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Life cycle sustainability assessment of crops in India

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A B S T R A C T

In India, the modernization in the agricultural sector is continuously growing to meet the food demand of rising population. However, along with addressing hunger, modern agriculture impacts the ecosystem, human health, and resources, due to huge consumption of agrochemicals, and emission-intensive farming hence urges sustainable assessment. Till now, no impact assessment is reported on world's second-largest agricultural country-India. This paper is the first of its kind in evaluating the impact of the cultivation of 21 commonly grown crops that possess high production and emissions in India. The results were discussed in the order of impact parameters in respective years with possible causes and remedial measures. The results showed that rice has topped in maximum indices followed by sugarcane, wheat, and banana. The study forecasted that coconut played a concentrated role in global warming, while potato and sugarcane have a higher impact on water and ozone depletion, respectively. The outcomes of this study suggested appropriate improvements in farming practices, which can bring the emissions down and make the system more sustainable. Besides, these 18 indices were individually assessed for their connection with the 17 sustainable development goals (SDGs) in the aspects of agricultural activities to select the appropriate indices to measure the agricultural sustainability along with the identification of gaps to upgrade the existing indices or formulate a new one. Subsequently, this helps in achieving the SDGs in India with the least impact on the environment without compromising the socio-economic aspects involved in crop production and agricultural systems.

1. Introduction

The agricultural sector forms the spine of various leading economies of the world. China is the largest, followed by India, the US being the third followed by Brazil, Nigeria, and Indonesia. While, the population of the planet is projected to rise by 9.6 billion in the year 2050 from 7 billion in 2012, to satisfy the food demand, for the ever-mounting population, food stocks need to rise by 60% (Alexandratos and Bruinsma, 1985). India, being an agriculturally dominant nation, produced 51 MT of food grain in 1950–51, 250 MT in 2011–12, and aims to generate 298 MT in 2020–21 to meet its population growth-based demand (Kumar et al., 2009; U. FAO, 1951; GOI, 2016a). The current revolution in the agricultural sector addresses the first two goals of SDGs (Sustainable Development Goals) "*no poverty*" and "*zero hunger*".

On the other hand, modern agricultural activities utilize natural resources such as land and water, consume a huge amount of toxic

Abbreviations: ALOP, Agricultural Land Occupation Potential; CFC, Chlorofluorocarbons; CRM, Crop residue management; EPA, Environmental Protection Agency; FAO, Food and Agriculture Organization; FAOSTAT, Food and Agriculture Organization Corporate Statistical Database; FD, Fossil depletion; FDP, Fossil depletion potential; FEP, Freshwater Eutrophication Potential; FETP, Freshwater ecotoxicity potential; FU, Functional Unit; GHG, Greenhouse gas; GWP, Global warming potential; HTP, Human Toxicity Potential; HYV, High Yield Variety; IRP, Ionizing radiation potential; ISO, International Organization for Standardization; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; MDP, Metal Depletion Potential; MEP, Marine Eutrophication Potential; METP, Marine Ecotoxicity Potential; NASA, National Aeronautics and Space Administration; NLTP, Natural Land Transformation Potential; NMVOC, Non-methane volatile organic compounds; NSSO, National Sample Survey Office; NUE, Nitrogen use efficiency; ODP, Ozone Depletion Potential; ODS, Ozone Depleting Substances; PDCP, P-Dichlorobenzene; PM, Particulate matter; PMFP, Particulate Matter Formation Potential; POFP, Photochemical Oxidant Formation Potential (POFP); SD, Sustainable development; SDG, Sustainable development goals; SRI, System of Rice Intensification; TAP, Terrestrial Acidification Potential; TETP, Terrestrial Ecotoxicity Potential; ULOP, Urban Land Occupation potential; URE, Unit risk estimate; UV, Ultra violet; WDP, Water depletion potential; WHO, World health organization.

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chemicals for crop growth, and utilize energy for irrigation (Devi et al., 2017; Mateo-Sagasta et al., 2017; GOI, 2016b). Besides, in India, the agricultural sector results in 10–25% of biomass as waste during crop production, which is either used for tillage or burnt. All these, directly and indirectly, deplete the environment, economy, and human health – the basic components of Sustainable Development (SD). Whereas SDGs insists on achieving the SD in all sectors by 2035. The SDGs 3, 6, and 11–15 on good health and well-being, clean water and sanitation, sustainable cities and communities, climate change, responsible consumption and production, climate action, life below water, and life on land, respectively compel to shift the current agricultural practices towards sustainable farming.

However, the systems are improved to fulfil the economic pressures as well as nutritional requirements of a global population but missed in seeing the ecological and collective well-being as a matter of priority (Devi et al., 2017; Mateo-Sagasta et al., 2017; GOI, 2016b; UNDG, 2017). Hence, it is necessary to assess the environmental and health risk using different indices, to address the hot spots to be worked on, to achieve the target SDG.

Knowing the importance of achieving SD in the agricultural sector, this study aims to utilize a standardized life cycle analysis (LCA) to evaluate the environmental and health risk potential indices associated with crop production in India. This is the first study carried out LCA of crop production by having the study area as India. The LCA was done for the 21 crops grown in India from six different crop categories as listed in Table 1. The crops were purposively selected based on their production, yield, emissions released during their production, and residue generated by them.

Recent research evidence that the LCA framework can be utilized for agricultural operations and products to calculate its impact on the environment and human health. Table 2 list the studies focusing on different countries, methods used, and processes involved for different crops. Integrating crop residue management as one of the agricultural practices during LCA is scarce in the literature, despite its environmental implications, as indicated in Table 2. India produces about 500 Mt. of crop residue per year (GOI, 2016) with a wide geographic distribution variability. Uttar Pradesh has the highest estimate of crop residue (60 Mt./year) (GOI, 2016a). Punjab (51 Mt./year) and Maharashtra (46 Mt./year) were two other high-residue-producing states. From March to May, the crop residue is often burnt on-site. Crop residue burning on farms emits greenhouse gases (CO_2, CO, CH_4, N_2O, SO_2), aerosols, particulate matter, and Volatile Organic Compounds (VOCs) (Devi et al., 2017). Another crop residue management option - tillage cracks the soil, disrupts the soil composition, causing surface runoff and soil erosion (Mateo-Sagasta et al., 2017; GOI, 2016b; UNDG, 2017; Frankowska et al., 2019). All these show the significance of crop residue management in agricultural practices. Hence, the system boundary of the LCA in this study wraps up the crop production and crop residue management.

To conduct the LCA of crops, previous studies used the database which is built for a few European countries as given in Table 2. This study uses AGRIBALYSE 3.0 which is developed for France and to overcome this limitation, many of the inputs are collected from (FAO, 2020) that are wholly Indian. Hence, it is expected that the outcome of this study will be more reliable when it comes to country-focused assessment and be a value add-on to the existing scientific knowledge.

Besides, a separate assessment is performed to forecast the indices for the years 2020, 2025, and 2050 which needs the past and present data, so that the two terms come into the picture: "overused" and "underutilized" - neither of which is ideal. Forecasting aims to curb this problem of overutilization and underutilization of resources. Therefore, a balance can be maintained between these to attain the right utilization of resources while growing crops. Hence, this study helps to know about the thrust present in agricultural strategies availing on natural resources and if same continued, its effects on the environment can also be studied so that we may change our practices to have better health and environment that leads to achieving sustainable agricultural practices.

Having understood the above-said background, the objective of the study is to evaluate the current and future impact of agriculture in India and related risk factors on the environment and human health using different indices as illustrated in Graphical Abstract. The specific tasks are i) collection and compilation of data ii) LCA and impact assessment iii) forecasting of impact and validation. Further studies on establishing the link between the 18 indices and the 17 SDGs have been carried out to select the optimum indices based on the type and focus of the assessment of agricultural and farming processes. It is hypothesized that the assessment of the association between the indices and the SDGs can not only assist in the evaluation of the current indices system on how much extend these indices can measure the sustainable development in the agricultural system but also to pick suitable indices to assess the maximum possible SDGs in the farming practices. Also, it can help in identifying the gaps in this research area to focus on to reach completeness in the evaluation of sustainability in agriculture.

This study is particularly unique in several ways. This is the first-ever study focusing on the country "India" where agriculture is the spine and having a continuously growing population. The other literature measured the impact of the maximum of three agricultural products. However, this paper evaluates 21 crops from 6 different categories considering a wide range of agricultural processes and their emissions, therefore chances of variation of data are comparatively less. It is the first literature that performs LCA to forecast the indices for the years 2020, 2025, and 2050 to eliminate overuse or underuse of natural resources. Data is collected separately from FAOSTAT to meet Indian agricultural inputs. Incorporation of crop residue management in LCA is scarce and here it is included. To prevent variations in agricultural activities such as climatic factors, soil variability, and geographic parameters, annual production data is used and the functional unit is chosen as cultivated area per year.

Table 1
Crops in this study.

Sl. no	Category	Selected crops
1	Cereals	Rice, wheat, barley, maize, and millets
2	Fruits	Apple, mango, banana, and grapes
3	Oilseeds	Castor, rapeseeds, oilseed, and sunflower seeds
4	Vegetables	Potato, tomato, carrots, and beans
5	Cash crops	Coffee and cocoa
6	Others (commercial and food)	Coconut and sugarcane

2. Methodology

2.1. Life cycle impact assessment of crops

The LCA of 21 crops was assessed using "Open LCA" software version 1.10.2 following the ISO norms as shown in Fig. S1. The software received the data and elucidated the results based on 18 environmental potential impact categories which are described in Table S1-S5. A standard LCA structure generally consists of the following steps.

(i) Goal and scope - to describe system boundaries and functional unit of the study.
(ii) Life cycle inventory - to define and quantify all input factors and resources included in the system boundary at each point of the life cycle.
(iii) Impact analysis - to quantify and formulate the impact categories.
(iv) Interpretation of impacts analysis – to discuss the obtained results.

Table 2
Existing works of literature on LCA of crops.

SN	Country	Crops	Focus of study	Method Use		Process involved	Residue management	Ref
				Software	Database			
1	California, U.S.	Tomato	Comprehensive life cycle assessment of California diced and tomato paste products.	ArcGIS	GaBi	Greenhouse transplant development, production of tomatoes, processing of tomatoes.	No	(States et al., 2010)
3	California, U.S.	Almond	To determine the climate effect and energy usage of California's almond production for one acre of almond farm.	GaBi 4, OFFROAD	Ecoinvent, GaBi, U. S. LCI database	Preparing orchards, developing nurseries, rising crops, production, and distribution.	No	(Wagner and Lewandowski, 2017)
4	Sweden	Tomato, Sugar-beets	To perform LCA of tomato ketchup.	LCAiT	Specific-site, Sweden	Agricultural production, food processing, storage and delivery, packaging, use, and recycling of waste.	Yes	(News, 2018)
5	Colombia	Cocoa	Develop a sound and comprehensive outlook through LCA on the sustainability of Colombia's cocoa production.	LCA-Manager 1.3	Ecoinvent (CML 2 baseline 2000 method)	Sowing in a nursery, site planning, and fertilization, phytosanitary maintenance, and energy use.	No	(Liu et al., 2016)
6	China	Rice, Potato, Cotton, Wheat, Corn, Rape	Consider the environmental burden of the agriculture sector on Shanghai's Chongming Island, using the LCA process.	GaBi 8.2.0.55	GaBi, Chongming Statistical Yearbook, Agricultural statistics Report (ReCiPe method)	agriculture material stage (agricultural machinery and Equipment), planting stage (sowing, fertilizing, and spraying of pesticides).	No	(BRE, 2018)
7	Southern France	Orchid Apple	Using LCA, compare the environmental effects of nine apples during their first years.	SALCA	SALCA, SYNOPS (CML01)	Machinery Manufacturing, Field Process (Fertilization, Plant-Protection, Harvesting), Fertilizer Production, Field Emissions	No	(Van Oers and Guinée, 2016)
8	Philippines	Rice	Analysis of environmental profiles, energy efficiency, grain yield and quality, and Greenhouse emission of Rice Production.	SIMAPRO	Ecoinvent 3.0	Field Preparation, seed establishment, crop protection, Harvesting, Rice Straw management.	Yes	(Frankowska and Jeswani, 2019)
9	Germany	Perennial crop (Miscanthus and Willow)	Using the LCA approach to reach the importance of environmental impact categories for perennial biomass production.	openLCA	Ecoinvent 3.1 (ReCiPe method)	Fertilizers and pesticides production, Land preparation, planting, fertilizing, mulching, and spraying.	Yes	(Balafoutis et al., 2017)
10	Poland	Potato	Assess environmental effect of the structure of potato production on plantations covering areas of different sizes.	SimaPro 8.1.0.60	SimaPro (ReCiPe End point)	Technological practices, Seeding of potato, Fertilizers and Pesticides, Fuel and water usage.	No	(Hardy et al., 2013)
11	Sri Lanka	Rice	Estimate the environmental impact of Sri Lanka's rice production, Using LCA.	SimaPro	IPCC GWP 100a, Eco Indicator 99	Cultivation, Harvesting of Rice, Paddy Cleaning, Milling, Polishing	No	(Margni et al., 2002)
12	Italy	Coffee	examine the aspects in which the coffee roasting and distribution company have an impact on environment from a life cycle perspective.	TEAM 3.0	CML, IPPC, WMO, Ecopoint	Cultivation, Processing, Packaging, Transportation, Consumption, Disposal.	Yes	(Winans et al., 2020)
13	U.S.A	American Wheat	Analysis of variability in the life-cycle of GHGEs of wheat as a component of wheat species, variability in farming methods, crop yield, and location of the field.	ArcGIS	GIS, GREET, AIST, USDA	Energy production, Fertilizer, Pesticide and Herbicide Production, wheat cultivation, and Transportation.	No	(Julian, 2019)
14	Mexico (avocado),	Avocado, Banana, Pineapple	Comparison of three different tropical fruits–	openLCA	ecoinvent_3.2_ cut-of	Production of fertilizers, Irrigation,	No	(Karin et al., 1998)

(continued on next page)

Table 2 (*continued*)

SN	Country	Crops	Focus of study	Method Use		Process involved	Residue management	Ref
				Software	Database			
	Costa Rica (pineapple), and Ecuador (banana)		avocado, banana, and pineapple, using LCA.			Land transformation, Harvesting, Packaging, Transportation, Biowaste		
15	Italy	Maize	To evaluate the ecological effects of maize for biogas production, using LCA.	SimaPro	Ecoinvent, LCA Food DK (CML 2000)	Field preparation, crop management (Fertilizers), harvesting, transportation, and storage.	No	(Oscar et al., 2014)
16	India	Rice, wheat, barley, maize, millets apple, mango, banana grapes, Oilseeds castor oil seeds, rapeseeds, sunflower seeds, potato, tomato, carrots beans dry, Coffee, cocoa Coconut and sugarcane	Current and future forecasting of Environmental and health risk impact assessment of 21 different crops grown in India	Open LCA	FAOSTAT, AGRIBALYSE	Crop cultivation, crop production, and residue management	Yes	This study

2.1.1. *Goal and scope*

The goal of the study is to (i) quantify the ecosystem and health-harming potentials which are related to the cultivation of commonly grown 21 crops in India using the indices based on the data collected from different sources for the years 2000, 2005, 2010, and 2015 and (ii) forecast the future production of crops and their associated impact for the year 2020, 2025 and 2050 to improve the resource allocation practices.

2.1.1.1. System definition and system boundaries. To calculate the life cycle, the focused system is split into two stages, namely agriculture material production and crop production stage. Material production deals with the upstream processes such as raw material extraction and production that were required for the second stage. Crop production includes the core processes such as land preparation, crop cultivation, and crop residue management as illustrated in Fig. S2. The associated processes and input requirements are listed in Tables S2 and S5.

2.1.1.2. Functional unit. The functional unit can be described on a comparative basis at the present LCA level. The chosen functional unit in this study is cultivated area per year in India.

2.1.2. *Life cycle inventory (LCI)*

The LCI lists all the inputs such as land use, energy usage (electricity and diesel oil), water consumption, pesticides and fertilizers consumption, and the outputs such as products, emissions, and waste which are dependent on the unit processes lying within the boundary. All the input inventories that are involved in the process are measured based on the functional unit. The final product of this step is known as the LCI result. The crop production life cycle is analyzed for every five years i.e. in the year 2000, 2005, and 2015. The data collection and compilation processes are explained in the supplementary information (section 2.2) that includes Figs. S3–S6 and Tables S1–S3. Also, Table S4 provides a detailed list identifying the different processes/inputs with their corresponding data sources in the life cycle of crop production.

