Sreejith et al. International Journal of Energy and Environmental Engineering 2013, 4:8
http://www.journal-ijeee.com/content/4/1/8

International Journal of
Energy and Environmental Engineering
a SpringerOpen Journal

ORIGINAL RESEARCH **Open Access**

Life cycle assessment of producer gas derived from coconut shell and its comparison with coal gas: an Indian perspective

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Abstract

Oil dependency and global warming have stimulated R&D activities on the utilization of secondary biofuels. This article investigates the suitability of coconut shell-derived producer gas (a secondary gaseous biofuel) as a substitute for coal gas from an environmental perspective using life cycle assessment (LCA) approach. Thermochemical gasification in an air-fluidized bed with steam injection is the gaseous fuel production process. LCA is carried out with respect to Indian conditions based on primary and modified Ecoinvent 2.0 data using IMPACT 2002+ environmental impact assessment methodology. The study indicates that coconut shell-derived producer gas life cycle is capable of saving 18.3% of emissions causing global warming potential, 64.1% of emissions causing ozone depletion potential, and 71.5% of nonrenewable energy consumption. The analysis of energy and exergy consumptions of the two life cycles reveal that the renewable fraction in the total energy demand is 62.9% for producer gas life cycle, while it is only 2.8% for coal gas life cycle. Allocation of the by-product, coconut palm residues, is the major responsible factor for this reduction in environmental burden. Based on the existing fertilization practice and the utilization of electricity from the Indian electric grid, substantial green house gas (GHG) emission savings cannot be achieved for producer gas life cycle over coal gas life cycle. However, the green electricity-aided catalytic gasification of coconut shell produced by organic farming can result in 43.4% reduction in GHG emissions, meeting European Union renewable energy directive.

Keywords: Life cycle assessment, Coconut shell, Gasification, Coal gas, Environmental impact

Background

Life cycle assessment (LCA) is a process of evaluating environmental burdens or benefits associated with the total life cycle of a product. This is conducted by identifying and quantifying the energy and materials used and waste products released into the environment [1]. It is performed in accordance with ISO 14040:2006 and ISO 14044:2006 standards. In simple terms, LCA is a holistic tool for evaluating the environmental impacts associated with a product, process, or activity. The ecological or environmental impacts include effects on the ecosystem, human health, and natural resources [2]. Generally, LCA is termed as a 'cradle to grave' approach since it accounts the environmental impacts throughout the product's life, right from raw material acquisition, processing, manufacturing, use, and finally its disposal [3]. The significance of LCA lies in the fact that it equips the policy makers and decision makers for adoption of suitable and sustainable energy supply systems. Increasing global concern due to air pollution and to limited oil reserves has generated much interest in environmental friendly alternatives to petroleum-based fuels [4]. This is more prominent in the context of the current substantial contribution of fossil fuels (over 85%) [5] to the global energy supply. Generally, biofuels produced from renewable energy sources (biomass) are considered to be an effective alternative to fossil fuels, and the concerned production technology is sustainable. To identify savings in energy and emissions from biofuel production and utilization, a thorough evaluation of the corresponding life cycle is to be carried out carefully [6]. LCA is an effective tool for this, which accounts for the relative environmental impacts of biofuel life cycle with respect to 'base case' such as fossil fuel-based life cycle. For example, for biodiesel, the

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base case may be petroleum diesel, and for producer gas derived from biomass, the base case may be coal gas. The adoption of LCA in the perspective of sustainable economy is more essential nowadays because of the boom in the installation of energy and heat production systems utilizing these sustainable energy techniques with the intention of meeting European Union (EU) targets of 20% renewable energy share by 2020.

The updated standard ISO 14044:2006 [7] specifies requirements and provides guidelines for life cycle assessment including definition of goal and scope of the LCA, life cycle inventory analysis (LCI) phase, life cycle impact assessment phase, life cycle interpretation phase, reporting critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.

LCA approach was adopted for assessing the environmental suitability of the utilization of various renewable energy resources such as solar PV, wind, and biomass by Manish et al. [8]. The base cases considered were coal-based thermal power generation and steam methane reforming for hydrogen production. The comparison of different options was made based on major indicators like life cycle cost, green house gas (GHG) emissions, and net energy ratio (NER). Secondary biofuels produced from unprocessed primary biomass-based materials are sustainable alternative to fossil fuels. Secondary biofuels may be of solid, liquid, or gaseous types which are produced by adopting various production routes. A state-of-the-art review of literature pertaining to liquid biofuels was reported by Nigam and Singh [9]. Producer gas is a secondary gaseous biofuel generated by the thermochemical gasification of biomass. NER and total energy ratio of the life cycle of rice straw-generated producer gas were evaluated by Shie et al. [10]. A comparison of biomass and coal in terms of several environmental indicators for integrated gasification combined cycles with [11] and without [12,13] CO_2 chemical absorption revealed the superiority of biomass. On further analysis of the potential of biomass to produce hydrogen, Koroneos et al. [2] reported the advantage of biomass gasification-syngas reformation-absorption route over biomass gasification-electricity generation-electrolysis route. Manish et al. [8] on reviewing the LCA studies on gasification with biomass and with biomass-coal blends for electricity generation reported an evident reduction in environmental impacts when biomass is used as energy source. However, the life cycle of biomass-based systems can have higher eutrophication potential [14] and acidifying emission potential. Consequences of using agricultural land for other purposes than food production [15] and the size and scale of the biomass-based combined heat and power (CHP) plant [16] are significant factors while utilizing biomass-based systems.

