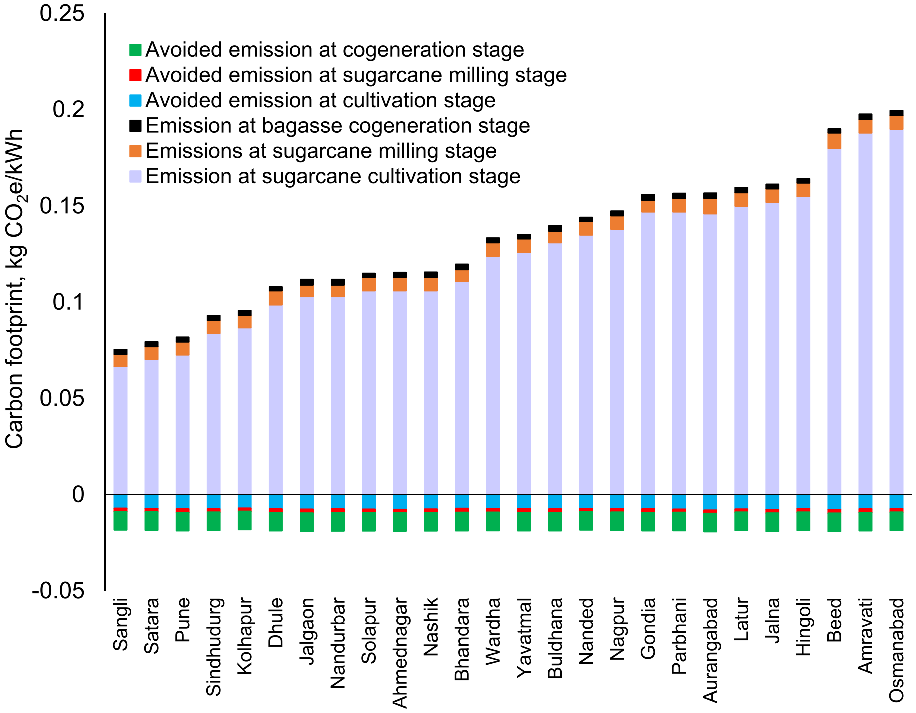


Fig. 5. District-wise life cycle GHGs emissions from bagasse electricity cogeneration in Maharashtra, India.

efficiency [14]. The present study reveals that the WF of sugarcane in Maharashtra is higher than the global average WF and other major sugarcane-producing nations. Further, the sugarcane cultivation in different districts of Maharashtra mainly depends upon groundwater-based irrigation (resulting in higher WF_{blue}) in contrast to the rainfall-reliant high sugarcane producing nations (Brazil, Thailand, etc.) [74]. Results from the present study indicate that heavily irrigated sugarcane cultivation in Maharashtra is not in line with natural water resource endowment of the region.

3.5. *Uncertainty analysis result and alternative scenario*

The results of Monte Carlo Simulation for Sangli and Osmanabad districts are presented at 90 % (5th and 95th percentile) and 75 % (25th and 75th percentile) confidence level in Table 9. Further details are given in the Supplementary file.

The result of alternative scenario analysis (S1 and S2) are presented in Table 10.

3.6. *Sensitivity analysis based on different allocation methods*

Different allocation methods give different LCA outcomes. The current study used energy allocation as a base case. To understand the sensitivity of the outcomes, the energy allocation result is compared with economic and mass allocation as presented in Table 11. Different allocations for sensitivity analysis purposes are applied to the sugar production stage of the system boundary only (sugar, molasses and bagasse are the products of this stage). Allocation percentage at the cogeneration stage kept the same (71 % and 29 % as discussed in Section 2.3.1. The comparison is presented only for Sangli and Osmanabad districts, the two extreme cases. Results for other districts lie within the values of these two districts. It is observed that bagasse cogeneration electricity performs best in terms of energy, carbon, water footprint under the economic allocation, followed by energy and mass allocation. Due to the significant difference in the price of sugar, bagasse, and molasses, most of the environmental burden is screwed towards sugar when economic allocation is applied. Under mass allocation, most of the burden is shifted towards bagasse (feedstock for cogeneration electricity) since bagasse recovery from sugarcane is higher than sugar or molasses.

The present analysis uses energy allocation at the cogeneration stage to allocate the total steam between process heat & electricity for internal use of a sugar mill and surplus electricity sold to the grid (detailed discussion in Section 2.3.1). Energy allocation at the cogeneration stage was also followed by Gil et al., 2013 [81]. Energy allocation was also suggested by Renouf et al., 2011 bagasse combustion and cogeneration [17]. Silva et al., 2014 also used energy allocation for an LCA study of bagasse cogeneration in Brazil [9]. Mohammadi et al., 2020 used exergy allocation between heat and electricity at the cogeneration stage [13]. In another study in South Africa, Mashoko et al., 2013 used economic allocation among sugar, molasses and cogeneration electricity [82]. The authors did not evaluate allocation between process heat & electricity required by a sugar mill and surplus electricity sold. In a recent study in India, Varshney et al., 2019 used economic allocation for different sugarcane bagasse utilization pathways such as ethanol, electricity and pellets [83].

4. Trade-off between CF and WF of bagasse and coal electricity

Bagasse electricity emits (0.075–0.2 kg CO_2e/kWh) about 4–12 times less GHGs than coal electricity (0.8–0.9 kg CO_2/kWh) [84]. From GHGs emission reduction standpoint, bagasse electricity is a promising alternative to coal electricity. However, the WF of bagasse electricity (206–516 L/kWh at district level, 334 L/kWh at state average) is significantly higher than coal electricity (0.3–7.6 L/kWh) [85]. In fact, WF of bioenergy is an emerging challenge to climate change mitigation through large-scale bioenergy with carbon capture and storage (BECCS) [86,87].