2.1.3. *Life cycle impact assessment (LCIA)*

The LCIA estimates the flow of each inventory to the potential environmental and health risk impact. These impact categories are formulated by applying the most widely used midpoint(H) ReCiPe method (developed in 2008). This study quantifies the 18 midpoint impact parameters under three major categories, say,

(i) Ecosystem quality (11 parameters) - agricultural land occupation (ALOP), climate change (GWP), freshwater ecotoxicity (FETP), freshwater eutrophication (FEP), marine ecotoxicity (METP), marine eutrophication (MEP), natural land transformation (NLTP), terrestrial acidification (TAP), terrestrial ecotoxicity (TETP), urban land occupation (ULOP) and water depletion (WDP)
(ii) Human health (5 parameters) - human toxicity (HTP), ionizing radiation (IRP), ozone depletion (ODP), particulate matter formation (PMFP), photochemical oxidant formation (POFP) and
(iii) Resources (2 parameters) - fossil depletion (FDP) and metal depletion (MDP).

The entire network is shown in Fig. S7. For the years 2000, 2005, 2010, and 2015, the results of 18 parameters were directly obtained from *openLCA* software for 21 crops. The forecasting was based on the extrapolation of the best-fit equation derived from the data of 2000–2015 to 2050. The rationality of the forecasted data was checked using the R^2 value. If the R^2 value is more than or equal to 0.7, the data is said to be valid otherwise not.

2.1.4. *Interpretation*

This last stage of the LCA elucidated the environmental and health consequences because of the inputs and outputs of the agricultural system. The data obtained from the inventory are converted into interpretable and understandable impact values. The obtained results were systematically depicted using graphs and tables. The discussion on 18 indices was elaborated using indices for the past years (2000, 2010, and 2015) and forecasted years (2020, 2025, and 2050) comprising effectual comparison between crops and years.

2.2. *Assessment of the link between the indices and SDGs*

The connection between the 18 indices and the 17 SDGs was evaluated based on the assessment of individual indices to each SDG and tabulated. The SDGs are a set of 17 integrated global goals adopted by the United Nations in 2015 as an initiative to create a more peaceful and prosperous world. The goals are all interconnected and can be used to recognize the effects of outcomes of an activity or action on different parameters. So, SDGs address the three different dimensions of sustainability viz. a viz. environmental, social, and economic sustainability of the 21 crops in this study. The 17 goals considered are 1) No Poverty, 2) Zero Hunger, 3) Good Health and Well-being, 4) Quality Education, 5) Gender Equality, 6) Clean Water and Sanitation, 7) Affordable and

Clean Energy, 8) Decent Work and Economic Growth, 9) Industry, Innovation, and Infrastructure, 10) Reduced Inequality, 11) Sustainable Cities and Communities, 12) Responsible Consumption and Production, 13) Climate Action, 14) Life Below Water, 15) Life on Land, 16) Peace and Justice Strong Institutions and 17) Partnerships to achieve the Goal. The given 17 SDGs are then assigned to these 18 impact indices in this study addressing the ecosystem quality, human health, and resources in agricultural systems.

3. Results and discussions

The harmful impacts of 21 crops are interpreted using the 18 indices for the years 2000, 2010, 2015 was discussed followed by the years 2020, 2025, and 2050. In the forecasting process, the trendlines belong to second-degree polynomial, power, logarithmic, linear, and exponential equations. For second-degree polynomial trendline, in most of the cases, R^2 is more than 90% which is a good indication of forecasting the future data. For the power trendline, R^2 varies in the range of 25–75%. For, logarithmic, linear, and exponential trendline, it was less than 15%, 60%, and 61%, respectively. For apple, coconut, coffee, sugarcane, and tomato, R^2 of all 18 indices, lies between 1 and 20% due to the higher variability of the data between years 2000 and 2015. Thus, the forecasting is restricted to the other 16 crops eliminating these 5 crops. Hence the discussion is there for all the 21 crops during 2000–2015 and, priority was given to the 16 crops considering the maximum number of indices that can be forecasted and/or being the topmost impacts during 2000–2050 as given in Table 3.

An impact group categorizing` different pollutions under one environmental consequence, various impact categories, category indicators, characterization models, equivalence factors, and weighting values have been used to understand the potential impact of data obtained in the LCI analysis. There are two kinds of assessments followed in this section (i) means based and (ii) effect based. The former checks the agricultural practices of farmers, and the latter considers the actual effects of the agricultural system. The results are discussed into three major categories such as the impact on ecosystem quality, human health, and resources based on crops as shown in Fig. 1(a-c) and Fig. 2(a-c).

3.1. Impact on ecosystem quality

3.1.1. Agricultural land occupation (ALOP)

The ecological damage resulting from the continuous use of land for agricultural activities is represented in ALOP. Every activity in farming on a certain area of agricultural land for a certain period can result in damage. Hence, to calculate ALOP, all the activities associated with the LCA of agriculture are considered. Again, the ecological damage resulting from land occupation depends on the level of environmental quality that is maintained during the occupation.

The continuous increase of ALOP values for most of the crops shows that the demand of land use for agriculture purposes keeps escalating to meet the food demand. The evaluation shows that the coconut in the year 2010 topped in ALOP (1.4×10^{13} m^2/kg) among all crops whereas oilseed holds the least value during 2000–2050 as shown in Fig. 1(a-c) and Fig. 2(a-c).

All cereals show a random trend and the order followed as rice > maize > wheat > millet > barley. For category fruits, apple production has maximum ALOP value for the year 2005 which is about 17% more than for the year 2000. Grapes production has a maximum value for the year 2005 which is about 5 times more in comparison of the year 2000. Mangoes production shows a decreasing trend from the year 2000 to 2010 and has a maximum value of 6×10^7 m^2/kg for the year 2015 as shown in Fig. S8 and S9. Another study on fruit consumption in the UK shows that ALOP was top for avocados, mangoes, and plums (1.9 m^2/kg) and the bottommost for melons (0.3 m^2/kg) among the selected fruits (). In the oilseeds category, rapeseed and sunflower seed set similar ALOP whereas castor oil seed has 80% of the impact.

Carrot production has maximum value for the year 2000. Potatoes production showed maximum ALOP for the year 2005 and minimum for the year 2010. Similarly, a study on vegetables in the UK shows that ALOP values for asparagus and peas required the paramount area of agricultural land (4.1 and 3.3 m^2a/kg, respectively), followed by potatoes and beans (1and 1.7 m^2/kg) (). For the other vegetables, the land occupation is much lesser (0.1–0.6 m^2/kg). For cash crops, cocoa production shows maximum ALOP value for the year 2010 and minimum value for the year 2015. Coffee production shows a decreasing trend from the year 2000 to 2020. Sugarcane and coconut caused almost the same ALOP value for the years 2000 and 2005, whereas coconut and sugarcane dominated during 2010 and 2015, respectively. The forecasting shows that rice requires more land occupation in the range of 10^{11}–10^{12} m^2/kg followed by mango and wheat for the years 2020 and 2050 due to their requirement of vast lands while farming. The others followed the order as- grapes (10^9) > cater oilseed (10^7–10^8) > millet (10^6) > coffee (10^5–10^6). However, land has become a restricted resource due to constant rivalry between forestry, agriculture, infrastructure, and natural ecosystems. It is estimated that agriculture is projected to occupy about 12% of the global land area. If this land area is to be increased by more than 15%, agricultural production would have to expand to less productive areas, resulting in a considerable increase in deforestation. (Mattila et al., 2011a).

ALOP dominates in the crop production stage as expected for all crops due to the direct impact causing activities such as ploughing, sowing, application of chemicals, and tillage of crop residue. Besides, land preparation is the key donor, accounting for more than 50% of all the crops especially for fruits followed by crop cultivation and residue management. The main environmental impacts with increasing values of ALOP include changes in biodiversity, resource availability and soil quality (natural carbon and nutrient), and water balances of the land area. All these have a direct link to agricultural needs and may impact the productivity in future. Additionally, changes in land use and land cover also affect water quality and availability. According to the IPCC, land-use change is the second-largest source of GHG emissions, after fossil fuel use (; Duraiappah and Naeem, 2005). Changes in land use and land cover, particularly the conversion of forests to agricultural land, release carbon from long-term storage. For example, one of the major causes of biodiversity loss, according to the Millennium Ecosystem Assessment, is land-use change (Maté, 2011). Therefore, rising land demand and its consequences are linked to several environmental issues that must be assessed.

3.1.2. Climate change (GWP)

The increase in the global average temperature and changes in meteorological events and perturbations in rainfalls due to anthropogenic activities are discussed here. These in turn cause damage to human health and ecosystem quality. The influence of climate change on the agricultural sector was widely reported but the study on the reverse viz. a viz. impact of agricultural activities on climate change is minimal, hence included in this study. According to the International Energy Agency, the year 2010 was recorded as the hottest year with the highest CO_2 emission of 30.6 Gt from various sectors. As a consequence, in 2010 and 2011, the world recorded more frequent floods, fires, and droughts. Similarly, the emission of greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O is considered as the main contributor to calculate the GWP which is the only climate forcing agent for the impact assessment at the specified time horizon among the 18 selected indices.

The crops, coconut, tomato, maize, and sugarcane caused the maximum GWP due to their massive production and land occupation in the same order. The LCA in this study shows that the crop production stage holds enormous activities and emits GHGs thus leads to GWP compared to material production. Among all, cropland preparation held the top followed by residue management and crop cultivation. The land preparation activities that release GHGs are enteric fermentation (CH_4), manure management (N_2O and CH_4), soil release (N_2O and CO_2), and

Table 3
Validated equations for the crops.

Crop	Index	equation	R^2	Crop	Index	equation	R^2
Banana	FDP	$y = 3E+09x^2 - 2E+10x + 3E+10$	0.8518	Beans Dry	NLTP	$y = 3E+09x^2 - 1E+10x + 1E+10$	0.9946
	FETP	$y = 6E+06x^2 - 4E+07x + 6E+07$	0.8692		TAP	$y = 1E+07x^{0.3719}$	0.8667
	FEP	$y = 2E+07x^2 - 1E+08x + 2E+08$	0.9282		TETP	$y = 3E+07x^2 - 1E+08x + 2E+08$	0.7
	HTP	$y = 8E+10x^2 - 4E+11x + 4E+11$	0.8088	O.seeds	ALOP	$y = 1E+06x^2 - 7E+06x + 1E+07$	0.7483
	IRP	$y = 1E+09x^2 - 5E+09x + 7E+09$	0.7894		ULOP	$y = 2E+06x^2 - 1E+07x + 2E+07$	0.9993
	METP	$y = 3E+10x^2 - 1E+11x + 2E+11$	0.7822	Millet	ALOP	$y = 4E+09x^2 - 2E+10x + 3E+10$	0.935
	MEP	$y = 2E+06x^2 - 1E+07x + 2E+07$	0.8791		FDP	$y = 5E+10x^2 - 3E+11x + 5E+11$	0.939
	MDP	$y = 7E+08x^2 - 5E+09x + 9E+09$	0.9102		FETP	$y = 1E+09x^2 - 7E+09x + 1E+10$	0.9354
	NLTP	$y = 5E+10x^2 - 3E+11x + 6E+11$	0.9298		FEP	$y = 4E+07x^2 - 2E+08x + 3E+08$	0.9355
	ODP	$y = 1416x^2 – 6859.9x + 8908$	0.7645		HTP	$y = 2E+12x^2 - 9E+12x + 1E+13$	0.9378
	PMFP	$y = 5E+07x^2 - 3E+08x + 5E+08$	0.7611		IRP	$y = 8E+09x^2 - 5E+10x + 7E+10$	0.9439
	POFP	$y = 1E+08x^2 - 7E+08x + 1E+09$	0.8997		METP	$y = 1E+12x^2 - 7E+12x + 1E+13$	0.9371
	TAP	$y = 1E+08x^2 - 7E+08x + 1E+09$	0.806		MEP	$y = 6E+07x^2 - 4E+08x + 5E+08$	0.9378
	TETP	$y = 2E+07x^2 - 1E+08x + 2E+08$	0.861		MDP	$y = 6E+09x^2 - 3E+10x + 5E+10$	0.9471
	ULOP	$y = 7E+07x^2 - 4E+08x + 8E+08$	0.8632		NLTP	$y = 3E+07x^2 - 2E+08x + 3E+08$	0.9341
Barley	GWP	$y = 2E+09x^2 - 1E+10x + 2E+10$	0.7		ODP	$y = 16957x^2 - 103,329x + 148,112$	0.9374
	MDP	$y = 2E+08x^{-0.901}$	0.7037		PMFP	$y = 8E+08x^2 - 5E+09x + 7E+09$	0.9417
	NLTP	$y = 4E+09x^2 - 2E+10x + 3E+10$	0.9578		POFP	$y = 5E+08x^2 - 3E+09x + 5E+09$	0.9442
	ODP	$y = 55.712x^2 – 278.51x + 464.82$	0.7		TAP	$y = 3E+09x^2 - 2E+10x + 3E+10$	0.9359
	POFP	$y = 3E+07x^{-0.695}$	0.7114		TETP	$y = 8E+07x^2 - 5E+08x + 7E+08$	0.9411
	ULOP	$y = 3E+07x^{-0.481}$	0.7359		ULOP	$y = 9E+08x^2 - 5E+09x + 8E+09$	0.9376
Carrot	GWP	$y = 4E+10x^{-2.252}$	0.8732		WDP	$y = 2E+10x^2 - 9E+10x + 1E+11$	0.9897
	FETP	$y = 7E+07x-2.382$	0.7	Potato	GWP	$y = 7E+10x^2 - 3E+11x + 3E+11$	0.9508
	NLTP	$y = 2E+06x^{-3.294}$	0.7		FDP	$y = 2E+10x^2 - 7E+10x + 8E+10$	0.9659
	PMFP	$y = 4E+07x^{-2.201}$	0.7		FETP	$y = 2E+08x^2 - 8E+08x + 8E+08$	0.9767
	TAP	$y = 1E+08x^{-2.553}$	0.7		FEP	$y = 5E+06x^2 - 2E+07x + 3E+07$	0.9572
	ULOP	$y = 5E+07x^{-2.469}$	0.7		HTP	$y = 4E+11x^2 - 2E+12x + 2E+12$	0.9765
Castor Oilseed	GWP	$y = 6E+09x^2 - 3E+10x + 5E+10$	0.8323		IRP	$y = 4E+09x^2 - 2E+10x + 2E+10$	0.9669
	FDP	$y = 1E+08x^2 - 5E+08x + 5E+08$	0.8638		METP	$y = 3E+11x^2 - 1E+12x + 1E+12$	0.9807
	FEP	$y = 508394x^2 - 2E+06x + 3E+06$	0.9572		MDP	$y = 4E+09x^2 - 2E+10x + 2E+10$	0.9726
	HTP	$y = 5E+09x^2 - 2E+10x + 2E+10$	0.9659		NLTP	$y = 957337x^2 - 4E+06x + 5E+06$	0.7
	IRP	$y = 6E+07x^2 - 3E+08x + 3E+08$	0.9311		ODP	$y = 3752x^2 - 16,519x + 17,365$	0.9566
	METP	$y = 2E+09x^2 - 7E+09x + 7E+09$	0.9693		PMFP	$y = 8E+07x^2 - 4E+08x + 4E+08$	0.9058
	MEP	$y = 170118x^2 - 832,394x + 1E+06$	0.8237		POFP	$y = 1E+08x^2 - 6E+08x + 7E+08$	0.9297
	MDP	$y = 2E+07x^2 - 9E+07x + 1E+08$	0.8652		TAP	$y = 3E+08x^2 - 1E+09x + 1E+09$	0.8774
	NLTP	$y = 1E+09x^2 - 6E+09x + 6E+09$	0.9788		TETP	$y = 2E+07x^2 - 1E+08x + 1E+08$	0.8393
	ODP	$y = 91.971x^2 – 408.17x + 438.58$	0.9429		WDP	$y = 7E+10x^2 - 3E+11x + 3E+11$	0.9785
	PMFP	$y = 1E+07x^2 - 5E+07x + 8E+07$	0.8463	Rapeseed	GWP	$y = 8E+10x^2 - 4E+11x + 4E+11$	0.9886
	POFP	$y = 6E+06x^2 - 3E+07x + 4E+07$	0.7493		FDP	$y = 7E+09x^2 - 3E+10x + 3E+10$	0.9649
	TAP	$y = 9E+06x^2 - 4E+07x + 5E+07$	0.9316		FETP	$y = 2E+08x^2 - 1E+09x + 1E+09$	0.9744
	TETP	$y = 1E+06x^2 - 5E+06x + 7E+06$	0.9225		FEP	$y = 4E+06x^2 - 2E+07x + 2E+07$	0.9786
	ULOP	$y = 6E+06x^2 - 3E+07x + 4E+07$	0.7878		HTP	$y = 3E+11x^2 - 1E+12x + 1E+12$	0.9719
	WDP	$y = 4E+06x^2 - 2E+07x + 2E+07$	0.9608		IRP	$y = 2E+09x^2 - 7E+09x + 8E+09$	0.9695
Cocoa	WDP	$y = 2E+07x^2 - 9E+07x + 9E+07$	0.9676		METP	$y = 2E+11x^2 - 1E+12x + 1E+12$	0.9844
Coffee	ALOP	$y = 6E+09x^{-4.688}$	0.809		MDP	$y = 1E+09x^2 - 6E+09x + 6E+09$	0.9873
Grapes	GWP	$y = 4E+09x^{0.9531}$	0.8867		NLTP	$y = 1E+06x^{1.662}$	0.7787
	FDP	$y = 8E+08x^2 - 3E+09x + 3E+09$	0.9795		ODP	$y = 509.08e^{0.6678x}$	0.7
	FETP	$y = 1E+07x^2 - 4E+07x + 5E+07$	0.9778		PMFP	$y = 1E+08x^2 - 6E+08x + 7E+08$	0.9758
	HTP	$y = 2E+10x^2 - 9E+10x + 9E+10$	0.9733		POFP	$y = 2E+08x^2 - 9E+08x + 1E+09$	0.9622
	IRP	$y = 2E+08x^2 - 9E+08x + 1E+09$	0.9625		TAP	$y = 3E+08x^{0.7825}$	0.9157
	METP	$y = 1E+10x^2 - 6E+10x + 6E+10$	0.9754		ULOP	$y = 7E+07x^2 - 3E+08x + 5E+08$	0.7
	MDP	$y = 2E+08x^2 - 8E+08x + 8E+08$	0.9851		WDP	$y = 1E+10x^2 - 5E+10x + 6E+10$	0.9914
	PMFP	$y = 7E+06x^{0.8472}$	0.7922	Rice	ALOP	$y = 8E+10x^2 - 3E+11x + 3E+11$	0.9266
	POFP	$y = 5E+06x + 4E+06$	0.8304		GWP	$y = 1E+12x^2 - 5E+12x + 5E+12$	0.8592
	TAP	$y = 8E+06x^2 - 3E+07x + 4E+07$	0.8607		FDP	$y = 6E+11x^2 - 2E+12x + 2E+12$	0.927
	TETP	$y = 2E+07x^{-1.613}$	0.7		FETP	$y = 1E+09x^2 - 4E+09x + 4E+09$	0.9255
	ULOP	$y = 7E+06x^{0.7717}$	0.7		FEP	$y = 2E+08x^2 - 9E+08x + 1E+09$	0.7334
	WDP	$y = 4E+09x^2 - 2E+10x + 2E+10$	0.9639		HTP	$y = 5E+13x^2 - 2E+14x + 2E+14$	0.9325
Maize	HTP	$y = 2E+11x^{5.267}$	0.7438		IRP	$y = 7E+11x^2 - 3E+12x + 2E+12$	0.9323
	IRP	$y = 1E+09x^{4.7659}$	0.8336		METP	$y = 2E+13x^2 - 6E+13x + 5E+13$	0.9321
	METP	$y = 8E+10x^{5.1191}$	0.7		MEP	$y = 3E+08x^2 - 1E+09x + 9E+08$	0.9176
	NLTP	$y = 5E+10x^2 - 3E+11x + 4E+11$	0.9331		MDP	$y = 6E+10x^2 - 2E+11x + 2E+11$	0.9157
	ODP	$y = 2417.8x^{5.036}$	0.7782		NLTP	$y = 2E+11x^2 - 1E+12x + 3E+12$	0.8898
	TAP	$y = 3E+08x^{4.1068}$	0.7264		ODP	$y = 925017x^2 - 4E+06x + 3E+06$	0.9322
Mangoes	ALOP	$y = 1E+10x^2 - 4E+10x + 3E+10$	0.9329		PMFP	$y = 1E+10x^2 - 4E+10x + 4E+10$	0.92
	GWP	$y = 1E+11x^2 - 6E+11x + 5E+11$	0.9273		POFP	$y = 8E+09x^2 - 3E+10x + 3E+10$	0.9075
	FDP	$y = 9E+10x^2 - 3E+11x + 3E+11$	0.9329		TAP	$y = 5E+10x^2 - 2E+11x + 2E+11$	0.9302
	FETP	$y = 1E+08x^2 - 5E+08x + 4E+08$	0.8914		TETP	$y = 4E+09x^2 - 1E+10x + 1E+10$	0.9267
	FEP	$y = 2E+07x^2 - 7E+07x + 6E+07$	0.9381		ULOP	$y = 8E+09x^2 - 3E+10x + 3E+10$	0.9159
	HTP	$y = 7E+12x^2 - 3E+13x + 2E+13$	0.9335		WDP	$y = 4E+10x^2 - 2E+11x + 1E+11$	0.9303
	IRP	$y = 1E+11x^2 - 4E+11x + 3E+11$	0.9333	Wheat	ALOP	$y = 1E+09x^2 - 7E+09x + 1E+10$	0.801
	METP	$y = 2E+12x^2 - 8E+12x + 6E+12$	0.9335		FDP	$y = 7E+09x^2 - 4E+10x + 8E+10$	0.7647
	MEP	$y = 4E+07x^2 - 1E+08x + 1E+08$	0.9325		FETP	$y = 2E+07x^2 - 1E+08x + 2E+08$	0.7891
	MDP	$y = 9E+09x^2 - 3E+10x + 3E+10$	0.9322		FEP	$y = 5E+07x^2 - 3E+08x + 6E+08$	0.8912