The choice of selected indicators for LCA can provide options for the improvement of the existing systems. Such a damage assessment based on the existing life cycle of natural gas combustion district heating system at a rural location in British Columbia was conducted by Pa et al. [17,18] recently. Similar region-specific LCA studies for woodchip-based 'green electricity generation' in Austria [1], post-consumer wood and forest residue-based gasification in a metropolitan area in Barcelona [19], and carbonization of several woody biomass (found plenty in Singapore) to charcoal [20] are worth mentioning. The comparatively lesser impacts on global warming, acidification, and eutrophication by the life cycle of biomass thermal technologies over that of biological routes were reported by Zaman [21] and Zhong et al. [22]. Iribarren et al. [23], on considering biofuel production systems from poplar biomass, stressed on the need for plantation and harvesting of the lignocellulosic biomass in terms of land occupation and fertilizer requirements. The utilization of hydrogen as fuels in vehicles and the progress in fuel cells have necessitated the need for LCA of the concerned hydrogen supply chains. Such analyses were reported for urban transportation with hydrogen vehicles [24] and for hydrogen refueling stations [25]. A comprehensive state-of-the-art review of environmental impacts of hybrid and electric vehicles was reported by Hawkins et al. [26].

Present study and its significance

India, one of the biggest agricultural countries in world, is in the process of setting up many large-and medium-scale biomass-based power plants for rural electrification, utilizing locally available feedstocks. Thermochemical gasification is a mature sustainable technology for gaseous fuel production from renewables [27,28]. The country has declared its commitments to the implementation of clean development mechanism, which is an arrangement under the Kyoto protocol. The abundantly available biomass materials in the subcontinent include eucalyptus wood, rice husk, paddy husk, coconut shell, cashew nut shell, and bamboo. The climatic conditions are not uniform in the country, making it suitable for these agricultural and forest biomass to grow in different parts of the country. For example, in the southern part of India, the most abundantly available biomass feedstock is coconut shell. Thus, utilization of coconut shells for bioenergy production for electrifying rural areas in southern India has significance. The environmental burdens associated with the utilization of these biomasses (and more) are largely different since irrigation schedule (depends on rain fall), fertilization schedule (depends on soil conditions), land requirement, yield of biomass per hectare, and heating value are different for these biomasses. Thus, it is vital to make assessments about various biomass feedstocks suitable for such power plants from an energy and environmental perspective. As a first step in the venture, coconut shell is taken for assessment in the present study, which will be followed by several other probable feedstocks mentioned already. Hence, the present work is a region-specific study for LCA of coconut shell-derived producer gas life cycle in the third largest coconut-producing country in the world. To the best of the authors' knowledge, no work has been reported on a comparative LCA of coconut shell-derived producer gas and coal-derived coal gas with respect to Indian conditions.

As the world is heading towards hydrogen energy economy, many attempts were reported for enhancing the hydrogen concentration in biomass-derived producer gas for the onward utilization in fuel cells and in hydrogen-fuelled vehicles. Steam reforming the producer gas generated by air-fluidized bed (AFB) gasification is one of the options for achieving this. Syngas (producer gas) can be made further rich in hydrogen by supplying more amount of steam to the AFB gasifier. However, the most common production method of steam utilizes fossil fuels which generate greenhouse gases and ozone-depleting gases, necessitating the optimization of steam utilization. Thus, the present study is significant as a 'well-to-tank' LCA approach to make comparison between two solid fuel-hydrogen-rich gaseous fuel life cycles, that is, the life cycles of fossil fuel-derived coal gas and its potential renewable alternative (coconut shell-derived syngas) are compared with respect to India, the world's largest low-ash-content coconut shell producer.

Location of the present study

Kerala, one of the southern states of India, is blessed with abundant rain fall in the range of 2,000 to 3,000 mm/year [29]. The fertile soil conditions in the region are well suited for coconut cultivation. Researches on a variety of coconut palm species have succeeded in developing new hybrids suiting varying conditions [30]. The specialty of coconut palm is that every part of it has valuable applications, as given in Table 1. The major use of coconut shell (main product) is for handicrafts and charcoal, the latter being one of the base materials for the manufacture of activated carbon. Coconut shell is also used as a primary biofuel for open combustion. The co-product (similar revenue to the main product) coconut oil can be used for edible and inedible (lubricant with nanoparticles addition) purposes. The by-product (lower revenue than that of the main product) palm residues find utilization as a fuel with energy content of 16 to 18 MJ/kg. The state is in the process of developing medium-scale gasification plants for rural electrification utilizing coconut shells as feedstocks for the past 2 to 3 years. The present study pertains to the conversion of coconut shell (primary biofuel) to producer gas (secondary biofuel), which has not yet been analyzed in this region on a life cycle basis.