5. Sugarcane cultivation *vs.* water crisis in Maharashtra

Sugarcane is a water-intensive crop due to its long duration of growth and accumulation of one of the highest biomass quantities among all agricultural crops [66,88]. The heavy use of green, blue, and

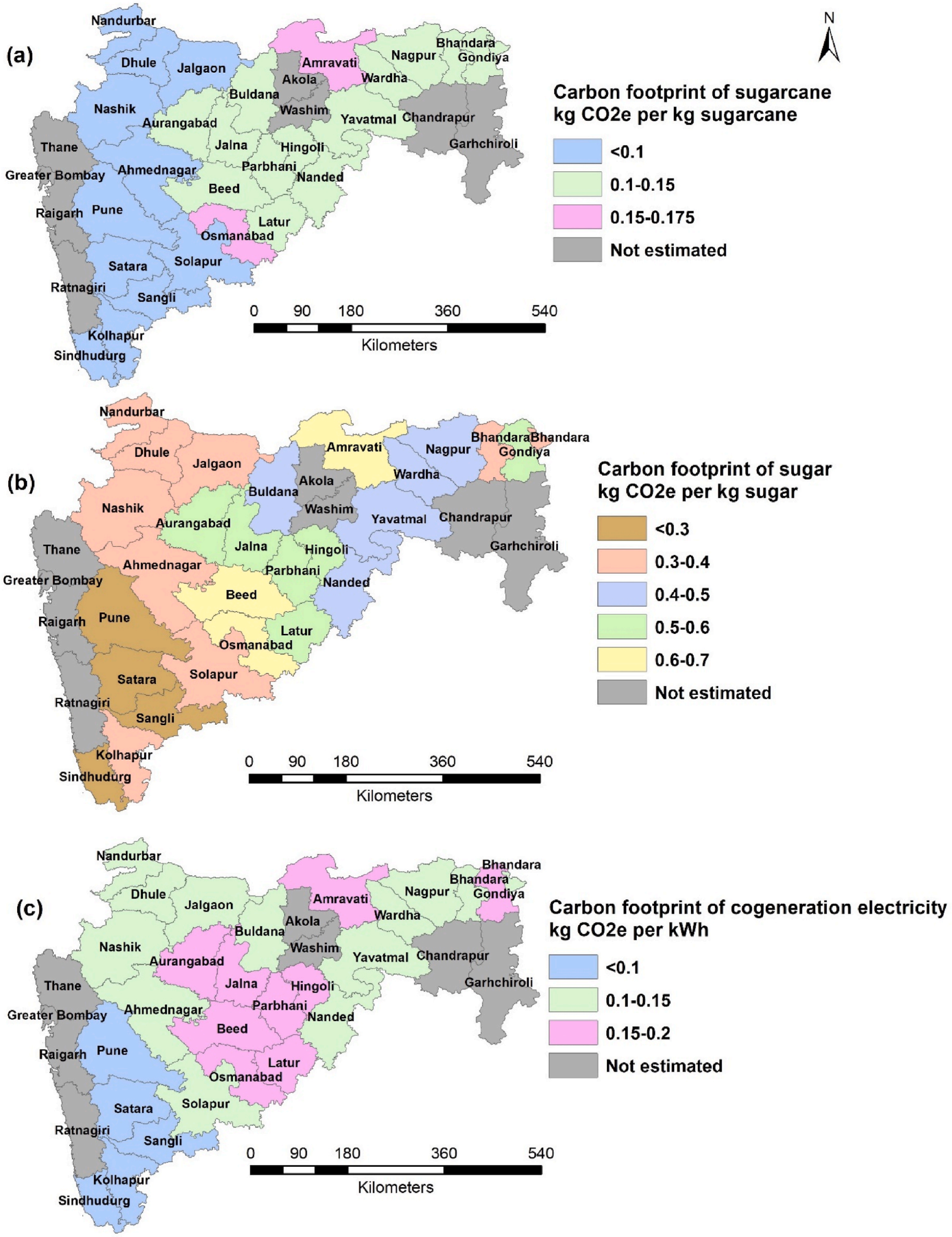


Fig. 6. District-wise carbon footprint (CF) of (a) sugarcane, (b) sugar, (c) bagasse electricity in Maharashtra, India.

grey water is a major concern in sugarcane cultivation [89].

Sugarcane cultivation vs. water crisis has become a major environmental and political issue in Maharashtra as well as in India [90]. Most of the parts of Maharashtra face drought conditions and critical water shortages for several months every year. The shift in sugarcane cultivation from traditional growing belts of Bihar and eastern Uttar Pradesh (tropical regions) to water-scarce regions of Maharashtra (sub-tropical) was driven by the sugar licensing policy of preferring co-operatives sugar factories over private ones towards Maharashtra [91]. Farmers prefer growing sugarcane because of the assured market and support price available to it, unlike other crops [79]. Further, the crop failures are less than vegetables and horticulture. Moreover, the yield of sugarcane in Maharashtra is also high in comparison to other parts of India due to longer crop duration and suitable climatic conditions with longer sunshine hours, cool nights with clear sky and the latitudinal position of the area which is favourable for sugar accumulation [91]. However, the

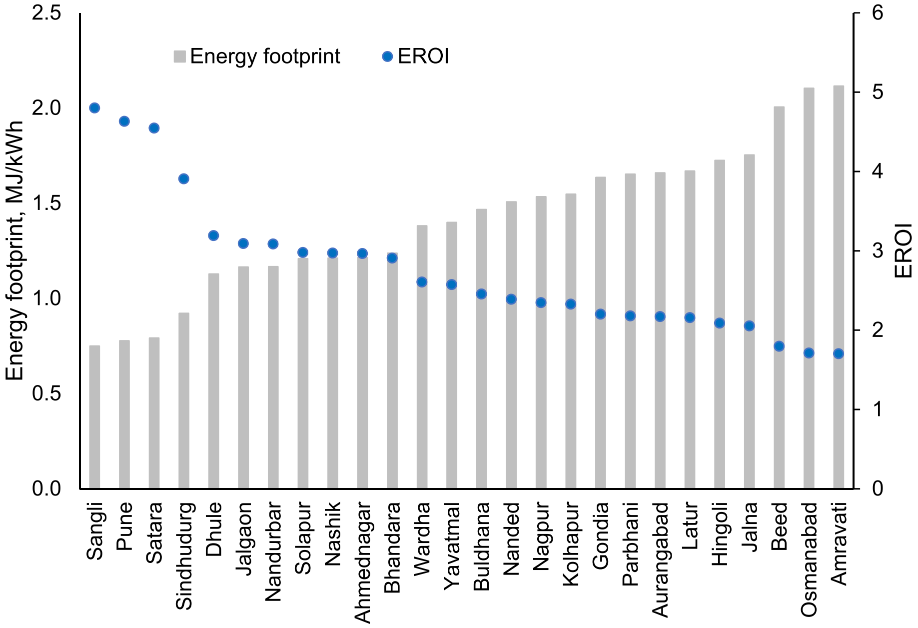


Fig. 7. Energy footprint and EROI differences of bagasse cogeneration among the districts of Maharashtra, India.

cultivation is primarily irrigation dependent indicating the significant misalignment in the cropping patterns and available water resources [92].

Sugarcane a water-guzzling crop, is cultivated in about 6 % of cultivable land in the state but consumes 70 % of total irrigation water demand [93]. About 70–80 % of sugarcane irrigation water requirement is met from groundwater [47]. Many districts in the north-east zone of Maharashtra face groundwater crisis and may not be suitable for sugarcane cultivation as the depleting groundwater resources is a concern. As shown in Fig. 8, these districts also have high WF of sugarcane, sugar, and bagasse electricity due to low sugarcane productivity.