(*continued on next page*)

Table 3 (*continued*)

Crop	Index	equation	R^2	Crop	Index	equation	R^2
	ULOP	$y = 1E{+}09x^2 - 4E{+}09x + 3E{+}09$	0.9311		HTP	$y = 2E{+}11x^2 - 1E{+}12x + 2E{+}12$	0.7706
	WDP	$y = 6E{+}09x^2 - 2E{+}10x + 2E{+}10$	0.9335		IRP	$y = 3E{+}09x^2 - 2E{+}10x + 2E{+}10$	0.7525
Sunflower	FETP	$y = 2E{+}07x^2 - 1E{+}08x + 2E{+}08$	0.949		MEP	$y = 8E{+}10x^2 - 4E{+}11x + 6E{+}11$	0.7555
	FEP	$y = 1E{+}06x^{-2.167}$	0.8389		MDP	$y = 9E{+}06x^2 - 5E{+}07x + 9E{+}07$	0.7798
	HTP	$y = 2E{+}10x^2 - 1E{+}11x + 1E{+}11$	0.9473		NLTP	$y = 2E{+}09x^2 - 1E{+}10x + 2E{+}10$	0.8621
	IRP	$y = 6E{+}07x^2 - 4E{+}08x + 6E{+}08$	0.9885		ODP	$y = 1E{+}11x^2 - 8E{+}11x + 2E{+}12$	0.8957
	METP	$y = 2E{+}10x^2 - x^2 - 1E{+}11x + 2E{+}11$	0.9396		PMFP	$y = 4466.3x^2 - 22{,}695x + 31{,}779$	0.7073
	MEP	$y = 4E{+}08x^{-6.131}$	0.7694		POFP	$y = 4E{+}08x^2 - 2E{+}09x + 3E{+}09$	0.7
	MDP	$y = 8E{+}07x^2 - 5E{+}08x + 7E{+}08$	0.9857		TAP	$y = 5E{+}08x^2 - 3E{+}09x + 4E{+}09$	0.7528
	ODP	$y = 35.901x^2–238.13x + 444.79$	0.834		TETP	$y = 6E{+}07x^2 - x^2 - 3E{+}08x + 6E{+}08$	0.7822
	TAP	$y = 5E{+}09x^{-5.645}$	0.8057		ULOP	$y = 3E{+}08x^2 - 2E{+}09x + 3E{+}09$	0.7431

Where, y - corresponding index value, and.
X - chosen year for analysis with the interval of 5 years (i.e. 2000, 2005, 2010,2015, 2020, 2025 … up to 2050).

indirect emissions (N_2O) for all the crops. A similar study conducted in Canada reported comparable observations such as enteric fermentation in ruminant animals and from the anaerobic decomposition of stored manure topped in CH_4 emission. Furthermore, Dr. James Hansen, NASA's famous climate scientist, warned in 2009 that the "climate is nearing critical tipping points" due to drought along the Yangtze River, up to 4 million people in China were without drinking water, and parts of the river were blocked from navigation. Up to 10 million people in North-East Africa are currently facing hunger and malnutrition as a result of a prolonged drought (Maté, 2011).

Being the most GHGs releaser, energy consumption in agricultural activities also tops in the GWP. Among the source, fossil fuel and oil-based energy consumption which combines carbon with oxygen in the air to make CO_2. The indirect N_2O emission is from volatilization and settlement of NH3 and agriculture-based N seepage during rain. Besides, crop residue management and fertilizer participate in the N_2O emissions. However, HFCs are one of the current preventative actions that the Montreal Protocol could adopt to reduce greenhouse gas emissions. The Montreal Protocol was able to decrease almost 135 G tons (Gt) of CO_2 emissions between 1990 and 2010 by phasing out CFCs and other ozone-depleting substances (ODSs).

Mostly, the crops followed a continuous increase pattern during the year 2000–2015 except a sink in the year of 2005 or 2010 for a few crops depends on the change of its production and the related contributors as shown in Fig. 1(a-c) and Fig. 2(a-c). This study shows that in India, carrot (a root vegetable) results in ~120 kg CO_2 eq./kg. According to the LCA study conducted in the UK, the root vegetables (carrots, onions, and beetroot), have a relatively low GWP of1.0–1.3 kg CO_2eq./kg (Frankowska et al., 2019). This study found the GWP as 2.86 and 3.38 kg CO_2eq./kg for mangoes and grapes in Indian conditions. The study also inferred that ~4.4 kg CO_2 eq./kg for mangoes and the soft fruits (grapes and berries), GWP varies between 2.2 and 2.7 kg CO_2 eq./kg. These variations may be due to the change of agricultural practices in India vs the UK.

The forecasting on barley, rice, rapeseed, carrot, and potato s carrot shows declined trend during 2050 compared to 2020 and all other crops showed continuously increasing pattern. The order of GWP contributors is as follows: rice > rapeseed > potato > mango > barley for both the years 2020 and 2050. The production of wheat and soy is predicted to change the climate more than any other crop. Due to the unavailability of the best fit model, this study could not predict the impact of a few crops. However, the 2000–2015 data as shown in Fig. S8 and S9 implies that maize, wheat, sugarcane, and coconut can be the culprits causing significant climate change. Furthermore, no such studies were previously conducted in India and this is the first study that talks about the impacts due to different crop production and their agricultural practices in India.

It is a well-known fact that agriculture retards climate change due to photosynthesis and carbon storage activities but the converse is lesser-known and underrated. A study found that if at a 1.5 °C rise in global average temperature, coral reefs can acclimatize and withdraw a portion of their die-off, at a 2 °C increase, the reclamation completely vanishes. With a 1.5 °C rise in temperature, the Mediterranean region will have a 9% reduction in fresh water and at a 2 °C rise, the deficit doubles. This further reduces wheat and maize production. Knowing the importance of every half-degree increase in global temperature, the revolution in any country's agricultural practices should concern and consider global warming (Duraiappah and Naeem, 2005; Maté, 2011; Silberg, 2016).

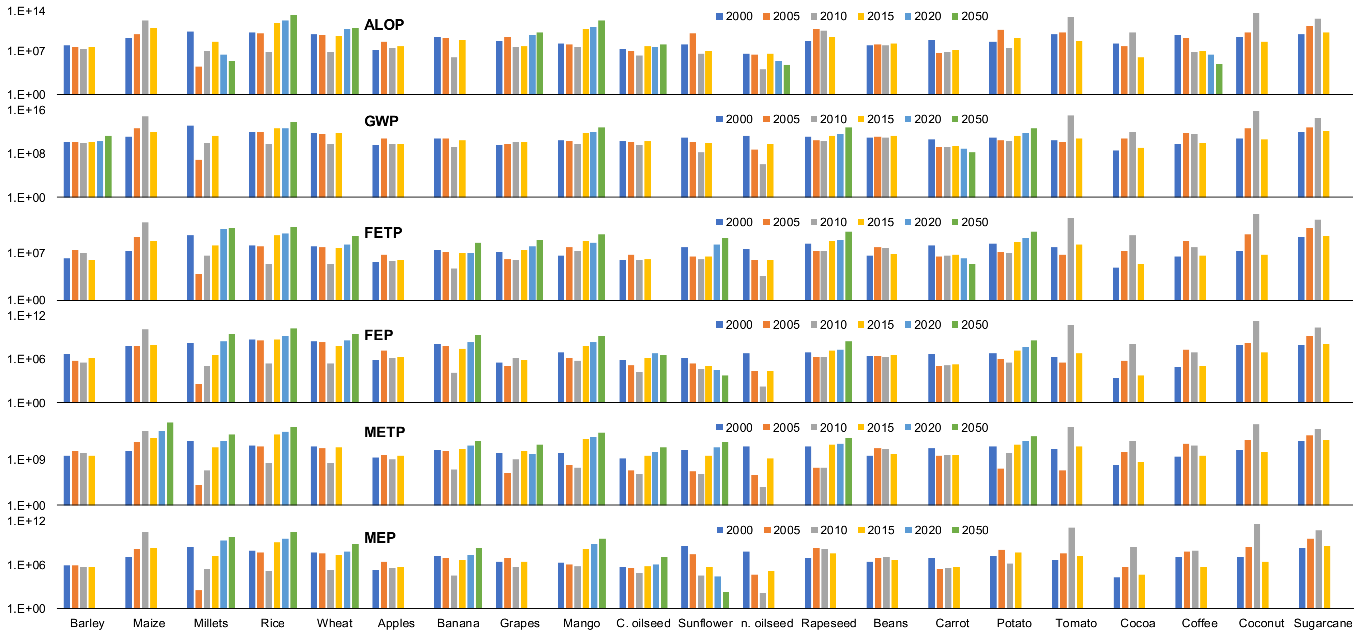
3.1.3. Freshwater ecotoxicity (FETP)

Freshwater ecotoxicity indicates the impact on the 21 crops in the freshwater ecosystems, as a result of emissions to the environmental components. It is stated as 1,4-DCB-Eq /kg emission. In agriculture, the main contributor is the chemical pesticides and growth enhancers. This study evidenced the equal contribution from the material and crop production stage (UNDG, 2017; Frankowska et al., 2019; Mensah et al., 2012).