Methods

Life cycle inventory analysis

Goal, scope, and functional unit

The major objective of the present analysis is to compare the environmental impacts of coconut shell-derived producer gas life cycle with that of the coal gas (generated by the gasification of coal) life cycle. Thus, the present LCA aims for a comparison of the relative environmental impacts of renewable and nonrenewable alternatives of energy production and quantifies the benefits from replacement of the latter with the former. In this study, contributions of various LCA phases to the overall environmental impacts are analyzed to identify the most significant phase in the life cycle. The reference functional unit for the study is 1 MJ energy content in the gaseous fuel (producer gas generated from coconut shell gasification or coal gas generated from coal gasification). This functional unit is selected since the energy content may be utilized for various purposes such as fueling transport system, production of electricity, and as a source of heat for systems like absorption refrigeration.

Producer gas life cycle

System boundaries. The coconut shell-derived producer gas life cycle is analyzed in the perspective of the agricultural scenario existing in the state of Kerala in India. The geographic boundary for the fossil fuel reference system is India except where resources are extracted and transported to India from other countries. A well-to-tank approach is adopted for the LCA because of the potential of the energy content of the generated gas for various

Table 1 Products, co-products, and by-products during coconut shell production

Category	Item	Uses
Product	Coconut shell	Charcoal, handicrafts, fuel for open combustion
Co-product	Coconut oil	Edible oil, lubricant
By-product (coconut palm residues)	Petioles and leaf	Fuel, hut thatching, organic manure
	Coconut seed cake	Cattle feed, organic manure
	Coconut husk	Fuel, organic manure, raw material for coir
	Stem	Piles, pillars, fuel

purposes, as mentioned in the section ‘Goal, scope, and functional unit’.

The life cycle of the producer gas is presented schematically in Figure 1, including crushed coconut shell production and gasification. The various important subsystems include sand bed preparation, coconut cultivation, fertilizing, irrigation, coconut shell production, shell crushing, generation of gasification agents, and coconut shell gasification in a FB gasifier.

Coconut cultivation. Coconut palms are generally cultivated in rain-fed conditions and in irrigated conditions. Irrigation is mainly required in the summer season at predetermined intervals. Average rain fall in Kerala based on the data [29] available for the past 50 years is shown in Table 2. Based on the data, the duration of the summer season is taken as 3.5 months, and irrigation is required in this season. The common schedule [31] of irrigation is represented in Table 3.

Inventory data for coconut cultivation. The following data [31] for coconut cultivation are applied for the development of the sub-modules: sand bed preparation, coconut seedling, coconut plantation, irrigation, and fertilizing. Crude coconut oil and palm residues are the co-product and by-product, respectively, in the coconut shell production process.

- Coconut seedlings are grown in a nursery as per established specifications of planting.
- Seedling survival rate is assumed as 65%, and the percentage of healthy seedlings which can be replanted is taken as 75% as per data from local farmers.
- Selected seedlings are planted in pits of 1-m^3 size, and 5 kg of organic manure is used.
- The tree density is 175 trees/ha.