In a state with only 18 % cropped area under irrigation, the debate of sugarcane vs. water has intensified due to 100 % allocation of irrigation water to sugar [94]. Some reports suggest WF footprint of sugar in Maharashtra is the highest in India, above 2000 L/kg sugar [95,96]. However, such studies did not follow an LCA method to allocate input/output and environmental burden among products and co-products of sugarcane. The present study observed state average WF of sugar is 1097 L/kg (varies from 674 to 1688 L/kg among the districts).

Micro-irrigation (drip and sprinkler) could be a solution against the commonly practiced flood irrigation to reduce the water requirement in cultivation of sugarcane [61,97]. Efforts should be made to increase the penetration of drip irrigation for sugarcane cultivation in Maharashtra, which could save almost 40%–50 % of water that in turn could be used for other crops [92]. It also increases productivity, further lowering the WF of sugarcane by-products. The Government of India has started a national program, '*Per Drop More Crop*' to promote micro-irrigation [98]. As of 2019–2020, nearly 1.2 million ha of area under different crops have been covered under the program (share of area under drip and sprinkler irrigation as 0.63 and 0.56 million ha). In Maharashtra, about 0.17 million ha area under different crops has been covered under micro-irrigation. However, the share of sugarcane area under micro-irrigation is just about 12043 ha as of 2019–2020. Increasing micro-irrigation in the districts of north-east zone can help the districts to reduce WF of sugarcane cultivation and bagasse cogeneration.

Thus, to resolve water crisis in Maharashtra due to sugarcane cropping, it is essential to search for alternatives in cropping patterns, crop cultivation practices, water use efficiency, water regulation, and equitable water access among different crops. A nexus study can deliver significant information for coordinating agriculture management practices to improvise the security and sustainability of energy and water resources.

6. Energy-carbon-water nexus management and economic opportunities for farmers

LCA studies provide a comprehensive analytical framework and necessary information about environmental pros and cons in decision making [99]. LCA-based evaluation of carbon footprint, water footprint, and energy footprint have gained traction worldwide [100]. Nevertheless, each footprint indicator has its own focus and way of interpretation. Nexus management is now widely being accepted as a field of study to understand the interconnectivity in these resources. To capture the nexus among water, energy, and carbon and the GHGs that occurs from anthropogenic activities such as agriculture, it is necessary to understand the scope of each footprint and how its indicator link to the resources used and GHG emissions.

The connections in carbon, energy, and water security are complex. There is a need to design equitable, efficient, and sustainable policies that respect the complex interdependency in these [101]. The present study attempts to understand and capture the trade-offs and the nexus among water, energy, and carbon footprint for sugarcane bioenergy in each district of Maharashtra and its environmental implications in a life cycle perspective. The task is accomplished by quantifying the three footprint indicators: carbon, energy, and water footprints which are strongly interlinked.

Sugarcane cultivation stage is the major activity affecting the Energy, Carbon and Water (ECW) footprints in Maharashtra and is primarily driven by coal-electricity requirement for irrigation. Electrical pump contributes 78 % to the irrigation energy requirements, and diesel pump accounts for 22 % irrigation energy needs in India [46]. Irrigation water demand in Maharashtra is mostly met through groundwater. High dependency on groundwater resources for irrigation has led to frequent drinking water crisis in many parts of the state, particularly in the districts of Marathwada and Vidarbha regions. Energy use pattern, irrigation methods significantly influence the sugarcane productivity along with the soil health and climatic conditions. Higher the productivity lower the ECW footprint, which is evident in the districts of Pune, Sangli, Kolhapur, Satara, and Solapur. Although these districts have high water consumption for irrigation due to the widespread cultivation of

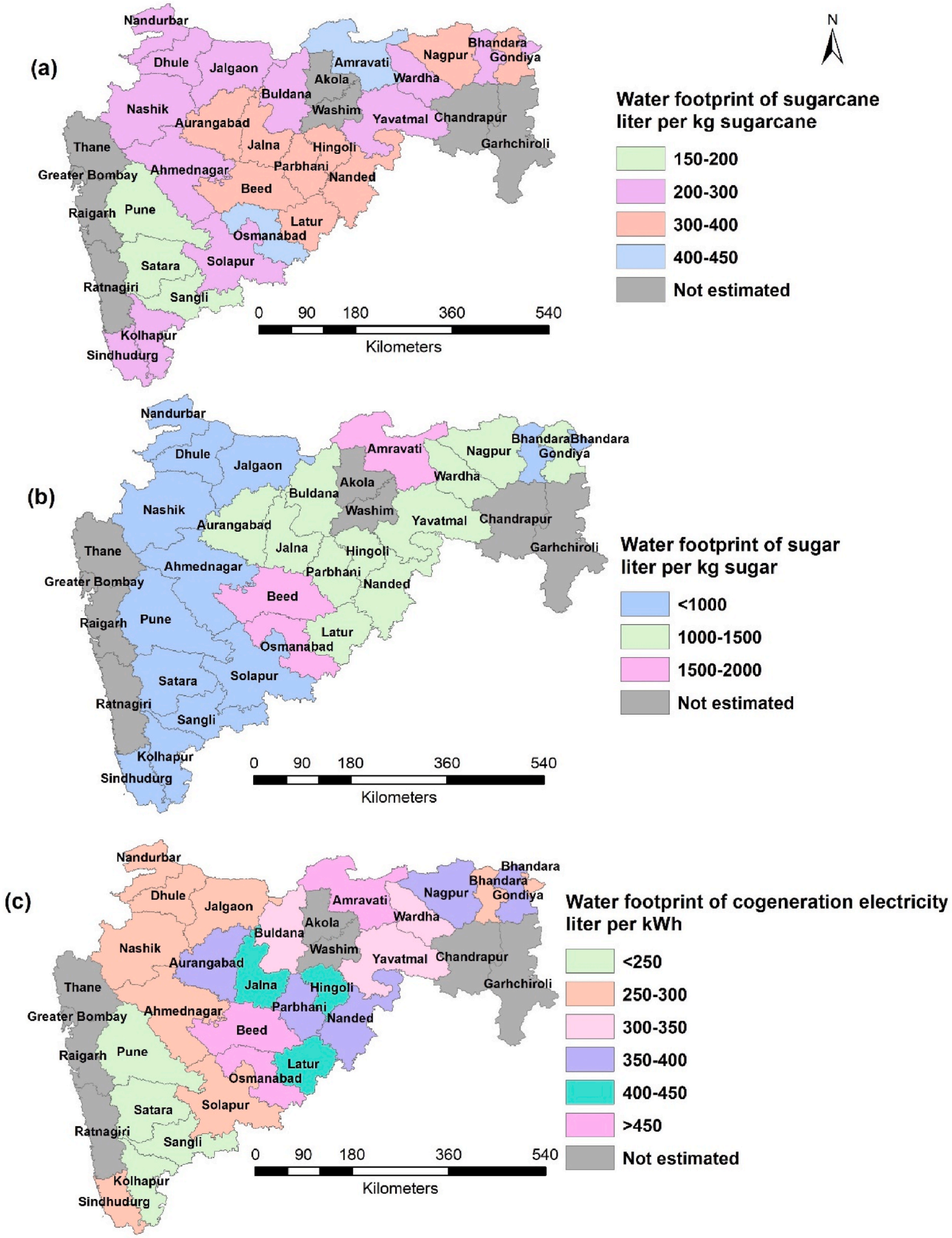


Fig. 8. District-wise ranges of Water footprint (WF) for (a) sugarcane, (b) sugar, (c) bagasse cogeneration electricity in Maharashtra, India.