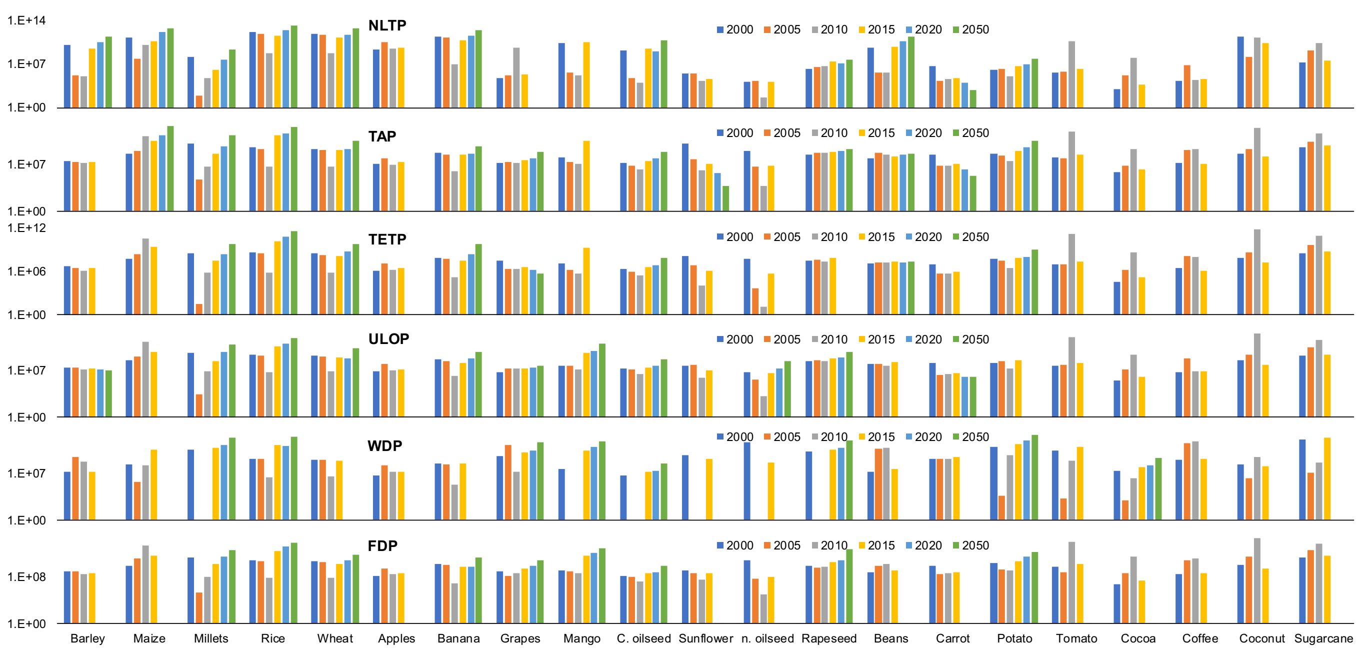
FETP has highlighted its maximum impact in the year 2000 contributed by the crops like banana, mango, coffee, coconut, wheat, sugarcane, and potatoes due to the high phosphate emissions from single superphosphate production. In the category of fruits, banana has a minimum FETP value for the year 2010 because of the least intake of chemicals such as chlorpyrifos, mancozeb, and myclobutanil. Mangoes have a maximum value of 6.17×10^8 kg 1,4-DCB-Eq for the year 2015 as shown in Fig. S8 and S9. Among cereals, millet, rice, and barley have the highest FETP of 4.4×10^9 kg 1,4-DCB-Eq, 4.63×10^8 kg 1,4-DCB-Eq, and 7×10^5 kg 1,4-DCB-Eq respectively in the year 2000. Wheat production shows a huge scattering of the results observed from the year 2000 to 2015. Similar observations of huge scattering between fields were observed by the study on the LCA of winter wheat covering from field practices to its selling. That study also proved that the total freshwater ecotoxicity impact is majorly due to pesticide use (Nordborg et al., 2017). Therefore, besides GHG and climate change, it would become essential to evaluate other impact categories freshwater ecotoxicity, freshwater eutrophication, terrestrial acidification in crop production.

Forecasting results show that rice, wheat, mango, grapes castor oilseed, potatoes, have an escalating fashion. This is due to the overuse of N and P containing fertilizers and nutrients over the capability of crops that are left on the soil surface and with runoff reaching the marine ecosystem. Due to the heavy cutting and deforestation activities to convert the forest to land, both coconut (1.75×10^{11} kg 1,4-DCB-Eq) and sugarcane (3.5×10^{11} kg 1,4-DCB-Eq) have the highest FETP value in the year 2010 as shown in Fig. 1(a-c) and Fig. 2(a-c).

Forecasting shows that for the fruit group, the production of mangoes and grapes will have a growing trend with a projected value of 1×10^9 kg 1,4-DCB-Eq due to the mass increase in export. The oilseeds, castor oilseed, rapeseed, and sunflower productions group both display a pattern with a maximum value of 3×10^8 kg 1,4-DCB-Eq for sunflower in the year 2025. For the group vegetables, potato production shows a



(a) Indices for all the crops

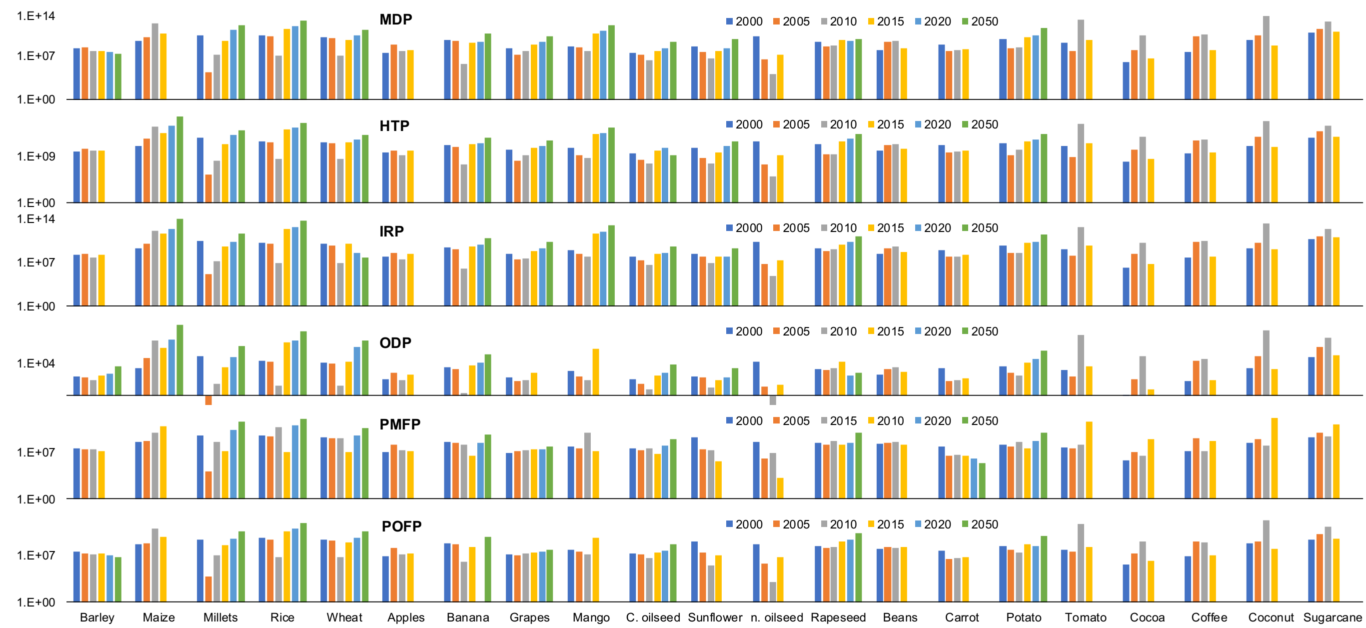


(b) Indices for all the crops

Fig. 1. (a) Indices for all the crops. (b) Indices for all the crops.(c) Indices for all the crops.

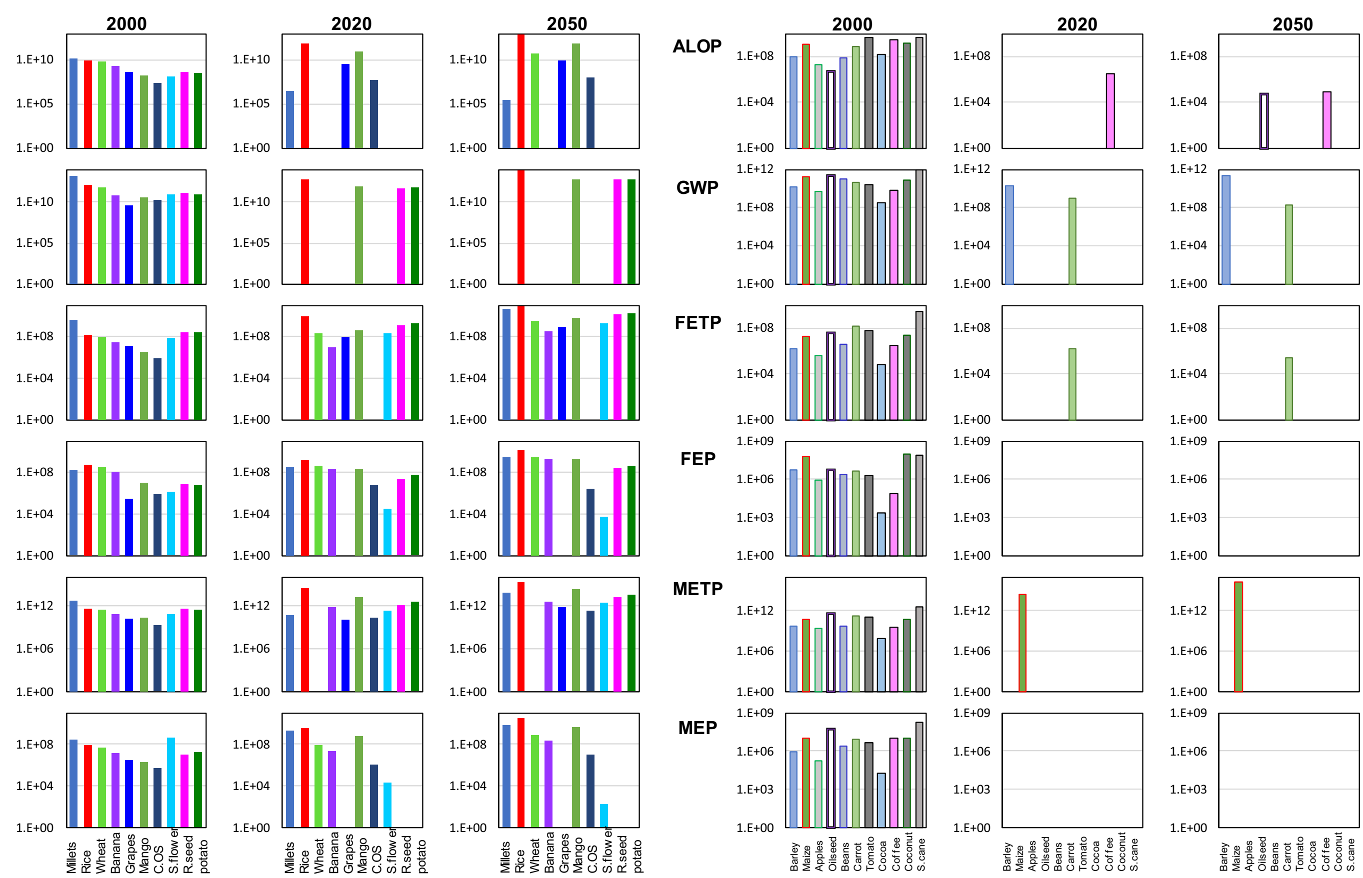
growing trend with the trendline being power while for the year 2025. For the category cereals, millet shows a downward trend with a minimum value of 3×10^5 kg 1,4-DCB-Eq for millet while the production of rice and wheat shows an increasing trend. Another similar study has also performed LCA of soybean supply chain in Brazil, being biggest soybean producer and exporter have cultivated area of 36.9 million hectares. The study has calculated results for 1 kg of fresh soybean without considering the stages of drying and warehousing grains, as well as the final consumption by customers. It has reported freshwater ecotoxicity as 1.99383E-2 kg 1,4-DCB-Eq have production system (95.4%) as the main hotspot which includes harvesting, fertilizing, sowing, tillage, transportation as input (Brito et al., 2021).

The fluctuations in the FETP values influence the normal function of marine flora and fauna and the reproduction and feeding of aquatic ecosystems. The root cause of agrochemicals must be controlled without compromising the crop yield (Nordborg et al., 2017). Sweden, for instance, has halved the use of pesticides, with barely influenced the crop reduction. Farmers in Indonesia reduced the use of pesticides on rice fields by 65% and experienced an increase in crops of 15%. Moreover, optimum quantities of fertilizers and pesticides used are proposed to further increase yields. Consequently, this will reduce the effect on the environment and decrease the cost of production (MFE, 2014).



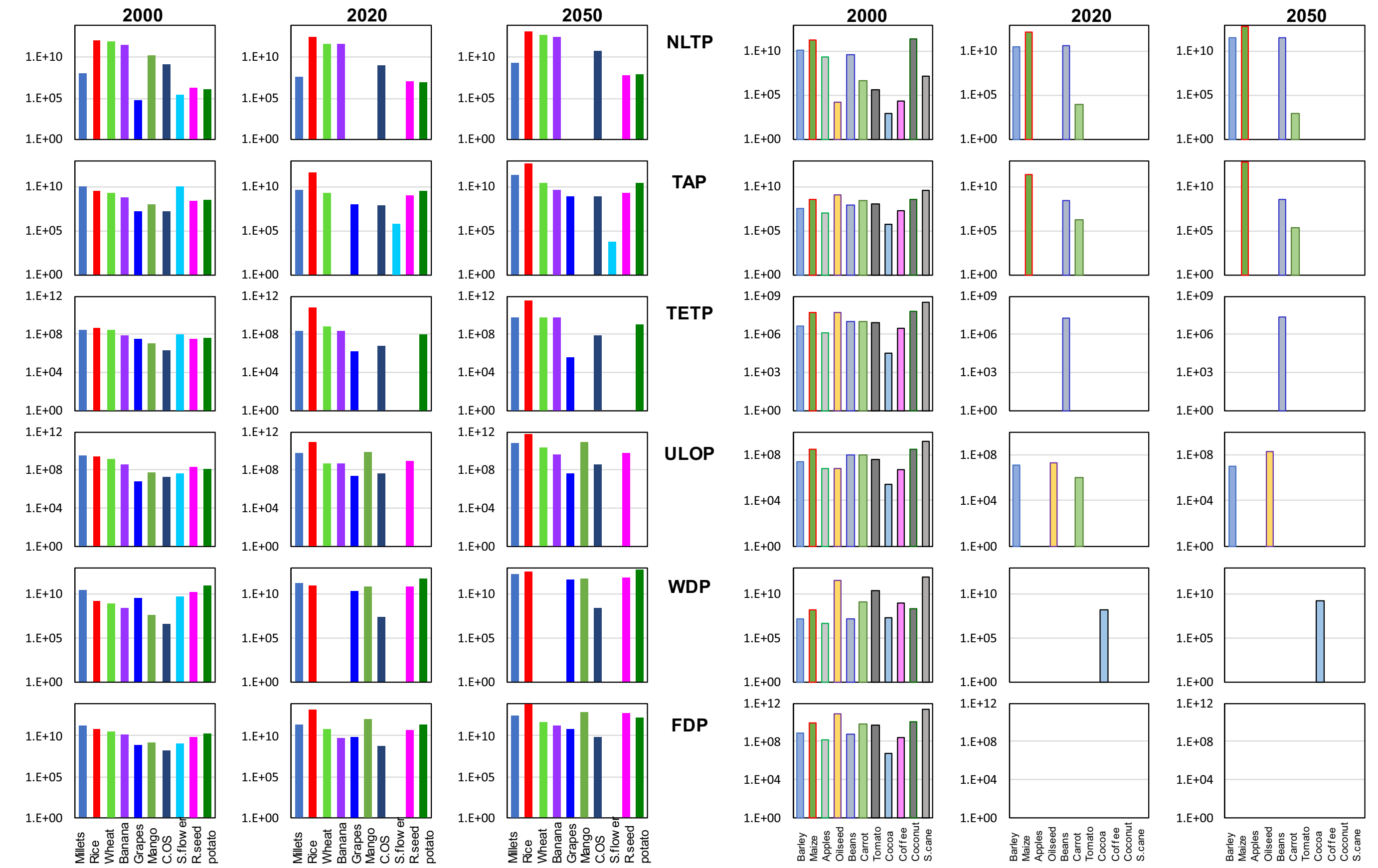
(c) Indices for all the crops

Fig. 1. (*continued*).



(a) Indices for crops at 2000 and forecasted years 2020 and 2050

Fig. 2. (a) Indices for crops at 2000 and forecasted years 2020 and 2050. (b) Indices for crops at 2000 and forecasted years 2020 and 2050. (c) Indices for crops at 2000 and forecasted years 2020 and 2050.



(b) Indices for crops at 2000 and forecasted years 2020 and 2050

Fig. 2. (*continued*).