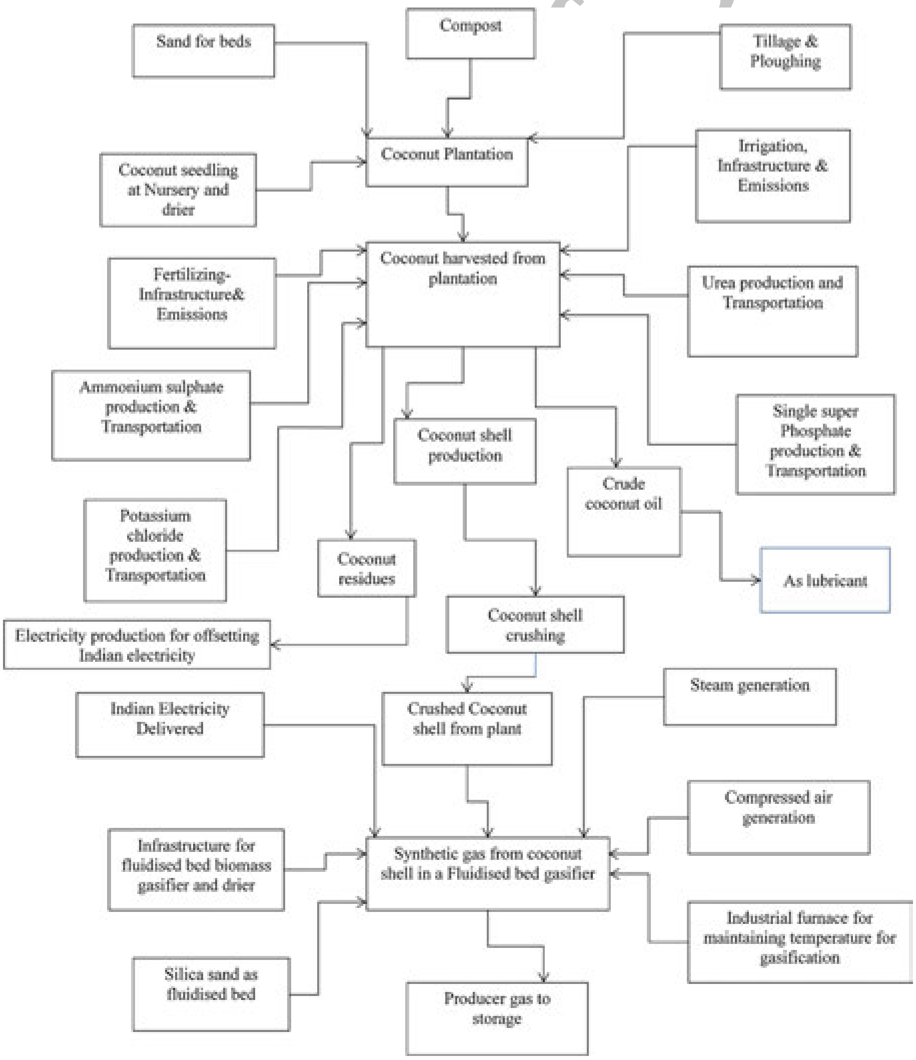

Figure 1 Schematic of producer gas life cycle.

Table 2 Average monthly rain fall in Kerala

Month	Rainfall (mm)
January	14.6
February	16.6
March	36.1
April	110.9
May	252.6
June	653.2
July	687.2
August	404.7
September	252.3
October	270.7
November	158.6
December	45.9

From [27].

- Irrigation and fertilization schedules are according to the principle of good management practices [31], as given in Tables 3 and 4, respectively.
- The coconut yield from a palm per year is 125 nuts, with an average weight of 1.6 kg for full nut and 0.5 kg for husked nut.
- The average quantity of dried copra from nuts is in the rate of 18 kg from 100 nuts (or from 50 kg of husked nut).
- The oil content of copra is about 70%, and the extraction efficiency is about 85%. Hence, expected oil recovery is about 60% of the weight of copra.
- Based on the above conditions, 4.7 kg of husked nuts (9.4 numbers equals approximately 10) is required to produce 1 kg of coconut oil.
- Also, 0.64 kg of shell is obtained from 1 kg of husked nut. It means that from a palm per year, 40 kg of nut shell can be obtained. Thus, 3.1 numbers of husked nuts are required to produce 1 kg of shell.
- Palm residues include the leaves and the dried leaf weighing 2 kg per tree on average and has a heating value of 16,500 kJ/kg.

In the coconut cultivation phase, chemical processes for the production of fertilizers, the utilization of these substances, physical infrastructure for coconut cultivation, and emissions from fertilizers and irrigation are included in the system boundary. Thus, almost all the sub-modules under the modules such as seedling, irrigation, composting, and fertilization in coconut cultivation are based on primary data. For fertilizer production, Ecoinvent 2.0 data were modified with respect to Indian electricity generation and transmission.

Coconut shell gasification. The technology for gaseous fuel production from solid feedstocks (coal or coconut shell) considered in this study is thermochemical gasification. Producer gas or coal gas with more hydrogen concentration is generated by steam injection into an AFB gasifier as mentioned in the section ‘Present study and its significance’.

A gasification module is developed for the thermochemical treatment of crushed coconut shell. The producer gas production phase consists of sub-modules such as steam and compressed-air generation, sand preparation for its utilization as bed material, physical infrastructure for the gasification plant, and electric furnace for maintaining the reactor temperature. A carbon conversion efficiency of 100% for gasification is assumed, and the by-products of gasification (tar and ash) are neglected. The energy requirements (data modified with respect to Indian electricity mix) for all the relevant processes such as fertilizer production, coconut crushing, steam and compressed-air production, irrigation, and thermochemical gasification are included while developing the model.