long-duration adsali sugarcane, but high sugarcane productivity compensates for the high input. Districts in the drought-prone Marathwada and Vidarbha regions prefer ratoon cultivation which requires less water than adsali due to shorter growing season, but low productivity (2–3 times less than adsali) ultimately leads to high ECW.

Water availability in agriculture directly influences the crop yield and crop economics. In water scarce sugarcane cultivating districts of Maharashtra higher amount of fertilizers, human labour, and groundwater based irrigation is needed [79]. High requirement of groundwater-based irrigation and fertilizer leads to higher energy input for water pumping ultimately resulting in higher carbon footprints. Therefore, water consumption is directly linked with the GHG emissions of groundwater irrigation, and there is an opportunity for concurrent reduction of ECW by employing efficient irrigation techniques. Adoption of efficient irrigation techniques, including micro-irrigation (drip, sprinkler) instead of traditional flooded or furrow irrigation, can lead to

Table 9
Results of uncertainty analysis of sugarcane cultivation stage.

Parameter	Unit	Sangli	Sangli	Osmanabad	Osmanabad
		90 % confidence level (5th and 95th percentile)	75 % confidence level (25th and 75th percentile)	90 % confidence level	75 % confidence level
Sugarcane productivity	t/ha	95–121	102–113	26–52	34–44
Bagasse recovery	%	27.8–28.5	28–28.3	26.3–33.7	28.5–31.6
N-fertilizer application	Kg/ha	270–375	297–342	261–323	276–303
Water consumption	Million L/ha	179–231	191–214	174–199	180–191
Electricity consumption	kWh/ha	955–1509	1119–1361	1505–2386	1768–2151

Table 10
Comparative energy, carbon and water footprint of sugarcane products under different scenarios.

Footprint	Product	Unit	Sangli			Osmanabad		
			Original case	S1	S2	Original case	S1	S2
CF	Electricity	kg CO_2e/kWh	0.075	0.06	0.04	0.2	0.14	0.08
	Sugar	kg CO_2e/kWh	0.24	0.18	0.14	0.65	0.45	0.28
WF	Electricity	L/kWh	206	147	103	516	347	244
	Sugar	L/kg	674	481	357	1688	1134	842
EF	Electricity	MJ/kWh	0.75	0.58	0.40	2.1	1.47	0.83
	Sugar	MJ/kg	2.6	2	1.5	7	4.9	3
EROI	Electricity		4.8	6.2	8.9	2.1	2.5	4.3
	Sugar		6.4	8.2	10.8	2.4	3.4	5.5

Both S1 and S2 scenarios show significant reduction in CF, WF and EF values compared to the original case assessed, with S2 performing almost two times better. The decrease in WF is remarkable, for example, WF of sugar decreases from 674 to 357 L/kg for Sangli and from 1688 to 842 L/kg for Osmanabad. Similarly, doubling in the EROI is also observed.

Table 11
Carbon-water-energy footprint of bagasse cogeneration electricity under different allocations in Maharashtra, India.

Allocation type	Carbon footprint, kg CO_2e/kWh		Water footprint, L/kWh		Energy footprint, MJ/kWh	
	Sangli district	Osmanabad district	Sangli district	Osmanabad district	Sangli district	Osmanabad district
Energy allocation	0.075	0.200	206	516	0.75	2.10
Economic allocation	0.018	0.051	46	128	0.14	0.49
Mass allocation	0.103	0.264	283	686	1.04	2.80

enhanced water-use efficiency and increased sugarcane productivity, leading to low ECW footprint. The on-farm irrigation efficiency of drip-irrigation in India is reported to be more than 90 % in comparison to about 65–70 % for sprinkler and 45–50 % for surface irrigation systems [102]. A study in Maharashtra evaluated the impact of replacing flood irrigation with drip irrigation in sugarcane cultivation and observed an increase of crop productivity by 23 %, water-saving by 44 % per hectare, and electricity saving of 1059 kWh/ha [97]. Instead of giving free electricity, the government can provide incentives to the farmers for adopting these efficient irrigation technologies. Further, these irrigation technologies can directly translate into economic benefits to farmers compensating for the higher capital costs incurred in their installation.

As suggested by Ghani et al., 2019, sugarcane cultivation regions should be classified based on water scarcity index for better management of water resources [65]. This can help avoid over-exploitation of water resources by promoting cultivation of sugarcane in those areas where water scarcity is low. It can also increase crop diversity in districts by cultivation of crops considering the local water availability.

Since the cultivation stage is the most impactful life cycle stage in terms of ECW footprint, interventions must be done at this stage. Similar observation has also been made for sugarcane bioenergy in Thailand and Pakistan [65,103]. Replacing coal or diesel-based electricity with solar PV could significantly reduce carbon footprint [104]. Districts in Maharashtra with 250–300 clear sunny days, and irradiation of 4–6 kWh/m^2 have a high solar PV potential of generating 1.5 million units/MW/year, which could be used for irrigation purposes to avoid the adverse impacts of fossil fuels [105]. The tariff-free electricity to farmers for agricultural applications in Maharashtra is also a reason for energy wastage and higher irrigation energy consumption [90]. The cultivation practices need to be corrected by appropriately adjusting the price of electricity which will also help conserve water.

Replacing fossil-based chemical fertilizers and pesticides with organic fertilizers and bio-pesticides made from locally available biomass resources can also significantly reduce the CF. A sugarcane study in Maharashtra found that organic cultivation increased human labour employment by 20.2 % and lowered the overall cost of cultivation by 14.67 % than inorganic farming [106]. Despite a 6.2 % drop in the crop yield the study reported an overall 15.72 % higher profits for the farmer with organic cultivation.