3.1.4. Freshwater eutrophication (FEP)

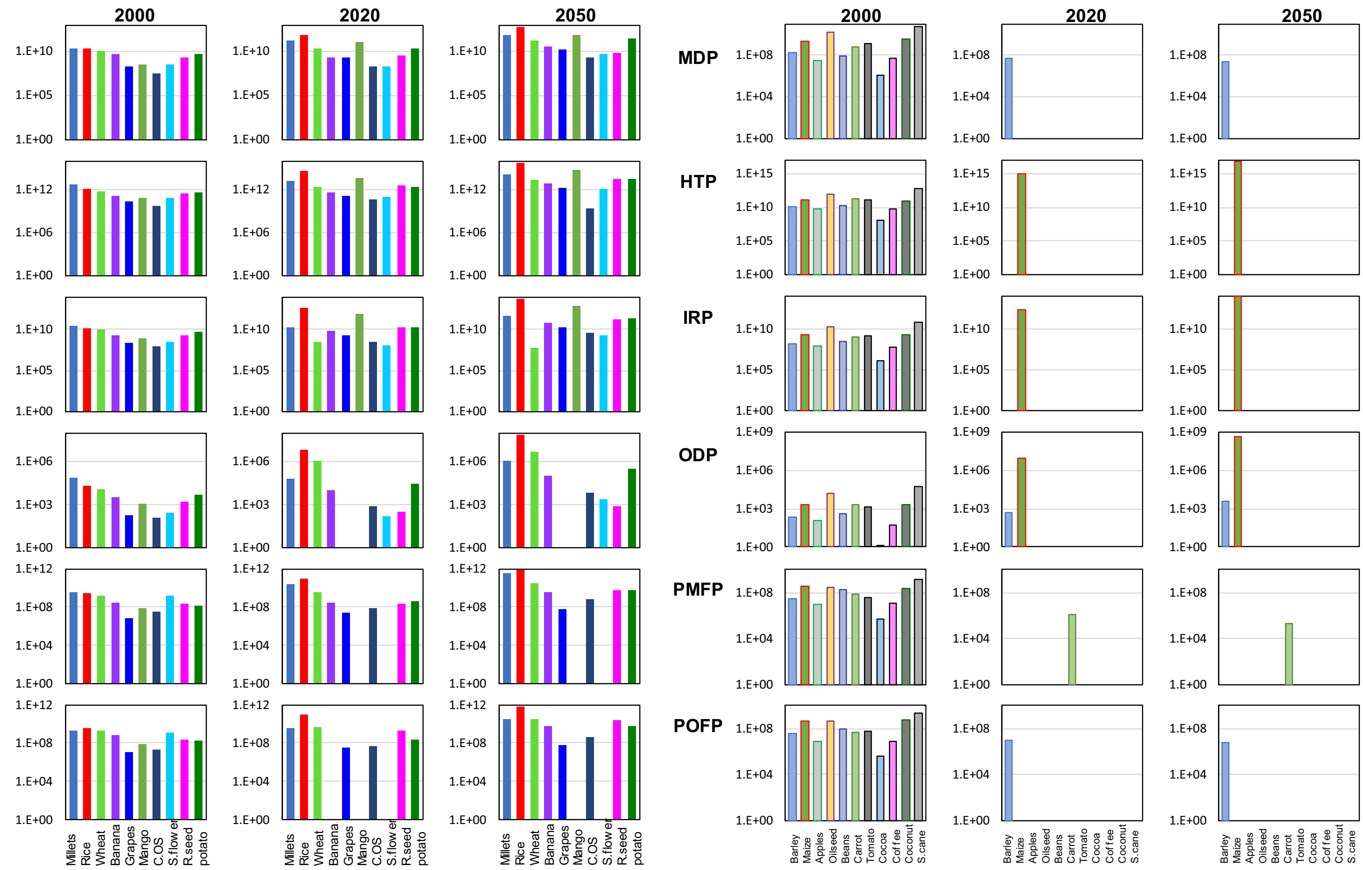
The main cause of freshwater eutrophication is the release of nutrients into the freshwater bodies, directly and indirectly, during agricultural activates. It is measured as (FEP) - kg P-Eq. The impact of FEP is evaluated by its proportion of phosphorous (P) discharged to soil entering the freshwater, the retention time of P in water bodies (also known as fate factor), and the subtle ecosystem at P levels (listed by the effect factor) ().

The major crops accounting for this potential are maize, rice, wheat, banana, coconut, and sugarcane during the year 2000–2015 due to the usage of P-containing agrochemicals. The LCA of maize cultivation (Bacenetti et al., 2013) shows that fertilization is responsible for 95% of FEP. Similar results are observed in this study where traces of ammonium sulfate led to contribute the highest in eutrophication. Rice is grown in a marshy environment for which the retention time of P was high and so the FEP. The banana was reported to cause the second-highest impact on climate change, natural land transformation, and water depletion among the tropical fruit categories (Hadjian et al., 2019) but no assessment was reported for FEP. In the case of sugarcane, the high FEP is due to the massive crop residue generation in the processing stage of its life cycle (Prasara-A and Gheewala, 2016).

During the year 2000–2015, the cereal, fruit, oilseed, and vegetable (except tomato) categories have the least value whereas cash and other crops have their highest FEP during the year 2015. The crops - apple, grapes, castor oilseed, sunflower, beans, and carrot contributed comparatively less to FEP. This fact is due to (i) comparative lower yield and (ii) less utilization of nitrogen and phosphate-based fertilizers for these crops. Tomato contributed the highest in the year 2010, being 8×10^{10} kg P-eq. The LCA of tomato cultivation and processing at California (Brodt and Kendall, 2018) also depicted the highest contribution of impacts because of the fertilizing process as observed in this study that is represented in Fig. 1(a-c) and Fig. 2(a-c). On average, oilseed and cash crop categories impacted 40% less than vegetables and cereals crops.

The FEP enabled impact on freshwater biodiversity accounted in most of the Danish lakes, is owing to the increased nutrient inputs from agricultural practices (Welch and Cronke, 1987; Jeppesen et al., 1999). The Washington lake, USA, and Lugano lake, (between Italy and Switzerland) are heavily eutrophic due to extreme agrochemicals' discharges (Simona, 2008). Further, the absorption of nutrients by photosynthetic organisms such as phytoplankton ultimately ends up in potential losses of freshwater biodiversity (Welch and Cronke, 1987; Garg and Garg, 2002). A study determined the probable fertility and floral ecology of lentic waters in the lakes of Bhopal, Madhya Pradesh (Upper Lake, Lower Lake, and Mansarovar Lake) in India and stated the role of agrochemicals in it. In Mansarovar lake, the highest degree of eutrophication was found which caused severe damage to lake flora and fauna (Garg and Garg, 2002).

It is forecasted that the rice, wheat, and millet followed by banana, mango, and potato causes FEP in the range of 10^{10}–10^{12} kg-P eq. Such a high eutrophication magnitude may lead to loss of freshwater biodiversity and thus insists the sustainable practices in the agriculture sector. Another similar study has evaluated the environmental impacts of selected traditional food manufacturing products namely: tempe (TP), lemang (LM), noodle laksam (LS), fish crackers (FC), and salted fish (SF) in Malaysia. The results showed that FC and LM were the main contributors for FEP with both at 0.572 kg P eq having a significant contribution from the production of starch and salt. Additionally, FEP were also emitted from chemicals and agricultural residue (Bong et al., 2020). Therefore, the responsible use of chemicals, monitoring, and treatment of agricultural run-off, implementation of effective filter



(c) Indices for crops at 2000 and forecasted years 2020 and 2050

Fig. 2. (*continued*).

ecosystems to remove nutrients present in the run-off water (such as phyto-purification plants) can be implemented to lessen the effect of FEP.

3.1.5. Marine ecotoxicity (METP)

Marine toxicity accounts for the impacts of farming the 21 crops on marine habitats. The potential effects chemicals in sediments and water that are sourced from the heavy use of fertilizers and pesticides in agriculture are on species of fish, invertebrates, and algae that live in the marine ecosystem. Contrary to other indices, METP is influenced during the material production stage equally to the crop production stage. Because the production of the chemicals used in irrigation activities also emits a lot of contaminants which are accounted for by the METP. The crops maize, coconut, and sugarcane secured the top rank in the averages of 2000–2015 followed by rice, barley, and coffee due to their voluminous usage of chemicals. In the year 2010, METP has a value, 10^{13} kg 1,4-DCB eq which is 100 folds increased in the year 2015 and was the topmost year having the highest value as shown in Fig. S8 and S9. Millet has 8×10^{3} kg 1,4-DCB eq METP value in the year 2010 and found to be the least METP value. While potato in the year 2015, and tomato, sugarcane, and coconut production in the year 2010 showed maximum METP value majorly due to the emissions from the use of the agricultural machinery. Hence, future research should focus on machinery with fewer emissions to overcome this issue.

For most of the crops, the pattern of METP during 2000–2015 is random due to the change in crop production pattern. Thus, finding the best fit was critical and the forecasting equations are valid only for the crops – maize, millet, rice, banana, grapes, mango, castor oilseed, sunflower oilseed, rapeseed, and potato. Rice, mango, rapeseed, and potato are forecasted to be the most METP creating crops from the categories of cereals, fruits, oilseed, and vegetables. The corresponding total METP values are 10^{14} and 10^{16} kg 1,4-DCB eq during 2020 and 2050 respectively. Practically, the marine ecotoxicity (MET) value continues to increase with years, due to the increased use of chemicals in farming as shown in Fig. 1(a-c) and Fig. 2(a-c). This massive METP value will result in a huge biodiversity loss in the marine ecosystem.

This is the first study that clearly shows the link between agricultural activities related to the major 21 crops in India and marine ecotoxicity. Hence, the focus should be on modifying the policies and act on agricultural water discharge into the marine ecosystem. Over the last century, legacy and new contaminants have worked towards global ocean health and marine species survival. Besides, attentiveness should be there on building treatment units before the emissions from the agriculture sector reach the marine ecosystem. Alternatives to chemical consumption in the agricultural sector must be done to monitor the rise in MET value. These may be the management of biological pests, push-pull techniques, poly-cropping techniques, and crop rotation.

3.1.6. Marine eutrophication (MEP)

Marine eutrophication is due to the input of a large number of nutrients. MEP results in the growth of a huge quantity of algae that promotes O_2 depletion. This ultimately leads to local septic conditions and further to the death of fishes and other aquatic animals. Finally, the marine ecosystem balance will be disturbed and become unfavourable for aquatic life.

The pattern of MEP matches exactly with FEP because of the similar input – nutrients in the agricultural sector. MEP was found to be slightly higher than FEP for all 21 crops. MEP reached the maximum in the year 2010 for maize, tomato, cocoa, coffee, coconut, and sugarcane. The crops like apples, tomatoes, rice, and grapes are the main backers of

MEP.

Rice (3×10^8 kg N-Eq), Mango (4×10^7 kg N-Eq), rapeseed (9×10^7 kg N-Eq), tomato (3×10^4 kg N-Eq), coffee (3×10 kg N-Eq), and sugarcane (3×10^8 kg N-Eq) achieved the top position of having the highest average values during 2000–2015 among all crops in cereal, fruit, oilseed, vegetable, cash, and other crops categories, respectively as shown in Fig. 1(a-c) and Fig. 2(a-c). Generally, denitrification is caused by the high rainfall and leaching of nitrates in the soil. However, the supply of a high amount of N to the soil before plantation and similar surplus application decreases N use efficiency (NUE) of crops. According to the data of world cereal production, it is found that only 33% of NUE of continuing fertilizers management process in crops. Besides, during the 1965–66 and mid-1990s, the crop fertilizer consumption was ~0.78 and 1 MT, respectively. The introduction of high-yielding variety (HYV) seeds raised it to 12.73 and 18.07 MT during 1991–92 and 1990–2000.

Forecasting results show that millet, rice, wheat, apples, banana, mango, castor oilseed having an escalating fashion. This is due to the (i) fast production of N and P containing fertilizers (ii) increasing trend of fertilizers' use in the production of these crops (rice, millets, wheat, and apples), and (iii) insufficient coordination between N applications and the demand of crops and (iv) nutrients over the capability of crops left on the surface of earth causing soil erosion, and with runoff, nutrients reach to the marine ecosystem. Another study also uses LCA to evaluate the environmental and health impacts of processing one tonne of food waste in the UK using four different technologies. The study proved that food waste processing significantly impacted the marine environment by having a value of 16.9 kg N eq./mPE year^{-1}. The analysis of the result shows that the energy consumption and fuel inputs involved in the shipping of feed ingredients such as soybean meal are the primary causes of marine eutrophication (Salemdeeb et al., 2017).

Another LCA study that was conducted on biofuel-ethanol production from different agricultural products stated that that the level of MEP is mostly attributed to the agriculture process (Luo et al., 2010). Especially, the nitrate (NO_3^-) to groundwater and nitrogen oxides (NO_x) to air from the application of N fertilizers are found to be the main contributors. Though, to support the aquatic life both N and P are required and found to be the key limiting nutrients, usage of a controlled amount of fertilizer avoids causing MEP and conserves the marine flora and fauna.

3.1.7. *Natural land transformation (NLTP)*

This impact category depicts the damage to the environment because of the effects of occupation and alteration of natural land and is represented in the area (m^2) (Mattila et al., 2011b). According to NSSO's report on land and livestock holdings reveals that about 95 million hectares of land were classified as operational holdings in India in the year 2012–13. However, this study shows that the total land transformation due to 21 crops in India is 2.48×10^{11} m^2 in the year 2010. This NLTP value is mainly due to the processes such as the production of agricultural machinery, natural gas, and ammonium sulfate, emissions from a chemical factory, transport, and diesel-burning. Mango production has an increasing trend having a maximum value of 3.7×10^{10} m^2 for the year 2015. This fact is due to the conversion of forests to agricultural land and seabed to land. Another study carried out the LCA of avocado, banana, and pineapple reported that NLTP of 0.0003, 0.000225, and 0.00019m^2, respectively because the LCA boundary did not include many components as this study has. (Hadjian et al., 2019) Rice and castor oilseed contributed the most and found to achieve their peak values of 3.11×10^{11} and 3×10^9 m^2 respectively for the year 2015. Tomato production has maximum value for the year 2010, this is because of high usage of pesticides, electricity, natural gas as shown in Fig. 1(a-c) and Fig. 2(a-c). Similar Study of Life cycle environmental impacts of fruits consumption in the UK in which grapes have the highest NLT (21.1 cm 2 /kg), followed by mangoes (17 cm 2 /kg), while melons cause the lowest impact (1.8 cm 2 /kg). For grapes, the processing stage contributes 80% due to the vegetable oil added to dried grapes. The processing stage is also a hotspot for fruits which are processed into juices or canned fruits. Moreover, fruits require 0.35 Mha of agricultural land and 315 Mm3 eq. of water per year. Oranges, bananas, and apples are responsible for more than half of the impacts at the national level as they account for 64% of the total fruit consumption in the UK (Frankowska et al., 2019).

In cereals, barley production has a declining pattern in the year 2015 with a slight kink for the year 2010 and have a maximum value of 1×10^{10} m^2 for the year 2000. Another study on the comparison of Finnish beer and Spanish wine found that the cultivation of barley accounted for 60%–80% of NLTP (Mattila et al., 2011b). In the case of forecasting years, mango and grapes production exhibit a rising trend with a maximum value of 3.2×10^{10} m^2 for mango production in the year 2025. In cash crops, cocoa and coffee production both reveal a falling fashion with a maximum value of 2×10^6 m^2 for cocoa for the year 2020. For category cereals, maize, millet, wheat, and rice production exhibit a growing fashion with the highest value of 4×10^{12} m^2 for rice for the year 2025. In oilseeds, castor oilseed and rapeseed productions both intimates a rising fashion with the maximum value of 6×10^9 m^2 for castor oilseeds for the year 2025. From similar studies, the whole UK fruit sector generates 7.9 Mt. CO2 eq. and consumes 94 PJ of primary energy. This is equivalent to 4% of the annual GHG emissions and 9% of the energy demand of the whole UK food sector (Frankowska et al., 2019).

The main environmental impact due to NLTP is on the soil quality which further imbalanced the natural carbon, nutrient, and water of the land area. This further decreases the net productivity and hence leads to poverty which needs the most immediate mitigation. Though NLTP is regional, due to the above connections, it has its impact on the globe and thus needs proper attention.

3.1.8. *Terrestrial acidification (TAP)*

The index considers NO_x, SO_2, NH_3, HF, and HCl from various agricultural activities, for calculation and expressed as SO_2-eq. (Westphal et al., 2019). The TAP is a direct outcome of the deposition of acids in the soil surface which decline the soil fertility and richness of plants. Besides, TAP impacts to water, soil, air, humans, the environment, and construction materials, negatively. Apart from coal industries, the agricultural sector also highlighted its space in SO_2 pollution globally. This study shows that the annual formation of SO_2 from 21 crops is ~33 MT in the year 2005 which is again 10 fold increased in the year 2015. These TAPs are due to heavy use of agricultural machinery, fertilizers and pesticides consumption, diesel combustion, clear-cutting from forest to land.