Coal gas life cycle

Coal gas life cycle is used as the reference system for comparison with that of coconut shell-derived producer gas life cycle. The important sub-modules involved are coal transport from foreign mines, coal mining in India from open and underground mines, transport of Indian and imported coal to regional storage, and gasification of this coal mix to generate coal gas. India is the third biggest hard coal producer (526 million tonne/year) after China (2,971 million tonne/year) and the USA (919 million tonne/year). Eighty-five percent of the total coal utilization in the country is from domestic production, and the remaining 15% is imported from countries like Australia, South Africa, and North America [32]. Out of the domestic production, 85% is from open mining, and the remaining is from underground mining. Major domestic coal mining companies are Coal India Limited, Neyveli Lignite Corporation, and Singareni Collieries Limited. Thus, domestic coal is considered to be mined by these companies at locations in Dhanbad, Neyveli, and Hyderabad, respectively. The study pertains to Calicut, a northern city in Kerala, which is the regional storage

Table 3 Irrigation schedule for coconut cultivation

Age of palm	Quantity of irrigation (Liters per palm)	Schedule (in the summer season, 3.5 months)
First 2 years	1,110	Once in 4 days
Third year onwards	600 to 800	Once in 7 days

From [29].

Table 4 Fertilization schedule for coconut plantations according to the principles of good management practices

Age of coconut palm	Nutrient dosage	Quantity of fertilizer to be added (g)			
		Ammonium sulfate	Urea	Single super phosphate	Muriate of potash
3 months	1/10 of full dose	250	110	180	200
First year	1/3 of full dose	800	360	590	670
Second year	2/3 of full dose	1,675	720	1,180	1,340
Third year onwards	Full dose	2,500	1,080	1,780	2,010

From [29].

location taken for modeling of the transport module for coal (imported and domestic). The mode of transport of coal to regional storage location and the corresponding distances are given in Table 5. For coal transport, the Ecoinvent database is modified with respect to Indian electricity consumption for diesel production for fuelling the transport system (rail, road). The transports of the imported coal in other countries are modeled using the respective data source available in the Ecoinvent 2.0 database. Figure 2 shows the coal gas life cycle map.

Supporting process

A schematic of Indian electricity generation is shown in Figure 3. India's specific electricity generation module was created based on the national average annual proportion of electricity generation by fuel type. LCA modules were developed with contributions of 12%, 70%, 2%, 1%, and 15% of the gross electricity generation [33] in the country by natural gas, coal, nuclear, renewable, and hydropower plants, respectively. Due to the unavailability of Indian data in the Ecoinvent 2.0 database, western European data were modified with respect to Indian electricity share for various energy sources.

Similarly, the fuel data (coal and natural gas) for the power plants in the Ecoinvent database were modified incorporating the proportion of domestic production and import. The transport data were also modified accordingly.

Allocation procedure

Allocation is necessary when a process produces more than one valuable product. In such cases, it is necessary to divide the environmental impacts from the process between the products. Crude coconut oil and coconut residues are the co-product and by-product, respectively, of coconut shell production process. The utilization of energy in the coconut palm residues (by-product of coconut cultivation stage) and production of coconut oil are two major cases in the present LCA study. The ‘division’ of the environmental impacts may be done either by allocation or by system expansion. According to Gnansounou et al. [34], environmental impacts in a life cycle may even vary with the allocation method (mass, energy, carbon content, or economy) adopted. In this study, system boundary expansion method is adopted for allocating the co-product and by-product.

Agricultural residues of coconut plantation play a significant role in the energy analysis because of its availability in large quantity and its energy content. As mentioned in ‘Inventory data for coconut cultivation’, palm residues include the leaves and the dried leaf weighing 2 kg/tree on average and have a heating value of 16,500 kJ/kg. The tree density is 175 palm/ha. The thermal energy that can be generated from the palm residues is calculated from its lower heating value (LHV), followed by the computation of its conversion into electrical energy with an overall conversion efficiency (from palm residues to electric energy) of 25%. This assumption does not take into account the technology used for this conversion. Based on the inventory data for coconut cultivation provided in ‘Inventory data for coconut cultivation’, the net electricity generated from coconut palm residues is computed for the reference functional unit (1 MJ) in SimaPro. This amount of electricity is assumed to offset the corresponding Indian electricity production from coal and natural gas. Thus, the system boundary (as explained in ‘System boundaries’) is expanded to include the system of processes which are involved in the production of Indian electricity from coal and natural gas.

The environmental burdens are allocated for coconut oil by assuming it replacing commercial paraffin oil lubricant [35]. As mentioned in ‘Inventory data for

Table 5 Mode of coal transport and distance to central location

	Mode of transport	Distance (km)	Remarks
Imported coal	Sea	36,336	Total distance from the three countries to the central storage location
	Rail	1,212	
	Road	110	
Domestic coal	Rail	3,994	Total distance from three domestic mining locations in India to the central storage location
	Road	377	