Income generation opportunities for farmers with sugarcane cultivation:

The Indian Government has targeted to double the farmers income by 2024 through increasing crop productivity, resource use efficiency, cropping intensity, shifting towards high-value crops [107]. In light of the above agricultural sector reforms introduced recently by the Government [108], following measures can be taken for the sugarcane sector to increase farmers' profitability:

(i) Cultivating high productivity sugarcane (adsali, preseasonal) in combination with micro-irrigation. Optimizing inputs for sugarcane cultivation is important because it accounts for 70–75 % of the total cost of sugar production [25].
(ii) Fully realizing cogeneration potential. As of now, only 334 sugar factories out of 740, have installed exportable cogeneration facilities in India [25]. Upgrading existing traditional, low pressure boiler in sugar mills with modern, high pressure boiler can further increase the clean bioenergy share in India.
(iii) Creating a dedicated welfare fund for sugarcane farmers and exploring sugar export possibilities to neighbouring countries [25,109].
(iv) Using not only molasses but also sugarcane juice and surplus sugar for ethanol production. In 2017-18 sugar season, Oil Marketing Companies (OMCs) tendered for 3.13 billion liters of ethanol, but existing infrastructure for ethanol production in India is 2.24 billion liters [25]. The recent 20% ethanol blending target with petrol by the Goverment of India is a right move in this direction.

Thus, a combination of the mentioned approaches can help to develop and manage the nexus around the energy-water-carbon while providing economic benefits to farmers and the Government by tackling challenges across India's resource sectors.

7. Conclusion

Agriculture is a major contributor to Indian economy. Almost 70 % of India's population is dependent on agricultural activities for subsistence. Nearly 50 million farmers are involved in sugarcane cultivation in India. Crop cultivation also results in a large amount of agro-residue production in India for potential use as a renewable energy. Agro-residue bioenergy can not only help to reduce GHGs emissions but also provide income opportunities for the farmers. Precise resource and environmental assessments are prerequisite for agro-bioenergy planning.

Sugarcane bagasse has been proven to be a successful feedstock for renewable heat and electricity generation around the world. The present research took a district-level approach to assess bagasse potential and environmental performance of bagasse cogeneration in Maharashtra, India. The state's annual bagasse cogeneration potential is 8206 GWh, 5.3 % of the state's annual electricity demand. The potential varies significantly among the districts, from 2 GWh in Amravati to 1500 GWh in Kolhapur.

The life cycle carbon, energy and water footprint of cogeneration electricity varies markedly among the districts. The carbon footprint of bagasse electricity at the state level is 0.13 kg CO_2e/kWh and at district level it ranges from 0.075 kg CO_2e/kWh in Sangli to 0.2 kg CO_2e/kWh in Osmanabad. The carbon footprint of bagasse cogeneration electricity is 5–12 times less than coal electricity. Sugarcane cultivation stage accounted for 88–95 % of the total emissions, followed by milling (4–8 %) and cogeneration (1–3 %). The key contributors to emissions at the cultivation stage include coal-based electricity for irrigation and N-fertilizer application (inorganic and organic manure). State-level water footprint of cogeneration electricity is 334 L/kWh. The footprint varies from 206 to 516 L/kWh among the districts. The water footprint of bagasse electricity is much higher than coal electricity, which could pose a challenge to large-scale utilization of bioenergy. Almost all the water demand occurs at the sugarcane cultivation stage therefore maximizing irrigation efficiency is important. Replacing conventional flood irrigation with sprinkler or drip irrigation can reduce 40–50 % irrigation water demand and thus water footprint of bagasse electricity. The energy return on investment (EROI), ranges from 1.7 to 4.8 among the districts with a state average of 2.8. By-product or waste such as sugarcane trash, press mud and bagasse ash should be used for alternative applications to further lower the environmental footprint of sugarcane.

The present study highlighted the need for local-level bioenergy planning and the various ways to manage the energy-carbon-water nexus. Interventions could be directed at the sugarcane cultivation stage through solar PV-based irrigation, efficient irrigation technologies, and nutrient management. These measures can concurrently improve the financial condition of both sugarcane farmers and the sugar industry.

Credit author statement

Moonmoon Hiloidhari: Conceptualization, Methodology, Software, Writing – original draft, review & editing. Vandit Vijay: Writing –review & editing. Rangan Banerjee: Conceptualization, Supervision, Writing –review. DC Baruah: Writing –review. Anand B Rao: Conceptualization, Supervision, Writing –review.

Funding

The present research did not receive any special grant from public, private, or non-profit sector based funding agencies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are thankful to the (i) Vasantdada Sugar Institute, Pune, Maharashtra (ii) Sugar Commissionerate, Pune, Maharashtra and (iii) Cogeneration Association of India for providing sugarcane and cogeneration related information and statistics. The first author (Moonmoon Hiloidhari) is thankful to Indian Institute of Technology Bombay for providing Institute Postdoctoral Fellowship (I-PDF). Moonmoon Hiloidhari is also thankful to Pre-Sustainability for providing SimaPro 9 Faculty licence without any charges.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111583.

References

[1] IRENA. More people have access to electricity, but world is falling short of sustainable energy goals. https://www.irena.org/newsroom/pressreleases/2019/May/More-People-Have-Access-to-Electricity-Than-Ever-Before. [Accessed 16 August 2020].
[2] IEA. SDG7: data and projections. https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity. [Accessed 16 August 2020].
[3] To LS, Seebaluck V, Leach M. Future energy transitions for bagasse cogeneration: lessons from multi-level and policy innovations in Mauritius. Energy Res Soc Sci 2018;35:68–77.
[4] MNRE. Ministry of new and renewable energy. India: Bioenergy; 2020. https://mnre.gov.in/bio-energy/current-status. [Accessed 25 July 2020].
[5] Carpio LGT, de Souza FS. Optimal allocation of sugarcane bagasse for producing bioelectricity and second generation ethanol in Brazil: scenarios of cost reductions. Renew Energy 2017;111:771–80.
[6] Gutiérrez AS, Eras JJC, Hens L, Vandecasteele C. The biomass based electricity generation potential of the province of Cienfuegos, Cuba. Waste Biomass Valori 2017;8:2075–85.
[7] MNRE. Bioenergy overview. Ministry of New and Renewable Energy, Government of India; 2021. https://mnre.gov.in/bio-energy/current-status. [Accessed 4 May 2021].
[8] MEDA. Maharashtra energy development agency. Bagasse based cogeneration project; 2020. https://www.mahaurja.com/meda/en/grid_connected_power/bagasse. [Accessed 25 July 2020].
[9] Silva DAL, Delai I, Montes MLD, Ometto AR. Life cycle assessment of the sugarcane bagasse electricity generation in Brazil. Renew Sustain Energy Rev 2014;32:532–47.
[10] Brizmohun R, Ramjeawon T, Azapagic A. Life cycle assessment of electricity generation in Mauritius. J Clean Prod 2015;106:565–75.