TAP has highlighted its maximum impact in the year 2010 contributed by the crops like maize, coconut, sugarcane, tomato, and cocoa. Another LCA study on maize interpreted that the fertilization of fields and their emission are responsible for about 95% of TAP (Nordborg et al., 2017). Carrots, potatoes, and tomatoes have the highest TAP value of 3×10^8, 9×10^8, 7.6×10^{11} SO_2-eq in the year 2000, 2015, and 2010 respectively, in the vegetable category and the main reason involves heavy use of urea fertilizers. Another study evaluated the LCA of cultivation and processing of tomato in California and found that diesel production and combustion are the main contributors of FEP across the supply chain, contributing around 30%–39% in the cultivation phase (NRC, 2010). In India, for potatoes and tomatoes, the highest TAP is due to the usage of outdated agricultural machinery which requires more fuel which emits abundant SO_2. The TAP is projected to hit the maximum record in the year 2020, mainly contributed by the crops like coconut, beans, maize, mango, rice, and sugarcane. Category-wise illustration during 2020–2050 shows that banana, maize, rapeseed, and potato have the values of 4×10^8, 4.71×10^{11},1.22×10^9, and 6×10^9 SO_2-eq, respectively as shown in Fig. 1(a-c) and Fig. 2(a-c). For category vegetables, potato production shows an increasing trend with a maximum value of 6×10^9 SO_2-eq for the year 2025 while carrot production shows a decreasing trend with a minimum value of 2×10^6 SO_2-

eq for the year 2025. Similar studies of global assessment of the effects of terrestrial acidification on plant species richness suggest that regions within the (sub)tropical moist broadleaf forest may suffer great changes in species richness following soil acidification. This is an alarming situation given that soils in the (sub)tropical climate zone have a very low acid-neutralizing capacity (Azevedo et al., 2013). The results of our study can be used with atmospheric pollutant transport and soil fate models to link acidifying air emissions to their ultimate biodiversity risk.

Rising TAP value ultimately contributes to decreased soil fertility, loss of seed germination, and in extreme situations, diminishes the whole plant. The higher concentration of SO_2 in the atmosphere can cause acidification followed by desertification which further expands the gap between the food demand and supply. Therefore, this forecasted data is advantageous to identify these hotspots and thereby provides the possible solutions and alternatives to improve farming practices towards sustainability. Besides, it helps decision-makers with strategic planning for the management of crop residue and other agricultural waste.

3.1.9. Terrestrial ecotoxicity (TETP)

Terrestrial ecotoxicity is the entry of toxins into the terrestrial atmosphere (vegetation/plant species and marine sediment inhabitants) through direct and indirect actions. The life cycle impact assessment of 21 crops aims to translate the amounts of a substance emitted during their life cycle into a potential impact on the terrestrial ecosystems. During agricultural activities, it starts with chemical contamination of soil and then by long-range transportation. Soil bacteria, invertebrates, insects, amphibians, reptiles, and birds are terrestrial receptors and the toxin exposures are through the skin, nasal, inhalation, and food chains. TETP is expressed as emission equivalents of 1,4-DCB/kg. 1,4-DCB is used as a pest repellent in farming.

This study shows that the annual formation of 1,4-DCB from 21 crops is 6.1 MT in India in the year 2005. However, in the USA in the year 2016, the production volume of 1,4-DCB for its multiple applications was 50 MT as reported by EPA (US EPA, 2019). The maximum impact of TETP has been observed in the year 2010 contributed mainly by the crops like maize, coconut, sugarcane, and tomato. Banana and grapes have the highest TEP value of 8×10^7 and 3×10^7 kg 1,4-DCB Eq respectively in the year 2000 due to the electricity and water usage for irrigation and/or other purposes over the field. In vegetables, carrots and potatoes have the highest TETP value of 1×10^7 and 5×10^7 Kg 1,4-DCB Eq respectively in the year 2000, mainly due to the steam production in the industry for material production, single-superphosphate production in the industry. Tomato being 1.5×10^{11} Kg 1,4-DCB Eq has highest TEP value in the year 2010 and decreased by 1/10000 times during 5 years span from 2010 to 2015 as shown in Fig. S8 and S9. While in cereals, barley, wheat, and millet have the highest TEP value of 5×10^6, $2.6 \times 10^{8,}$ and 3.1×10^8 kg 1,4-DCB Eq respectively in the year 2000, mainly due to emissions during chemical production, harvester production, and clear-cutting of the field from forest to land. A similar study was conducted on the effect of cultivation in Chongming ecological island, China. It revealed that terrestrial ecotoxicity was 5.87×10^4 kg due to the use of chemical fertilizers in the planting phase that results in the deficiency of P, $P_2O_4^-$, N, NO_3^-N, NH_4^+-N, and other substances into the soil (Li et al., 2019).

Furthermore, TETP seems to be rising constantly in the future and can have maximum impact in the year, 2050, mainly contributed by the crops like coconut, banana, coffee, maize, rice, sugarcane, and tomato. Banana, millet, castor oilseed and potato for year 2025 are 3.2×10^8, 9.4×10^{10}, 1×10^7, 2×10^8 Kg 1,4-DCB Eq respectively. Increasing values of TETP indicate the rising concentration of carcinogenic substances in the future years due to the accumulation and transportation of toxins in the environment. 1,4-DCB is not readily disintegrated by soil species and is water-insoluble. Being lipophilic, 1,4-DCB will collect in fatty tissue, if ingested by humans or animals. The Environmental Protection Agency, USA lists 1,4-DCB as a possible human carcinogen. Also, in 1994, 1,4-DCB was given an inhalation cancer unit risk estimate (URE) of 1.1 E-05 per μg m^{-3} (Chin et al., 2013; Borrion et al., 2012). The most common path of major access to PDCB is inhalation, which is readily absorbed by the lungs. Hence, adequate measures should be taken to control the TETP from agricultural activities such as diesel combustion, electricity usage, agricultural machinery, and emissions during chemical production.

3.1.10. Urban land occupation potential (ULOP)

Urban land occupation signifies the uninterrupted utilization over a certain period of a certain area of agricultural land. The unit is m^2a. All the activities associated with the LCA of crop production are considered to measure ULOP (Sala et al., 2016). The environmental degradation incurred by the occupation of land relies on the amount of ecological sustainability preserved during the occupation. The pattern of ULOP matches exactly with ALOP because of the similar input – nutrients in the agricultural sector. ALOP was found to be slightly higher than ULOP for all 21 crops.

As shown in Fig. 1(a-c) and Fig. 2(a-c), for category fruits, apple production has a maximum ULOP value for the year 2005 which is about 8% more than for the years 2010 and 2015. Grapes production has a maximum value for the year 2005 which is about 3 times more in comparison of the year 2000 due to the heavy use of fertilizers and agricultural machinery. In the oilseeds category, rapeseed and sunflower seed set similar ULOP value, 6×10^7 m^2a in 2005 and castor oilseed production has maximum ULOP value of 2×10^7 m^2a in 2015 mainly due to diesel burning. Rice production also shows a random trend with a maximum ULOP value of 3.23×10^{10} m^2a for 2015. Sugarcane production shows a maximum value for the year 2010 due to agricultural machinery. The forecasting shows that rice requires more land occupation in the range of 10^{10}–10^{11} m^2a/kg followed by mango, rice, and wheat for the years 2020 and 2050. The others followed the order as-grapes (10^9 m^2a) > cater oilseed and coffee (10^7–10^8 m^2a) > millet (10^6 m^2a) > carrot (10^5–10^6 m^2a).

The ULOP for most crops continues to rise over the years because the land use for agricultural purposes continues to increase over time. From the assessment done, coconut in the year 2010 has topped in ULOP (2.93×10^{12} m^2a) among all crops. The crop production stage dominates in ALOP than the production of the material as expected for all crops. Land preparation is the chief contributor and accounts for >50% of all fruits followed by crop cultivation and residue management. Another study followed a different approach of including biodiversity as a measure. It is found that the transition from Mediterranean forests to constant urban use results in more negative impacts than its conversion to traditional farming. (Koellner et al., 2013) The changes in biodiversity, resource abundance, and soil quality (natural carbon and nutrients) that increase the ULOP consequently can change the climate parameters. This further affects the quantity and quality of the groundwater and hence needs prior attention in setting the rules and regulations. (Koellner et al., 2013).

3.1.11. Water depletion (WDP)

WDP measures the consumption of non-biological resource – water, measured in terms of withdrawal, consumption, and degradation in m^3. Water use impact assessment at the midpoint characteristically emphasizes water deprivation (Vellampalli and Babu, 2014). The hitch with water is reliant on where and when water is available. Along with these, the water quality also is essential to be reflected during the assessment of water depletion.

This study evidenced that the production of urea (46% N), ammonia steam reformation, and phosphoric acid production are the major contributors of WDP. In 2015, high magnitudes are found overall in the following order: rice > potato > sugarcane > tomato > rapeseeds. Sugarcane (4.96×10^{12} m^3) shows a maximum value for the year 2015 and 3 times less value for the year 2000 while coconut has a maximum WDP value of 2.33×10^8 m^3 for the year 2010. For these crops, the production stage is responsible for high WDP which generates from the process of irrigation depleting nearby sources of water. For category cash crops, coffee (4.85×10^9 m^3) shows the highest magnitude in the year 2010 followed by cocoa (3.22×10^8 m^3) in 2015. For these crops, the irrigation area increased from 139 million hectares in 1961 to 320 million hectares in 2012. This doubling of area transferred multiple folds of agricultural pollution to water bodies (FAO, 2019). Discharge of large quantities of agrochemicals, agriculture in India accounts for 30–50% of the degradative use of water. These increasing magnitudes may lead to extreme water depletion and water pollution and hence deteriorating aquatic flora and fauna which will further cause damage to terrestrial species and leads to malnutrition among them.

The assessment also shows that WDP keeps on increasing over the years. For both the years 2020 and 2050, the following order is observed-potato > rice > rapeseeds > mango while the lowest magnitude is found for castor oilseeds (2.1×10^6 m^3) as shown in Fig. 1(a-c) and Fig. 2(a-c). Potato (5.74×10^{12} m^3) contributes the highest in the year 2050 followed by mango (4.23×10^{11} m^3) and rice (2.6×10^{11} m^3) due to the associated agrochemicals. Further, the WDP aggravates the droughts and flooding. Subsequently, it aggregates the gap between demand and accessibility around the world. To overcome these problems, the solutions may be of (i) creating pollution-reduction zones near surface water sources, within farms, and around farms could be effective in reducing pollution migration to water bodies. Further, the WDP aggravates the droughts and flooding. Subsequently, 10 aggregates the gap between the demand and accessibility around the world. To overcome 11 of these problems, the solutions may be of (i) creating pollution-reduction zones near surface 12 water sources, within farms, and around farms could be effective in reducing pollution 13 migration to water bodies (ii) Crops, vegetables, cattle, trees, and fish can all be managed as part of an integrated system to improve production stability, resource productivity, and environmental sustainability (iii) Integrated farming ensures that waste from one business becomes inputs for another, allowing for more efficient resource use and, in particular, reduced water pollution. For an instance, pisciculture along with water-loving crops would be recommended as water which is wasted in case, is suitable for rearing fishes and other aquatic animals.

3.2. Impact on human health

3.2.1. Human toxicity (HTP)

Human toxicity measures the possible harm caused by the toxic chemicals released into the atmosphere. It depends on both a compound's intrinsic toxicity and its respective potential intake. It is given as 1,4-dichlorobenzene equivalents. Due to scarce land resources, high usage of agrochemicals such as phosphate fertilizer is essential for better growth of plants leading to increased HTP. The effects of cultivation in Chongming ecological island (Li et al., 2019) reported that 90% of the effects are due to the agriculture material especially the production of fertilizer. In this study, it is evident that 70% of the HTP causing factor was triazine, benzothiazole, acephate, and the associated emissions (Xue et al., 2015). Highest magnitude of HTP is found in the year 2010 in the following order tomato > coconut > sugarcane > maize. For category fruits, apple (4×10^9 kg 1,4-DCB-Eq) shows maximum HTP value for the year 2005 which is about 4 times more than for the year 2000. The cause of such high value is the high dose of potash fertilizers used in crop production.

Mangoes production shows a decreasing trend from the year 2000 to 2010 and has a maximum value of 2.86×10^{13} kg 1,4-DCB-Eq for the year 2015 during the tillage stage. A similar study on the analysis of pesticides used in Indian agriculture also shows that in the year 2014–15, pesticide intake was 0.29 kg/ha (GCA). It is about 50% higher than what was used in 2009–10 (FICCI, 2015). For category cereals, maize (6.45×10^{14} kg 1,4-DCB-Eq) shows the highest value in 2010 followed by rice (4.5×10^{12} kg 1,4-DCB-Eq) and wheat (3.7×10^{10} kg 1,4-DCB-Eq) in the year 2015. An LCA of maize cultivation (Li et al., 2019) stated that the accelerated production and application of pesticide is the most influential factor for HTP causing a high level of toxicity. (Damalas and Koutroubas, 2016).

Almost for all the crops, the HTP value keeps on increasing with years because of the increasing use of pesticide consumption and its production. In India, however, the use of pesticide per hectare is minimum compared with nations like China (13.06 kg/ha), Brazil (4.57 kg/ha), Japan (11.85 kg/ha), and other Latin American countries (Subash et al., 2017; Taj et al., 2019). Besides, the results stated that the trace elements of arsenic and lead concentrations from pesticides mix with the water and the crop thus leading to toxicity.

For the year 2020, the top 5 major contributing crops are maize, rice, mango, rapeseed, and potato. For category fruits, mango has topped (5.6×10^{11} kg 1,4-DCB-Eq) in the year 2050 and 2020. While in the cereals category, maize topped in the years 2020 and 2050. In the oilseeds category, rapeseed shows the highest values for 2020 and 2050 followed by sunflower as shown in Fig. 1(a-c) and Fig. 2(a-c).

Human toxicity potential increases the human health impacts induced from continuous production and the use of harmful agrochemicals over a large span of years. These impacts may include carcinogenicity, developmental effects, reproductive toxicity, neurotoxicity, and chronic effects on other individual organs (Harder et al., 2017). The bioaccumulation of pesticides can be caused by the consumption of food prepared using the agrochemicals applied to crops. The associated toxicity is not accounted for in this study which may again magnify the impacts into multiple levels. To control this increase in the value of HTP, we have to come up with some alternatives to pesticide consumption. The policies should focus on the complete ban or controlled use of toxicity causing agrochemicals in case of unavoidable situations and alternative measures such as traditional eco-friendly agents. (Subash et al., 2017).

3.2.2. Ionizing radiation (IRP)

Ionizing radiation is the harm to public exposure and habitats related to radionuclide pollution over the life cycle of the 21 crops. (Huijbregts et al., 2016) This study witnessed that agricultural machinery production, tillage, diesel burned in building machines, and power sawing are the major factors contributing to IRP. The top 5 highest values of HTP follows the order as: coconut > tomato > mango > rice > maize. For category fruits, apple has a maximum IRP value of 5.7×10^8 kg U235-Eq for the year 2005 which is about 4 times more than for the year 2000. It was found that agricultural machinery production and tillage are the main cause behind high IRP. Grapes have a maximum value of IRP for the year 2015 (8×10^8 kg U235-Eq) which is about 4 times more in comparison of the year 2000. The detrimental effect of grapes production is the production of superphosphate typical concentrations of radium (^{226}Ra) in phosphogypsum responsible for its enhanced radioactivity. (Falls and Siegel, 2005).

As shown in Fig. 1(a-c) and Fig. 2(a-c), coffee shows a random trend with the highest magnitude of 3.3×10^{10} kg U235-Eq for the year 2010. The life cycle assessment applied to coffee production in another study found that the huge application of muriatic potash which left traces of radioactive toxins may be main the cause of this potential (Salomone, 2003). For category cereals, maize (7.56×10^{10} kg U235-Eq) shows the highest value in the year 2010 followed by rice (1.3×10^{10} kg U235-Eq) in 2015 and millets (2.91×10^8 kg U235-Eq) in 2005. The maximum value for the year 2020 will be given in the following order- rice > mango > maize > rapeseeds > potato. For the year 2050, rice (8.9×10^{13} kg U235-Eq) contributes highest among cereals, mango (4.5×10^{12} kg U235-Eq) tops in fruits category and rapeseed (5.69×10^{10} kg U235-Eq) in oilseed category shows the highest value.

The massive consumption of urea during the plantation stage of the crops contains traces of radon. Radon's primary pathway is through the air space in the soil leading to the toxic effects via consumption of food in human beings (Land, 2012). The damage caused to tissue and/or organs due to these radiations depends on the dosage of radiations conceived. The most common effect of IRP is the stochastic induction of cancer and chronic myelogenous leukemia with a latent period of a long time may be decades after the exposure (World Health Organization (WHO), 2016). Hence, the high use of fertilizers and their responsible products has to be restricted by stringent laws and guidelines.