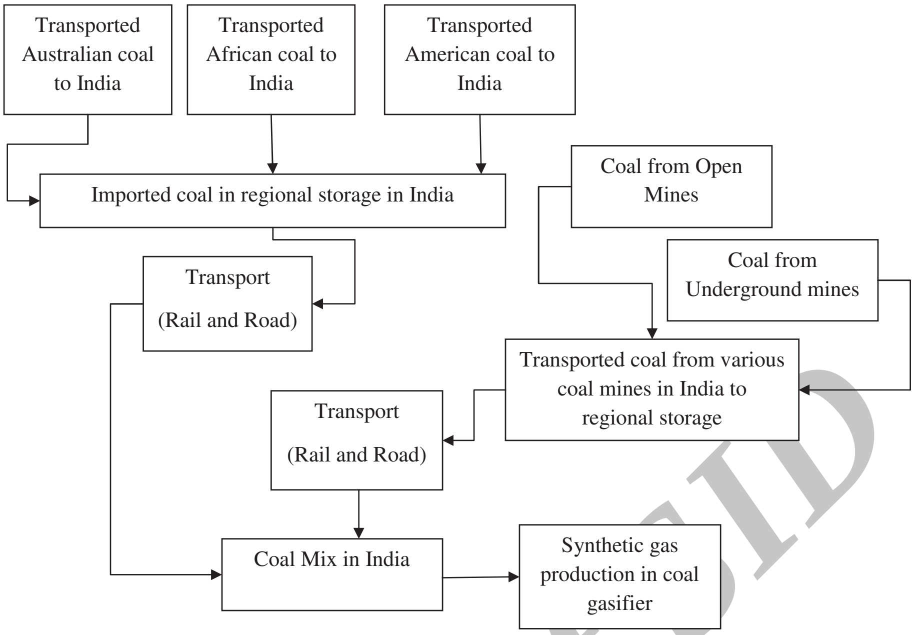

Figure 2 **Schematic diagram of coal gas life cycle.**

coconut cultivation', 4.7 kg of husked nuts (9.4 numbers equals approximately 10) is required to produce 1 kg (or 1.08 l) of coconut oil. Thus, corresponding to the generation of 1 MJ of syngas energy (reference functional unit), the net quantity of 'lubricant' (coconut oil) production can be computed and modeled in SimaPro. A separate module is created for paraffin oil lubricant production (modified Ecoinvent module), and the producer gas life cycle system boundary is expanded to include the system of processes in the commercial paraffin oil lubricant production. By proceeding like this, the net emissions associated with the production of producer gas with 1 MJ of energy are determined by subtracting the sum of the emissions (or impacts) associated with the saved fossil fuel-based electricity production and the saved commercial lubricant production from the emissions associated with the generation of producer gas.

Life cycle impact assessment

Following cutoff criteria are adopted in the study:

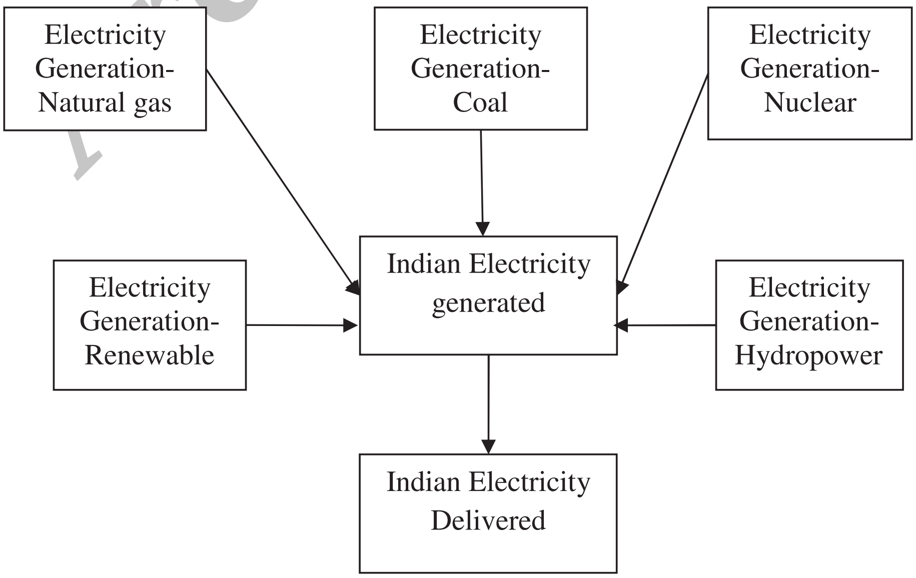

Figure 3 **Modeling schematic for Indian electricity generation.**

a. Since the maturity duration for coconut palm is 10 years, the study is conducted to analyze the impacts of producer gas life cycle corresponding to this duration.
b. Application of pesticides, insecticides, and herbicides for coconut cultivation is avoided due to lack of readily available local data.
c. CO_2 emissions from the utilization of producer gas are taken as nullified by the CO_2 absorption during the growth of coconut tree. This cutoff criterion is made in the context of unavailability of a well-established database to define the rate of sequestration of carbon by coconut palms.
d. Potential land use changes are not evaluated assuming the plantations are long-term existing coconut plantations.
e. Transport of personnel to carry out the different stages in the life cycle is not included.