[11] Pachón ER, Vaskan P, Raman JK, Gnansounou E. Transition of a South African sugar mill towards a biorefinery. A feasibility assessment. Appl Energy 2018;229:1–17.

[12] Prasara -AJ, Gheewala SH, Silalertruksa T, Pongpat P, Sawaengsak W. Environmental and social life cycle assessment to enhance sustainability of sugarcane-based products in Thailand. Clean Technol Environ Policy 2019;21:1447–58.

[13] Mohammadi F, Roedl A, Abdoli MA, Amidpour M, Vahidi H. Life cycle assessment (LCA) of the energetic use of bagasse in Iranian sugar industry. Renew Energy 2020;145:1870–82.

[14] Contreras AM, Rosa E, Pérez M, Van Langenhove H, Dewulf J. Comparative life cycle assessment of four alternatives for using by-products of cane sugar production. J Clean Prod 2009;17:772–9.

[15] Amezcua-Allieri MA, Martínez-Hernández E, Anaya-Reza O, Magdaleno-Molina M, Melgarejo-Flores LA, Palmerín-Ruiz ME, Eguía-Lis JAZ, Rosas-Molina A, Enríquez-Poy M, Aburto J. Techno-economic analysis and life cycle assessment for energy generation from sugarcane bagasse: case study for a sugar mill in Mexico. Food Bioprod Process 2019;118:281–92.

[16] Contreras-Lisperguer R, Batuecas E, Mayo C, Díaz R, Pérez FJ, Springer C. Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica. J Clean Prod 2018;200:390–401.

[17] Renouf MA, Pagan RJ, Wegener MK. Life cycle assessment of Australian sugarcane products with a focus on cane processing. Int J Life Cycle Assess 2011;16:125–37.

[18] Zubaryeva A, Zaccarelli N, Del Giudice C, Zurlini G. Spatially explicit assessment of local biomass availability for distributed biogas production via anaerobic co-digestion–Mediterranean case study. Renew Energy 2012;39:261–70.

[19] Tolessa A, Zantsi S, Louw TM, Greyling JC, Goosen NJ. Estimation of biomass feedstock availability for anaerobic digestion in smallholder farming systems in South Africa. Biomass Bioenergy 2020;142:105798.

[20] Næsset E, McRoberts RE, Pekkarinen A, Saatchi S, Santoro M, Trier ØD, Zahabu E, Gobakken T. Use of local and global maps of forest canopy height and aboveground biomass to enhance local estimates of biomass in miombo woodlands in Tanzania. Int J Appl Earth Obs Geoinf 2020:102138.

[21] Fazio S, Monti A. Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass Bioenergy 2011;35:4868–78.

[22] VSI. Vasantdada sugar Institute. 2018. Pune, India, http://www.vsisugar.com/.

[23] MoAFW. Ministry of agriculture and farmers welfare. Govt. Of India. Crop production statistics information system; 2019. https://aps.dac.gov.in/APY/Public_Report1.aspx. [Accessed January 2019].

[24] CACP. Commission for agricultural costs and prices, price policy for sugarcane (2015-16 sugar season). India: Ministry of Agriculture and Farmers Welfare; 2014.

[25] Anekant Prakashan. Sugar India yearbook 2018-2019. Kolhapur (Maharashtra): Published by Anekant Prakashan; 2019. http://www.anekantprakashan.com/.

[26] Mamaye M, Kiflie Z, Feleke S, Yimam A, Jabasingh SA. Valorization of Ethiopian sugarcane bagasse to assess its suitability for pulp and paper production. Sugar Tech 2019;21:995–1002.

[27] Kamate SC, Gangavati PB. Exergy analysis of cogeneration power plants in sugar industries. Appl Therm Eng 2009;29:1187–94.

[28] MTIR PHOL. Biomass power: high efficiency boiler technology for sugar industry. In: Seminar on renewable energy technology implementation in Thailand October 4; 2012. 2019, http://www.eeas.europa.eu/archives/delegations/thailand/documents/thailande_eu_coop/energy_efficiency/renewable_energy_technology_implementation_in_thailand/final_presentations_4oct/6_high_efficiency_boiler_technology_sugar_industry_suwat_en.pdf.

[29] ISO 14040:2006. Environmental management – life cycle assessment– principles and framework. Geneva: International Organisation for Standardization; 2006.

[30] ISO 14067:2018. Greenhouse gases – carbon footprint of products– requirements and guidelines for quantification. Geneva: International Organisation for Standardization; 2018.

[31] Seabra JE, Macedo IC, Chum HL, Faroni CE, Sarto CA. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. Biofuel Bioprod Bior 2011;5:519–32.

[32] García CA, Fuentes A, Hennecke A, Riegelhaupt E, Manzini F, Masera O. Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. Appl Energy 2011;88:2088–97.

[33] SAACKE. Liquids with low heating value. https://www2.saacke.com/fileadmin/Media/Documents/pdfs/EN/Brochures/0-0750-0020-02_Ansicht.pdf. [Accessed June 2020].

[34] Phyllis2. Sugarcane bagasse (#2806). https://phyllis.nl/Biomass/View/2806. [Accessed 15 June 2020].

[35] Balakrishnan M, Batra VS. Valorization of solid waste in sugar factories with possible applications in India: a review. J Environ Manag 2011;92:2886–91.

[36] CSRS. Central sugarcane research station, padegaon. http://www.iisr.nic.in/aicrp/pages/padegaon.htm; 2019.

[37] Gupta N, Tripathi S, Balomajumder C. Characterization of pressmud: a sugar industry waste. Fuel 2011;90:389–94.

[38] Anacleto LR, Roberto MM, Marin-Morales MA. Toxicological effects of the waste of the sugarcane industry, used as agricultural fertilizer, on the test system Allium cepa. Chemosphere 2017;173:31–42.

[39] Jha B, Kapoor RM, Vijay V, Vijay VK, Chandra R. Biogas: a sustainable and potential fuel for transport application. J Biofuels Bioenergy 2015;1:28. https://doi.org/10.5958/2454-8618.2015.00004.8.

[40] Khan IU, Othman MHD, Hashim H, Matsuura T, Ismail AF, Rezaei-DashtArzhandi M, Azelee IW. Biogas as a renewable energy fuel–A review of biogas upgrading, utilisation and storage. Energy Convers Manag 2017;150:277–94.

[41] Ramjeawon T. Life cycle assessment of electricity generation from bagasse in Mauritius. J Clean Prod 2008;16:1727–34.

[42] Sales A, Lima SA. Use of Brazilian sugarcane bagasse ash in concrete as sand replacement. Waste Manag 2010;30:1114–22.

[43] Xu Q, Ji T, Gao SJ, Yang Z, Wu N. Characteristics and applications of sugar cane bagasse ash waste in cementitious materials. Materials 2019;12:39.