3.2.3. Ozone depletion (ODP)

Precisely, ozone depletion potential (ODP) of a given substance is defined as the ratio of the global loss of ozone due to the given substance to the global loss of ozone due to trichlorofluoromethane (CFC-11) of the same mass (Atmosphere, 1997). The ODP values for almost all crops show a random trend being the lowest valued index among all the 18 indices. Coconut has the maximum ODP value in the year 2010 while cocoa has the least value in the year 2000. For category fruits, mango production has a maximum ODP value for the year 2015 which is about 480 times higher in comparison to the year 2000 as shown in Fig. S8 and S9 and other fruits follow the order as banana > apple > grapes. A similar study for fruits conducted in the UK (Mattila et al., 2011a) shows that the worst choice is berries for ODP with 3.3–3.6 μg CFC-11 eq./kg, majorly because of the usage of pesticide, dichloromethane. Pears, the best option, have around four times lower impact (0.9 μg CFC-11 eq./kg). The other fruits follow the order of grapes > banana > apple. Comparatively, this study shows that the impact for the year 2020 for various fruits is from 215 to 5268 times more. Fresh chilled and frozen products have generally the highest due to refrigerant leakage. Dried and frozen products, as well as juices, account for significant impacts due to high energy requirements for drying, evaporation, and freezing.

For category vegetables, tomatoes have the maximum ODP value for the year 2010 of the order of 10^7 and other vegetables follow the order as potato > carrot > beans. A similar study (Mattila et al., 2011a) conducted in the UK for vegetables also shows that beetroot has the lowest ODP and asparagus has the highest, with 0.08 and 2.84 g CFC-11 eq./kg, respectively. Due to refrigerant leakage, the retail and transportation stages are the primary contributors to most vegetables. Because of the large proportion of imported produce, transportation has the greatest impact on the ODP of squash and beans, accounting for more than 85% of the total. Increased UV radiation levels at the Earth's surface resulting from ozone layer depletion. UV radiation has an impact on human and aquatic life, as well as terrestrial and aquatic ecosystems, causing changes in growth, food chains, and biochemical cycles (Heimsoeth, 1983). This shows the importance of controlling the related emissions and changes in policies towards them.

3.2.4. Particulate matter formation (PMFP)

Particulate matter (PM) is a fluid mezzanine of incredibly tiny elements such as acids (nitrates and sulfates), organic chemicals, metals, and soil or dust particles. A mass of health issues is related to particle contamination, particularly of the respiratory tract. PM is expressed in equivalents of PM10, that is, particles of 10 μm diameter (Atmosphere, 1997). Wet and dried precipitation of particulate sulfate and nitrate species from agriculture is a significant contributory element to the atmospheric production of sulfur, ammonia, and soil acidity. The PMFP values for most of the crops show a random trend. Barley, sunflower, beans, and carrot shows a declining trend. Maize, grapes, and tomato shows a rising trend and eventually enhances the PM formation capacity.

From the evaluation done as shown in Fig. 1(a-c) and Fig. 2(a-c), coconut is the major contributor among all the crops in the year 2010 and millet is least in the year 2005. For category fruits, mangoes production has maximum PMFP value for the year 2015 which is about 200 times more in comparison to the year 2000 and other fruits follows the order as banana (10^8 kg PM10-Eq) > apple (10^6–10^8 kg PM10-Eq) > grapes (10^6–10^7 kg PM10-Eq). Mangoes have the highest value (9.4gPM10eq./kg) in the UK, and crop production contributes the most, followed by transportation. (Mattila et al., 2011a).

At the farm level, the effect is primarily caused by the use of electricity for irrigation, fertilizer production, and pollution during cultivation. For category cash crops, cocoa and coffee have the highest PMFP value in the year 2010 and 2005 respectively and both have the lowest value which is equivalent to 1/100 times of PMFP in the year 2000. For category vegetables, tomatoes show the highest PMFP value (2.74×10^{11} kg PM10-Eq) in the year 2010 and other vegetables follow the order as potato > beans > carrot. In a similar study conducted in the UK for vegetables (Mattila et al., 2011a), Cabbage is the finest vegetable, with 1.19 g PM10 equivalent/kg. As for most other categories, asparagus is the least sustainable, with an eight-fold higher impact (8.64 g PM10eq./kg) and other vegetables follow the order as tomato > potato > carrot. Comparing to this study, our study shows that the impact for the year 2020 for various vegetables like carrot, potato, and tomato is about 68×10^5, 1.17×10^8, and 1.39×10^9 times higher respectively. Energy consumption is the primary source of PMFP, with farming, transportation, and packaging as the main hotspots throughout the vegetables.

Forecasting shows that rice production will have the maximum PMFP value from years 2020 to 2050 in the range of 10^{10}–10^{11} and other crops will follow the order as millet (10^{10}–10^{11}) > wheat (10^9–10^{10}) > rapeseed (10^8–10^9) > castor oilseed (10^7–10^8) > carrot (10^5–10^6). The increased value of PMFP results in significant environmental problems and leads to increased mortality. Besides, it is evident that (i) PM suppresses water evaporation from the Indian ocean resulting in more sluggish Indian monsoons due to global drought (ii) PM pollution can increase drought worldwide by pushing tropical rainfall towards the south (NRC, 2010) and (iii) by transforming NO_x, NH_3, and SO_2 in atmospheric air to secondary aerosols, it could participate in global climate change and needs attention. All these can further cause a huge impact on the agricultural sector.

3.2.5. Photochemical oxidant formation (POFP)

The nitrogen oxides and reactive hydrocarbons are released during the different stages of 21 crops' production. Under the sunlight, these pollutants react and result in a POFP and hence accounted for in this study. The POFP value of a given hydrocarbon is a quantitative indicator of the concentration of ozone measured at a single location. POFP is measured in kg of non-methane volatile organic compounds (NMVOC)/kg emission (Fairbrother and Hope, 2005) The NMVOC from the agricultural sector is mainly due to the chemical factory, ammonia production, market group for electricity, agricultural machinery production, fertilizer and pesticides production, market group for transport. Biogenic NMVOC is released by plants, and the concentrations depend on the crops. NMVOCs add to ground-level ozone formation and it is estimated that NMVOC contributes roughly 37% of ozone formation. (States et al., 2010).

This study shows that the annual formation of NMVOC from 21 crops is 4.4623×10^{10} Kg NMVOC Eq in the year 2015. It is highlighted that the POFP reached its maximum impact in the year 2010, mainly contributed by crops like coconut, maize, sugarcane, and tomato among all four years, 2000, 2005, 2010, and 2015. As shown in Fig. 1(a-c) and Fig. 2(a-c), in the category fruits, grapes and mangoes have the highest POFP value in the year 2015, 2×10^7 and 4×10^9 Kg NMVOC Eq respectively while apple has the highest POFP value of 1×10^8 kg NMVOC Eq in the year 2005, increased around 100 times from its preceding five years. This is mainly due to the heavy consumption of mineral fertilizers and pesticides for having higher output and usage of old and outdated agricultural machinery over the field. Another study evaluated the effect of perennial crop biomass fabrication and reported that the combustion process has a 50% effect, especially on POFP. (Wagner and Lewandowski, 2017) Among crops, rice and beans have the highest POFP value of 3×10^{10} kg NMVOC Eq and 1.4×10^8 kg NMVOC Eq respectively in the year 2015 except for maize being 9.9×10^{10} kg NMVOC Eq, having a sharp rise in the year 2010 due to massive use of superphosphate and clear-cutting to land from the forest. For oilseeds, castor oilseed and rapeseed have the highest POFP value of 2×10^7 and 9.4×10^8 kg NMVOC Eq respectively in the year 2015, mainly due to diesel-burning for irrigation. A similar study conducted in the UK for vegetables (Mattila et al., 2011a) shows that the highest impact is estimated for asparagus, followed by beans, peas, and sweetcorn, while cabbage has the lowest value. This impact is mainly due to the use of fuels and energy. Comparing to this study, our study shows that the impact for the year 2020 for various vegetables like carrot, potato, and tomato is about 5.34×10^5, 3.3×10^7, and 1.02×10^9 times higher respectively.

The POFP has projected its maximum record in the future year, 2050, mainly contributed by crops like coconut, rice, and tomato as compared to other forecasted years, 2020 and 2025. Banana, rice, rapeseeds, and potato production shows an increasing trend with a maximum value of 4×10^8, 1.4×10^{11}, $3 \times 10^{9,}$ and 7×10^8 kg NMVOC Eq for the year 2025. The major problems that may increase POFP are smog creation and long-term changes in atmospheric chemistry. These further slowdowns the overall growth of certain plant species and substantially decline the productivity of food grains (News, 2018). Furthermore, the average concentration of ground-level ozone is reported as 100 ppb in India (Liu et al., 2016) while China is considered as the hotspot of ozone pollution (160 ppb). It is a well-known fact that POFP influence the cardiovascular, respiratory and nervous system. It was found that there is a direct correlation between ambient ozone and all-cause, respiratory and circulatory mortality with 2%, 12%, and 3% increased risk per 10 ppb. In addition to the main regulation intended to safeguard human health, additional control measures should be taken to avoid further unwanted effects from the agricultural sector.

3.3. Impact on resources

3.3.1. Fossil depletion (FDP)

The extraction of natural gas, oil, and coal reserves at a faster rate than nature replenishes them is known as fossil fuel depletion. When it comes to agriculture, oil is the scarcest of the three fossil fuels. In agricultural activities, fossil fuels are a valuable source of energy and feedstock for both materials and crop production. This study shows that the FDP of the crops continuously increases with time which means that fossil fuel consumption keeps on increasing with years.

From the evaluation, coconut production is the highest contributor to FDP in the year 2010. As shown in Fig. 1(a-c) and Fig. 2(a-c), for category fruits, mangoes have the maximum value of 3.44×10^{11} kg oil eq./kg for the year 2015 among all the fruits and other fruits follow the order as- apple > grapes > banana. A similar study in the UK was conducted for fruits and vegetables which showed that FDP of the other fruits except for melons and mangoes in the UK ranges between 0.3 and 0.7 kg oil eq./kg. In the vegetable category, asparagus again has the highest impact, estimated at 1.4×10^9 kg oil eq./kg. This is followed by aubergines, tomatoes, and beans (0.69–0.95 kg oil eq./kg) (Mattila et al., 2011a). But in India as per this study, FDP for fruit's category varies from 0.1238×10^{10} to 0.99×10^{10} kg oil eq./kg. All the cereals except barley show a random trend in the order maize > rice > millet > wheat. In vegetable's category, the highest FDP is for carrot ($19.71 \text{x} 10^{09}$kg oil eq./kg), followed by potatoes (0.76×10^9 kg oil eq./kg), tomatoes (0.75 kg oil eq./kg), and beans (0.2×10^8 kg oil eq./kg). No study has been done for oilseeds in the UK, but after evaluating FDP for oilseeds in India, it is found that castor oilseed production has the maximum FDP value of 4×10^8 kg oil eq./kg for the year 2015. Similarly, studies conducted in the UK evidence that the transport and retail stage is the highest contributor for overall FDP but this study found farm production as the hotspot of high overall FDP values (Mattila et al., 2011a).

The forecasting shows that rice production will require more fossil fuels in coming years in the range of 1.5×10^{13} to 7.0×10^{13} kg from the year 2020 to 2050 and other crops will follow the order: mango (10^{12}) > potato ($10^{11}-10^{12}$) > wheat (10^{10}–10^{11}) > banana (10^9–10^{11}) > grapes (10^9–10^{10}). Despite the increased focus on clean energy, fossil fuels continue to account for 80% of global energy consumption and 75% of greenhouse gas emissions (BRE, 2018). The effects of rising FDP values can be understood as fossil fuels increase economic vulnerability by exposing nations and businesses to volatile fuel prices; many are dependent on expensive energy imports. Coal, oil, and gas all make people more vulnerable: According to the World Health Organization, dangerous outdoor air pollution caused by fossil fuel burning kills 4.2 million people worldwide each year. Renewable energy has the potential to eliminate these dangers while also providing a variety of economic opportunities for businesses and communities (NRC, 2010). More so, the increased use of fossil fuels, will also affect climate change and impact agriculture as in a loop.

3.3.2. Metal depletion (MDP)

Metal depletion is a part of abiotic resource depletion (ADP) which is the highest debated impact category. It talks about the depletion of metals used in agricultural activities and hence has high values during the material production stage. The issue of metal depletion can be characterized in a variety of ways, including a reduction in the amount of the resource itself, a reduction in global reserves of usable energy/exergy, or a gradual change in the environmental impact of extraction processes such as the extraction of lower-grade ores or the recovery of materials from scrap (Van Oers and Guinée, 2016). MDP has highlighted its maximum impact in the year 2010 contributed by the crops like tomato, maize, and coconut. Maize production shows the highest value being 2.3×1012 kg Fe-Eq in the year 2010 due to agricultural machinery and fossil fuels used to run the machinery as a major source of metal depletion. This study reveals that the agricultural machinery using diesel as fuel for tillage leads to the depletion of 1.98% of nickel and 1.04% of silicates in the ore. Another study comparing the LCA of fuel ethanol production from sugarcane found that when gasoline is replaced with fuel ethanol, the level of metal depletion is greatly reduced, owing to the switch of fuel resources to biomass (Mattila et al., 2011b).

For category fruits, mango (2.06×10^{10} kg Fe-Eq) topped in the year 2015 followed by banana (5×10^{08} kg Fe-Eq) in the year 2005 as shown in Fig. 1(a-c) and Fig. 2(a-c). A similar study in the UK found mangoes to be the highest contributor to MDP and stated that farm production is responsible for more than 70% of the total impact of apples, berries, and avocados (Mattila et al., 2011a). Cereals in this study show a random trend and the order are as follows- rice > wheat > millet > barley. Among oilseeds, oilseed-nes contributed highest in the year 2000 and least in the year 2010. Among vegetables, tomato (3.01×10^{11} kg Fe-Eq) topped in the year 2015 followed by potato (5.6×10^{09} kg Fe-Eq) in the year 2000. But a study in the UK found MDP ranges from 19.4 to 341 g Fe eq./kg, with the highest impact found for spinach and the lowest for Brussels sprouts (Frankowska and Jeswani, 2019). In 2010 sugarcane (4.1×10^{11} kg Fe-Eq) depicted the highest value followed by coconut (6.1×10^{09} kg Fe-Eq). The extreme use of fertilizers for the cultivation of coconuts leads to a high value of MDP. This study shows that the market for chemical factory parameters is the major contributor to the increasing magnitude of MDP.

A category-wise illustration of forecasted years shows that rice, mango, millets, and wheat are the highest contributors of MDP. Among cereals, rice (2.6×10^{12} kg Fe-Eq) shows the highest value. In fruits, mango (5.4×10^{10} kg Fe-Eq) contributes the highest while oilseeds, sunflower (1.8×10^{09} kg Fe-Eq) topped the list followed by potato (4×10^{07} kg Fe-Eq) among vegetables. Rising values of MDP are a reason of great concern as these metals are non-renewable resources which if depleted once, can't be regained again. Hence alternatives like lowering the use of fossil fuels and promoting the use of solar energy for driving machines electrically can save a lot of extraction of abiotic resources. Crop rotation and cover crop planting help to keep the soil healthy. It's also possible to assist by using fewer chemicals and incorporating biological pest control and natural fertilizers. Precision agriculture, which employs technology to maximize resource use, may assist farmers in using less fertilizer, pesticides, water, and other inputs, thus reducing the ongoing degradation of abiotic resources (Balafoutis et al., 2017).

From the above discussion, it may be summarized that among all 18 environmental indices, GWP, FDP, HTP, METP, TAP, WDP seems to be the major contributors affecting the adverse environment due to the production of crops in India. The crops like coconut, tomato, maize, and sugarcane caused the maximum climate change due to their massive production and land occupation in the same order. The crop production stage holds enormous activates that emit GHGs and thus leads to a GWP compared to the material production. But a similar study on Greenhouse Gas Emissions from SRI and flooded rice production in southeast India depicted that rice is the most greenhouse gas-intensive staple crop, producing about four times more GHG emissions per ton than wheat or maize (Hardy et al., 2013).

Coconut production is the highest contributor to FDP in the year 2010 due to fossil drive activities which may ruin the objectives of SDGs as fossil conservation is the utmost need of an hour. For almost all the crops, the value of HTP keeps on increasing mainly due to the scarce land resources in India, high use of phosphate fertilizer which is essential for better growth of plants leading to increased HTP. A study LCIA of pesticides on human health and ecosystems evidenced that for human toxicity, estimates of pesticide residues show that food intake results in the highest toxic exposure, about 10^3 to 10^5 times higher than that induced by drinking water or inhalation (Margni et al., 2002). This shows that better evaluation practices of pesticide residues in food need to be established in priority.

Production of crops also accounts for the impact on the marine environment causing marine toxicity. The crops like maize, coconut, and sugarcane cause maximum METP due to the heavy use of agrochemicals used in irrigation activities emits a lot of contaminants affecting marine life. TAP is a direct outcome of emitting acids to the atmosphere and eventually depositing them in the soil surface (Winans et al., 2020). TAP has highlighted its maximum impact in the year 2010 due to the heavy use of agricultural machinery, fertilizers and pesticides consumption, diesel combustion, clear-cutting from forest to land. Another LCA study on maize interpreted that the fertilization of fields and their emission are responsible for about 95% of TAP (Bacenetti et al., 2013). Also, the production of urea, ammonia steam reformation, and phosphoric acid production are the major contributors to WDP.