Environmental impact assessment of the two life cycles is conducted by computational implementation of the inventories collected, using the software SimaPro 7.3.3® developed by Product Ecology Consultants (Amersfoort, The Netherlands) [36]. This software is widely used [8,12,21] for the inventory analysis and LCA of chemical and energy system chains. All the modules of the life cycle are developed using the Ecoinvent 2.0 database available in SimaPro. Tables 6 and 7 represent the corresponding module descriptions in SimaPro for producer gas life cycle and coal gas life cycle, respectively. Table 8 provides details of the inventory data (primary and sourced from

Table 6 SimaPro module descriptions for coconut cultivation and shell gasification in a FB gasifier

Module	Purpose
Sand for beds	Ecoinvent 2.0 module for production and related emissions of sand to be used in the nursery for coconut seedlings
Compost	Custom module for production and related emissions of compost to be used in planting coconut seedlings
Tillage and plowing	Modified Ecoinvent 2.0 module for land preparation for plantation and related emissions. Diesel source modified to Indian conditions
Coconut seedling at nursery	Custom module to represent the requirements for coconut seedlings at nursery
Coconut plantation	Custom module built from three inputs. Tillage, seedlings, and compost
Fertilizing: infrastructure and emissions	Modified Ecoinvent 2.0 module representing impacts of fertilizing 1 ha of plantation using the required machinery
Irrigation, infrastructure, and emissions	Modified Ecoinvent 2.0 module representing impacts of irrigating 1 ha of plantation using the required machinery
Ammonium sulfate production and transportation	Ecoinvent 2.0 module representing impacts of fertilizer production for usage in 1 ha of plantation over the lifetime
Urea production and transportation	Ecoinvent 2.0 module representing impacts of fertilizer production for usage in 1 ha of plantation over the lifetime
Potassium chloride production and transportation	Ecoinvent 2.0 module representing impacts of fertilizer production for usage in 1 ha of plantation over the lifetime
Single super phosphate production and transportation	Ecoinvent 2.0 module representing impacts of fertilizer production for usage in 1 ha of plantation over the lifetime
Coconut harvested from plantation	Custom module representing impacts associated with managing and operating the plantation. Energy from the combustion of biomass residues is used to offset Indian electricity delivered.
Coconut shell production	A custom module to represent the impacts associated with coconut shell production from the harvested coconuts
Crude coconut oil	Impacts of crude coconut oil production and related emissions in an oil extraction plant. Modified Ecoinvent 2.0 module is used with coconut harvesting and electricity utilization corrected to suit Indian conditions.
	Crude coconut oil (by-product) is allocated as lubricant for machinery with the addition of CuO nanoparticles.
Crushing of the shell	Impacts of grinding the coconut shell in biomass crusher for utilization in FB gasifier. Modified Ecoinvent 2.0 module is used with electricity utilization and input material quantity modified to suit Indian conditions.
Coconut shell gasification	Modified Ecoinvent 2.0 module for assessing the impact associated with crushed coconut shell gasification in a FB gasifier with steam and air as gasification medium
Steam for gasification	Modified Ecoinvent 2.0 module for steam generation. Modified with respect to Indian electricity mix
Compressed air for gasification	Modified Ecoinvent module for the assessment of impacts of producing compressed air at 2 bar pressure for fluidizing the bed

Table 7 SimaPro module descriptions for coal mining and gasification

Module	Purpose
Silica sand in the gasifier plant	Ecoinvent 2.0 module for production and related emissions of sand (SiO_2) to be used as bed material including the energy for drying the sand
Indian electricity delivered	Custom module to represent the impact of production and delivery of electricity for coal gasifier plant operation. The proportion of electricity generation is as given in Figure 4.
Steam generation at the site	Modified Ecoinvent 2.0 module for steam generation and related emissions. Electricity production and delivery modified to Indian conditions
Compressed-air generation	Modified Ecoinvent 2.0 module for compressed-air generation supply. The module includes a screw-type compressor, lubricating oil, electricity delivery, and transport of compressor and lubricating oil to the installation site.
Infrastructure for coal gasifier	Ecoinvent 2.0 module representing impacts of developing infrastructure for a typical coal gasifier. The dataset includes land use, building and facilities, dryer, gasifier, and gas treatment facility.
Industrial furnace for maintaining the temperature of the gasifier	Ecoinvent 2.0 module representing impacts of an oil furnace of 1-MW capacity. The module includes the production of oil, the infrastructure for the oil boiler, and transport to site.
Domestic coal mining and transport	Modified Ecoinvent 2.0 module representing impacts of domestic mining (underground and open) in India and its transport to a regional storage
Imported coal	Modified Ecoinvent 2.0 module representing impacts of coal imports from three countries, South America, South Africa, and Australia, in the ratio 2:1:7 to the regional storage location in India. Built-in Ecoinvent module for coal mining and transport in the respective countries were taken into account.
Coal transport to the plant site	Modified Ecoinvent 2.0 module including the impacts of road and rail transport in India.
Synthetic gas production in coal gasifier	Modified Ecoinvent 2.0 module representing impacts of gas production in fluidized bed coal gasifier with steam and air as gasifying medium

Ecoinvent) collected for model development. The impact assessment method selected is IMPACT 2002+ (IMPact Assessment of Chemical Toxics) available in the SimaPro methods library. IMAPCT 2002+ methodology links the LCI results to four broad damage categories: human health, ecosystem quality, climate change, and resources. The schematic of the IMPACT 2002+ framework [36] is shown in Figure 4. The following three specific environmental impact categories are selected in this study. Brief descriptions on the mentioned impact categories are given in the Appendix.