[44] Jamsawang P, Poorahong H, Yoobanpot N, Songpiriyakij S, Jongpradist P. Improvement of soft clay with cement and bagasse ash waste. Construct Build Mater 2017;154:61–71.

[45] SimaPro. SimaPro database manual-methods. https://simapro.com/wpcontent/uploads/2020/06/DatabaseManualMethods.pdf. [Accessed 27 July 2020].

[46] Dharmadhikary S, Bhalerao R, Dabadge A, Sreekumar N. Understanding the electricity, water, agriculture linkages volume 1: overview. Pune, India: Prayas (Energy Group); 2018.

[47] PMKSY. Pradhan mantri krishi sinchayee yojana. District Irrigation Plan (DIP) of Satara District; 2017. http://www.pmksy.gov.in/mis/Uploads/2017/20170201033508473-1.pdf. [Accessed January 2020].

[48] CGWB. Central Ground water board, government of India. 2019. http://cgwb.gov.in/District%20wise%20depth%20to%20water%20premonsoon2019.html. [Accessed 1 August 2020].

[49] CEA. Central electricity authority. Load generation balance report 2019-20; 2020. http://cea.nic.in/reports/annual/lgbr/lgbr-2019.pdf.

[50] Baruah DC, Bora GC. Energy demand forecast for mechanized agriculture in rural India. Energy Pol 2008;36:2628–36.

[51] Dyjakon A. Harvesting and baling of pruned biomass in apple orchards for energy production. Energies 2018;11:1680.

[52] EPA. Emission factors for greenhouse gas inventories. https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf. [Accessed 5 July 2020].

[53] WRI. World resource Institute. Greenhouse Gas Protocol: Calculation tools; 2017. https://ghgprotocol.org/calculation-tools#cross_sector_tools_id. [Accessed 1 August 2020].

[54] Klein CD, Novoa RSA, Ogle S, Smith KA, Rochette P, Wirth TC, McConkey BG, Mosier A, Rypdal K. 2006 IPCC guidelines for national greenhouse gas inventories, Volume 4 Chapter 11: N2O emissions from managed soils, and CO2 emissions from lime and urea application. Intergovernmental Panel on Climate Change (IPCC); 2006.

[55] Paturau JM. Alternative uses of sugarcane and its byproducts in agroindustries. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); 1987.

[56] Sundaram MS. Water conservation in sugar complex. Pune, India: 4th Annual Symposium, VSI; 2016.

[57] EPA. Bagasse combustion in sugar mills. 2020. https://www3.epa.gov/ttn/chief/ap42/ch01/final/c01s08.pdf. [Accessed 5 July 2020].

[58] Huijbregts MA, Steinmann ZJ, Elshout PM, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 2017;22:138–47.

[59] iPoint. Life Cycle Impact Assessment – which are the LCIA indicator sets most widely used by practitioners? Germany: iPoint-systems gmbh; 2018. https://www.ipoint-systems.com/blog/lcia-indicator/. [Accessed 5 August 2020].

[60] Murphy DJ, Hall CA. Year in review—EROI or energy return on (energy) invested. Ann NY Acad Sci 2010;1185:102–18.

[61] Gorain S, Singh DR, Kumar P, Venkatesh P, Jha GK. Economics of sugarcane and banana cultivation under drip irrigation system: a case study of northern Maharashtra. Econ Aff 2020;65:151–9.

[62] Chauhan MK, Varun, Chaudhary S, Kumar S, Samar. Life cycle assessment of sugar industry: a review. Renew Sustain Energy Rev 2011;15:3445–53. https://doi.org/10.1016/j.rser.2011.04.033.

[63] Yuttitham M, Gheewala SH, Chidthaisong A. Carbon footprint of sugar produced from sugarcane in eastern Thailand. J Clean Prod 2011;19:2119–27. https://doi.org/10.1016/j.jclepro.2011.07.017.

[64] García CA, García-Treviño ES, Aguilar-Rivera N, Armendáriz C. Carbon footprint of sugar production in Mexico. J Clean Prod 2016;112:2632–41. https://doi.org/10.1016/j.jclepro.2015.09.113.

[65] Ghani HU, Silalertruksa T, Gheewala SH. Water-energy-food nexus of bioethanol in Pakistan: a life cycle approach evaluating footprint indicators and energy performance. Sci Total Environ 2019;687:867–76.

[66] Vijay V, Subbarao PMV, Chandra R. An evaluation on energy self–sufficiency model of a rural cluster through utilization of biomass residue resources: a case study in India. Energy Clim Chang 2021;2:100036. https://doi.org/10.1016/j.egycc.2021.100036.

[67] Carvalho M, Bernardino Da Silva Segundo V, Gama De Medeiros M, Albuquerque Dos Santos N, Moreira Coelho Junior M. Carbon footprint of the generation of bioelectricity from sugarcane bagasse in a sugar and ethanol industry. Int J Glob Warming 2019;17.

[68] Hiloidhari M, Haran S, Banerjee R, Rao AB. Life cycle energy–carbon–water footprints of sugar, ethanol and electricity from sugarcane. Bioresour Technol 2021;330:125012. https://doi.org/10.1016/j.biortech.2021.125012.

[69] Varun, Bhat IK, Prakash R. LCA of renewable energy for electricity generation systems-A review. Renew Sustain Energy Rev 2009;13:1067–73. https://doi.org/10.1016/j.rser.2008.08.004.

[70] Hartmann D, Kaltschmitt M. Electricity generation from solid biomass via co-combustion with coal: energy and emission balances from a German case study.