Similar to the crop-wise discussion, section 3 in supplementary material demonstrates the year-wise comparison of all crops based on environmental indices. From the above discussion, it can be also being concluded that millets and sugarcane contributed the highest for most of the indices for the year 2000. Millet production used a large area and electricity consumption along with high use of chemicals which resulted in high values for most of the impact categories. For the year 2020, coconut contributed the highest due to the high use of agrochemicals followed by rice due to the large area of land occupation for production. As given in Table 4, the top 5 repeated contributors during 2000–2015 were found to be maize and rice. It also shows that during 2020–2050, the major contributors will be maize, millet, rice, wheat, and mango. This forecasting is limited majorly with the unavailability of data as discussed in section 2.4 in the supplementary material. For the year 2050, coconut and maize seem to be the major contributors to many of the environmental indices followed by tomato and sugarcane. Special care has to be taken for the production of such crops in the future to control the rising values. Better farming techniques and the use of eco-friendly agrochemicals are the best ways to curb environmental pollution due to crop production.

3.4. Assessment of the connection between the indices and SDGs

The present study evaluated the sustainability assessment of 21 crops using a total of 18 impact categories. Further, Table 5 emphasizing the influence of 18 impact indices on the addressed 17 SDGs was created using three validation criteria: high, medium, and low. The considered impact indices are primarily designated into three major categories as ecosystem quality, human health, and abiotic resources depletion. On contrary, with other impact groups, ecosystem quality is further divided into three subcategories of terrestrial ecosystem, climate change, and aquatic ecosystem. In consonance with the endowed data, ecosystem quality encompasses 11 parameters among ALOP, NLTP, TAP, TETP, and ULOP comes under terrestrial ecosystem, the only indices GWP under climate change and other five indices such as FETP, FEP, METP, and MEP are categorized under aquatic ecosystem.

The impact of the agricultural system on the terrestrial ecosystem mainly relies on the changes developed in the land use patterns and species adapted on it, mostly because of anthropogenic activities. Table 5 entails that the impact parameters related to the terrestrial ecosystem (ALOP, NLTP, TAP, TETP, and ULOP) express the high influence on the goals of zero hunger, responsible consumption and production, and life on land, which denoted as SDGs of 2,12 and 15, since

Table 4
Details of the crops in the study.

No	Category	Selected crops in this study	Number of indices forecasted	Repetitions as top 5 during 2000–2015	Repetitions as top 5 during 2020–2050	Repetitions as top 5 during 2000–2050
1	Cereals	Barley	6	0	0	0
2	Cereals	Maize	6	3	2	5
3	Cereals	Millet	17	1	2	3
4	Cereals	Rice	18	3	2	5
5	Cereals	Wheat	15	2	2	4
6	Fruits	Apple	0	0	0	0
7	Fruits	Banana	15	0	0	0
8	Fruits	Grapes	13	0	0	0
9	Fruits	Mango	12	1	2	3
10	Oilseeds	Castor oilseed	16	0	0 00	0
11	Oilseeds	Sunflower seed	9	0	0 0	0
12	Oilseeds	Oilseed	2	1	0	1
13	Oilseeds	Rapeseed	15	0	0	0
14	Vegetables	Beans	3	0	0	0
15	Vegetables	Carrot	6	0	0	0
16	Vegetables	Potato	15	0	0	0
17	Vegetables	Tomato	0	0	0	0
18	Cash crops	Cocoa	1	1	0	1
19	Cash crops	Coffee	1	1	0	1
20	Others	Coconut	0	2	0	2
21	Others	Sugarcane	0	4	0	4
		TOTAL	170	19	10	29

Table 5
The link between the SDGs and the Indices used in this study.

Sl. No	SDGs/Indices used in this study	ALOP	GWP	FETP	FEP	METP	MEP	NLTP	TAP	TETP	ULOP	WDP	HTP	IRP	ODP	PMFP	POFP	FDP	MDP
	End point area to be protected	TE	CC	AES				TE				AES	HH					ARD	
	Categories	Ecosystem quality											Human health					Resources	
1	GOAL 1: No Poverty	M	M	M	M	L	L	M	M	M	M	M	M	M	M	M	M	L	L
2	GOAL 2: Zero Hunger	H	M	M	M	M	M	H	H	H	H	M	H	H	H	H	H	L	L
3	GOAL 3: Good Health and Well-being	M	M	L	L	M	M	M	M	M	M	M	H	H	H	H	H	L	L
4	GOAL 4: Quality Education	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
5	GOAL 5: Gender Equality	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
6	GOAL 6: Clean Water and Sanitation	L	M	H	H	H	H	L	L	L	L	H	H	H	H	H	H	L	L
7	GOAL 7: Affordable and Clean Energy	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	H	H
8	GOAL 8: Decent Work and Economic Growth	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	H	H
9	GOAL 9: Industry, Innovation and Infrastructure	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	H	H
10	GOAL 10: Reduced Inequality	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
11	GOAL 11: Sustainable Cities and Communities	L	M	L	L	L	L	L	L	L	M	L	H	H	H	H	H	M	M
12	GOAL 12: Responsible Consumption and Production	H	M	H	H	H	H	H	H	H	H	H	L	L	L	L	L	H	H
13	GOAL 13: Climate Action	L	H	L	L	M	M	M	L	L	M	L	L	L	L	L	L	L	L
14	GOAL 14: Life BeL Water	L	M	H	H	H	H	L	L	L	L	H	L	L	L	L	L	L	L
15	GOAL 15: Life on Land	H	M	L	L	L	L	H	H	H	H	L	L	L	L	L	L	L	L
16	GOAL 16: Peace and Justice Strong Institutions	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
17	GOAL 17: Partnerships to achieve the Goal	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

Note: H-High, M-Medium, L-Low, TE-Terrestrial ecosystem, CC-Climate change, AES-Aquatic ecosystem, HH-Human health, ARD-Abiotic resource depletion.

these exhibit strong direct affiliation with the agriculture and food production, too. Fluctuations in terrestrial characteristics due to agricultural activities such as land preparation imply a strong impact on zero hunger, consumption and production process, and the existence of species on their native ecosystem as reported in the previous sections.

Since zero hunger affects the poverty level, all the terrestrial parameters exhibit a medium impact on poverty. It implies that when the number of people below the poverty line decreases, chances to achieve zero hunger state increase. According to this, zero hunger also shows connection with good health and well-being goal, hence impart medium contribution. In contrary to this common behaviour of terrestrial impact potential on SDGs, natural land transformation creates a moderate approach towards climatic variability due to the change in ecological conditions in land due to the influence of agriculture. Also, urban land utilization for agricultural purposes attributes to medium effect on sustainable cities and communities, in line with climatic change which dominates human involvement. Urban land occupation and land transformation during various agricultural activities cause terrestrial ecotoxicity and acidification which further damages the terrestrial species that in turn results in ecological degradation.

Impact of climatic changes, in terms of GWP, illustrates supremacy on climatic action (goal 13) and hence show moderate influence on SDGs of no poverty, zero hunger, good health and well-being, clean water and sanitation, sustainable cities and communities, responsible consumption and production, life below water and life on lands. Variation in climatic changes mainly incorporates the anthropogenic contribution such as the use of agrochemicals and energy consumption in the agricultural sector as discussed in the previous discussion, which reflects deviation on the terrestrial, freshwater ecosystem, and agricultural patterns, thereby hold an influence on both poverty and human health also. Global warming induces a severe threat to human health by causing increased malnutrition and other carcinogenic diseases. Besides that, it also engenders instability of ecosystem and threatening of existing species.

The third subcategory of ecosystem quality - aquatic ecosystem-related indices display high involvement on goals of clean water and sanitation, production and consumption, and life below water. This high impact is implying that excessive water depletion and leaching of nutrients leads to change in the quality and quantity of fresh and marine water also affects the existence of aquatic species (flora and fauna). It also gives the importance of agricultural production and consumption relies on water utilization. Both FETP and FEP show medium variation on zero hunger and poverty since it relates to production and consumption. METP and MEP display medium influence on SDGs 2,3 and 13. In addition to zero hunger and poverty, excessive water depletion shows an affinity towards good health and well-being because of its interrelation with poverty. Fresh water and marine ecotoxicity, as well as eutrophication due to these 21 crops, results in the destruction of respective species and their surroundings, which are mainly introduced by the extensive usage of fertilizers and pesticides in agriculture.

The five indices in human health impacts follow a similar pattern of effect on given goals and exhibit maximum variation in concerned goals zero hunger, good health, clean water, and sustainable cities and communities. The presence of toxic emissions like photochemical oxidants and particular matter shows an inverse effect on health which in turn interrupt the sustainability of cities. Ozone depletion directly associated with the releasing of radiation and cause impacts on living organism and water resources. Release of the particular matter and photochemical oxidants cause respiratory problems, along with that enhanced ozone depletion and radiations as part of the greenhouse gas emissions induce cancerous and non-cancerous diseases. Besides this, human toxicity also indicates the level of damage of human health.

The last category deals with abiotic resource depletion, involving the exploitation of fossil and mineral resources. It is denoted by two parameters fossil depletion (FDP) and metal depletion (MDP), which exert high variation on affordable and clean energy (Goal 7), decent work and economic growth (Goal 8), industry, innovation, and infrastructure (Goal 9) and responsible consumption and production (Goal 12). The utilization of fossil fuels and minerals sources plays a crucial role in production, economic growth, and industrial development. Over-exploitation of these resources induces escalation of fuel expenses, which leads to the appropriate necessity of sustainable energy resources which affordable to common people. Also, a decrease in available minerals results in the increased cost of extraction or mining cost. The denoted indices demonstrate a moderate impact of energy depletion on sustainable cities, because of its connection with highly affected goals. Differing from other goals SDGs 4,5,10,16 and 17 shows the lower influence on the endowed indices because it mainly describes the socially allied impacts.

Further, the extend of the 18 indices meeting the 17 SDGs is better understood from Table S6(a-b), which summarizes the total number of impact indices causing high, medium, and low influence on each SDG. This further helps to

(i) select the optimum indices based on the target of a study to cover more SDGs
(ii) identify the limitations of the used indices system which enlighten the gaps in the focused research area.

Among the 18 indices, 12 indices have a high influence on achieving responsible consumption and production goal whereas the goal of achieving both zero hunger and clean water and sanitation is affected mainly by 10 impact indices. The moderate effect of other indices further adds up the overall hold of the impact of 21 crops on these SDGs. Likewise, the impact of 21 crops also addresses the goals of no poverty and good health and well-being by having a medium influence of 14 and 9 indices respectively. The goal of achieving good health and well-being is also highly influenced by the other 5 indices. A broad analysis done by summing up both high and medium influenced indices portrays that these five SDGs viz. a viz. SDG 1,2,3,6 and 12 are the major goals affected by these 18 indices. As per Table 6(a), all the 18 considered impact indices have a low influence on the sustainability goals 4,5,10,16, and 17, and future research should focus on the achievement of these goals. These 21 crops have a moderate influence on the remaining SDGs.

The potential impact of three impact category groups (containing a total of 18 indices) and their contribution towards the achievement of different SDGs are summarized in Table 6(b). Also, it is clear that the impacts indices make varying contributions to the realization of different SDGs. For example, each index in the impact category groups human health and abiotic resource depletion highly influence the achievement of 4 among the total SDGs. Also, they show a medium effect on one more SDG thus contributing to the realization of a total of 5 goals. Likewise, most of the indices mentioned in the terrestrial ecosystem impact group show influence (both high and medium) on a total of 5 SDGs. An exception is shown in the case of NLTP and ULOP which have a bit more influence on the realization of goals by affecting a total of 6 and 7 SDGs, respectively. A similar trend is exhibited by aquatic ecosystem indices also. They highly control 3 SDGs and further slightly contribute to other 2 or 3 SDGs also. A different observation is conveyed by climate change impact index GWP where it highly influences only one SDG but adds up its contribution in sustainability achievement by having a medium influence on other 8 SDGs thus affecting around 9 SDGs in total. Even though each index contributes to a maximum of 5 SDGs, they fail to meet or lowly influence the achievement of the remaining 10–12 SDGs. Among these, the SDGs 4,5,10,16, and 17 are not much addressed by these 18 impact indices and future research focus on improvising the existing indices or formulating new impact indices to measure agricultural sustainability accurately.

4. Summary and conclusion

The present study is the first study that estimated the impact of agricultural processes on sustainability in terms of ecosystem, human health, and resources for the commonly grown 21 crops in India. The impact was calculated for 21 crops for the years from 2000 to 2050. Millet in the year 2000, sugarcane in the year 2005, coconut in the year 2010, and rice in the year 2015 are the major contributors to impact the sustainability out of all 21 crops. The forecasting shows that rice is the major contributor in the year 2020 among all the crops and by the year 2050, rice and maize will be the major contributors. This study reveals that the increment rate in impacts is mainly due to the augmentation of the area harvested, and the consumption of pesticides, fertilizers, and electricity. The suggestions to reduce the impact without compromising the crop yield to meet the food demands are discussed for every impact category. The application of the current LCA model can be extended for the comparative assessment and spot of the best alternative among a variety of crops and production techniques.

The study also assessed the order of achieving 17 SDGs using these 18 indices. It was found that SDGs 4,5,10,16 and 17 which belong to quality education, gender equality, reduced inequality, peace, and justice strong institutions, partnerships were met at a lower level due to their lesser connection with emissions mediated the impact of 21 crops and the entire agricultural system. However, all the other SGDs were well addressed by the selected indices. To measure agricultural sustainability accurately, future research should focus on (i) developing a single index that incorporates all 17 SDGs which is complex due to multi-facets of agricultural activities, and (ii) update the current indices to measure the low attention-ed SDGs by accounting respective parameters. This will be the major and foremost future scope of this study in the area of development of indices in agricultural sustainability.

The present study is challenged by the following limitations (i) it did not account for the processes like manure management, land use, enteric fermentation, manure applied to soils, manure left on pastures, synthetic fertilizers usage, storage, transportation, packaging, consumption, and waste dumping (ii) it does not take into account all the fertilizers that are used in India rather accounted only a few of them (iii) one of the database (Agribalyse) used is basically for French products not for India and (iv) the trendlines of the forecasted data are considered only if $R^2 > 0.7$. Hence, the discussion on forecasting is limited to a few crops and indices. The addressed limitations are because of the unavailability of required data. If these data would have been available, the study would be much better and reliable not only for the present scenario but for future years also.

However, this study deepened the knowledge of possible impacts because of agricultural activities and if the right decisions are made, many of these forecasted impacts can be prevented or reduced. It is expected that this study will enlighten the researchers for deep studies on alternatives for agrochemicals, to help in policy-making decisions, and to set rules and regulations in handling the agricultural practices and crop residue management.

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Statement of Novelty

- The paper is one of its kind to perform LCA and evaluate the environmental burdens associated with cultivation of 21 commonly grown crops in India possessing high production and emissions, in the form of 18 environmental potential indices for the years 2000, 2005, 2010 and 2015 and the rationality of the forecasted data 2020, 2025 and 2050 is checked using the R^2 value.

- Many researchers have used the databases like AGRIBALYSE, USAD, Eco-invent, etc from the software that consists of predefined processes. On the other hand, in our study most of the data was collected from FAOSTAT for every particular process and their emissions, providing less variation of data as compared to other papers.
- When it comes to opting for functional unit, many researchers have taken per kg crop or per hectare production as their functional unit. However, we have used area harvested per year as functional unit in order to avoid complexities related to farming practices, weather and climatic parameters, soil homogeneity and heterogeneity and other regional variations.
- A very few studies have incorporated the crop residue management in their LCA boundary. However, knowing its negative impact, this study has put up burning and tillage process into system boundary. Moreover, the results of the study were presented in an immensely effective manner. It includes the crop wise and year wise discussion of all eighteen indices through ReCiPe midpoint method using openLCA software.
- The study comprised the assessment of the link between the 18 indices and 17 SDGs to measure the order of accuracy in addressing the SDGs by each indices. This analysis could find the most and least addressed SDGs which will further be useful in (i) selecting the optimum indices in agricultural sector and (ii) identifying the gap areas that will be helpful in formulating new indices or upgrade the existing indices to measure the agricultural sustainability accurately.
- This LCA model can be used for the comparative assessment and differentiating the best among different crop production practices, approach and related technologies and to improve production process, farming practices, product development, and waste management to have the least impact on environment without compromising the socio-economic aspects involved in crop production and agricultural systems.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2021.100074.

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