Biomass Bioenergy 1999;16:397–406. https://doi.org/10.1016/S0961-9534(99)00017-3.
[71] Seabra JEA, Dourado Hernandes TA. Water footprint of biofuels in Brazil: assessing regional differences. Biofuels, Bioprod Bioref 2013. https://doi.org/10.1002/bbb.1454.
[72] Nguyen TLT, Gheewala SH, Garivait S. Full chain energy analysis of fuel ethanol from cane molasses in Thailand. Appl Energy 2008;85:722–34. https://doi.org/10.1016/j.apenergy.2008.02.002.
[73] Khatiwada D, Silveira S. Net energy balance of molasses based ethanol: the case of Nepal. Renew Sustain Energy Rev 2009;13:2515–24. https://doi.org/10.1016/j.rser.2009.06.028.
[74] Hiloidhari M, Banerjee R, Rao AB. Life cycle assessment of sugar and electricity production under different sugarcane cultivation and cogeneration scenarios in India. J Clean Prod 2021;290:125170. https://doi.org/10.1016/j.jclepro.2020.125170.
[75] Hoekstra AY, Chapagain AK, Mekonnen MM, Aldaya MM. The water footprint assessment manual: setting the global standard. Routledge; 2011.
[76] Scholten W. The water footprint of sugar and sugar-based ethanol. University of Twente; 2009.
[77] Mekonnen MM, Hoekstra AY. The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci 2011;15:1577–600.
[78] Shukla SK, Sharma L, Awasthi SK, Pathak AD. Sugarcane in India (Package of practices for different agro-climatic zones). New Delhi, India: AICRP (S) Technical Bulletin - No. 1; 2017.
[79] Sharma BR, Gulati A, Mohan G, Manchanda S, Ray I, Amarasinghe U. Water productivity mapping of major Indian crops. Indian Council for Research on International Economic Relations; 2018.
[80] Scarpare FV, Hernandes TAD, Ruiz-Corrêa ST, Kolln OT, de Castro Gava GJ, dos Santos LNS, Victoria RL. Sugarcane water footprint under different management practices in Brazil: tietê/Jacaré watershed assessment. J Clean Prod 2016;112:576–4584.
[81] Gil MP, Moya AMC, Domínguez ER. Life cycle assessment of the cogeneration processes in the Cuban sugar industry. J Clean Prod 2013;41:222–31.
[82] Mashoko L, Mbohwa C, Thomas VM. Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry. J Clean Prod 2013;39:42–9.
[83] Varshney D, Mandade P, Shastri Y. Multi-objective optimization of sugarcane bagasse utilization in an Indian sugar mill. Sustainable Production and Consumption 2019 Apr 1;18:96–114.
[84] Raghuvanshi SP, Chandra A, Raghav AK. Carbon dioxide emissions from coal based power generation in India. Energy Convers Manag 2006;47:427–41.
[85] Mekonnen MM, Gerbens-Leenes PW, Hoekstra AY. Future electricity: the challenge of reducing both carbon and water footprint. Sci Total Environ 2016;569:1282–8.
[86] Holmatov B, Hoekstra AY, Krol MS. Land, water and carbon footprints of circular bioenergy production systems. Renew Sustain Energy Rev 2019;111:224–35.
[87] Fajardy M, Mac Dowell N. Can BECCS deliver sustainable and resource efficient negative emissions? Energy Environ Sci 2017;10:1389–426. 2017.
[88] Zhao D, Momotaz A, LaBorde C, Irey M. Biomass yield and carbohydrate composition in sugarcane and energy cane grown on mineral soils. Sugar Tech 2020;22:630–40. https://doi.org/10.1007/s12355-020-00807-0.
[89] Fito J, Tefera N, Demeku S, Kloos H. Water footprint as an emerging environmental tool for assessing sustainable water use of the bioethanol distillery at metahara sugarcane farm, oromiya region, Ethiopia. Water Conserv Sci Eng 2017;2:165–76. https://doi.org/10.1007/s41101-017-0038-y.
[90] Lee JY, Naylor RL, Figueroa AJ, Gorelick SM. Water-food-energy challenges in India: political economy of the sugar industry. Environ Res Lett 2020;15:84020. https://doi.org/10.1088/1748-9326/ab9925.
[91] Upreti P, Singh A. An economic analysis of sugarcane cultivation and its productivity in major sugar producing states of Uttar Pradesh and Maharashtra. Econ Aff 2017;62.
[92] NITI Aayog. Sugarcane and sugar industry. 2020. New Delhi.
[93] Dingre SK, Gorantiwar SD. Determination of the water requirement and crop coefficient values of sugarcane by field water balance method in semiarid region. Agric Water Manag 2020;232:106042.
[94] Shah A, Mathur N. Contestations around water allocation during a climate crisis in India: the case of 'IPL vs. drought. Global Environ Change 2019;57:101927. https://doi.org/10.1016/j.gloenvcha.2019.05.011.
[95] Bhardwaj A. Indian Sugar Mill Association. Benefits of micro irrigation system: sugar recovery & productivity. 2013. https://www.indiansugar.com/uploads/Workshop-Micro-irrigation.pdf.
[96] The Hindu. Maharashtra math: 1 kg sugar = 2,515 litres water. https://www.thehindubusinessline.com/economy/agri-business/maharashtra-math-1-kg-sugar-2515-litres-water/article27072657.ece. [Accessed 12 September 2020].
[97] Narayanamoorthy A. Drip irrigation in India: can it solve water scarcity? Water Pol 2004;6:17–130.
[98] PMKSY. *Pradhan mantri krishi sinchayee yojana* (PMKSY). Government of India; 2020. https://pmksy.gov.in/. [Accessed 19 August 2020].
[99] Zhang C, Chen X, Li Y, Ding W, Fu G. Water-energy-food nexus: concepts, questions and methodologies. J Clean Prod 2018;195:625–39. https://doi.org/10.1016/j.jclepro.2018.05.194.
[100] Finkbeiner M, Schau EM, Lehmann A, Traverso M. Towards life cycle sustainability assessment. Sustainability 2010;2:3309–22. https://doi.org/10.3390/su2103309.
[101] Li H, Zhao Y, Lin J. A review of the energy–carbon–water nexus: concepts, research focuses, mechanisms, and methodologies. Wiley Interdiscip Rev Energy Environ 2020;9:e358. https://doi.org/10.1002/wene.358.
[102] Sivanappan RK. Prospects of micro-irrigation in India. Irrigat Drain Syst 1994;8:49–58. https://doi.org/10.1007/BF00880798.
[103] Silalertruksa T, Gheewala SH. Land-water-energy nexus of sugarcane production in Thailand. J Clean Prod 2018;182:521–8. https://doi.org/10.1016/j.jclepro.2018.02.085.
[104] Wettstein S, Muir K, Scharfy D, Stucki M. The environmental mitigation potential of photovoltaic-powered irrigation in the production of South African Maize. Sustain Times 2017;9:1772. https://doi.org/10.3390/su9101772.
[105] Elavarasan RM, Selvamanohar L, Raju K, Vijayaraghavan RR, Subburaj R, Nurunnabi M, et al. A holistic review of the present and future drivers of the renewable energy mix in Maharashtra, state of India. Sustainability 2020;12:6596. https://doi.org/10.3390/su12166596.
[106] Kshirsagar KG. Impact of organic farming on economics of sugarcane cultivation in Maharashtra. International Water Management Institute; 2008.
[107] Chand R. Doubling farmers' income: rationale, strategy, prospects and action plan. National Institute for Transforming India (NITI), Government of India; 2017. NITI Policy Paper No. 1/2017, . [Accessed 3 October 2020].
[108] Singh SK, Rosmann M. Government of India issues three ordinances ushering in major agricultural market reforms. USDA; 2020. Report Number: IN2020-0074.
[109] CACP. Commission for agricultural costs and prices, price policy for sugarcane (2020-21 season). India: Ministry of Agriculture and Farmers Welfare; 2019.