1. Global warming potential (GWP): Net emission of Intergovernmental Panel on Climate Change (IPCC)-identified greenhouse gases are calculated and expressed in terms of kilograms of CO_2 equivalent for a 100-year lifetime.
2. Ozone depletion potential (ODP): The emission of gases, mainly CFC-10, halon 1301, and halon 1211, is calculated and expressed in kilograms of CFC 11 equivalent.
3. Fossil fuel depletion potential (FDP): The degree of fossil fuel consumption is determined and expressed in terms of megajoules of energy surplus.

Results and discussion

In the following paragraphs, impact assessment results of the two life cycles are discussed in terms of the corresponding normalized unit for each impact category. The comparison between the life cycles and contributions of various sub-processes to these impacts are also discussed.

Global warming potential

A 100-year GWP value in kilograms of CO_2 equivalent, normalized by the functional unit of the study, i.e.,1 MJ heating value, is presented in Table 9. Results show that a saving of 18.3% in GHG emissions causing GWP can be obtained for the producer gas life cycle over coal gas life cycle. Process contributions of GHG emissions causing GWP in the two life cycles are given in Tables 10 and 11. From these tables, it is evident for the producer gas life cycle that the major contributions are from (1) steam generation, (2) coconut oil production, (3) fertilization, and (4) irrigation. Utilization of fossil fuel-based Indian electricity for steam generation and irrigation purposes is responsible for the emissions of greenhouse gases such as CO_2. The major source of potential emissions of fertilizer application is nitrogen oxides, computed according to Equation 1 [37].

$$N_2O_{\text{direct}} = \left[\sum_i m_{F,i}.\text{NC}_{F,i}\left(1 - \text{Frac}_{\text{gasf}}\right)\right] \text{EF}.\text{mw}_{N_2O}.\text{GW}_{N_2O} \quad (1)$$

where N_2O_{direct} is the direct N_2O emissions (tonne CO_2 equivalent), $m_{F,i}$ is the mass of synthetic type i fertilizer applied (tonne), $NC_{F,i}$ is the nitrogen content of synthetic

Table 8 Details of inventory data

Process/module	Data type and representativity to local conditions
Electricity generation	Primary data
	Electricity production mix is as follows: coal 70%, natural gas 12%, hydropower 15%, nuclear 2%,renewable 1%
	For each plant type, the import and domestic production of the corresponding fuel in India is accounted.
	For example, for coal power plants, the import/domestic production ratio in India is 8.5:1.5, whereas for the Ecoinvent European database, the ratio is 0.03:9.97.
	Similar modification is applied to other energy sources for a better representation of Indian conditions.
	For hydropower plants, the production capacity (kWh) is modified as the ratio between run-off river plant and reservoir plant in the ratio 0.2:0.8
Transport of coal	Modified Ecoinvent data
	For transport of fuels to a central location, the modules in the Ecoinvent database are modified incorporating the average distances by rail, road, and sea, as given in Table 5. Ecoinvent data are utilized for the development of modules for coal transport in the three countries from where coal is imported.
Infrastructure for electricity generation and transmission loss	Modified Ecoinvent data
	For the sub-process, infrastructure for electricity generation, the Ecoinvent database is modified by changing the land area required for each type of power plant for the process.
	For the sub-process transmission loss, modification is made in terms of Indian transmission loss of 35%.
Steam and compressed-air generation for gasification	Modified Ecoinvent data
	Western European data in the Ecoinvent database are modified with respect to electricity production and delivery in India.
Infrastructure for biomass gasification plant	Modified Ecoinvent data
	The Swiss database is modified with Indian electricity supply and vehicle transport (rail, lorry) suitable to Indian conditions.
Coconut shell production and crushing	Primary data
	A primary module with all the sub-modules developed based on the data corresponding to southern Indian conditions. The sub-modules include coconut plantation, irrigation, fertilization, composting, sand mix, tillage and plowing, crushing, etc. Allocation is made for crude coconut oil and coconut palm residues.

type *i* fertilizer applied (gN/100 g fertilizer), $\mathrm{Frac}_{\mathrm{gasf}}$ is the fraction that volatilizes as NH_3 and NO_X for fertilizers (dimensionless), EF is the emission factor for emissions (tonne N_2O), mw_{N_2O} is the ratio of the molecular weights of N_2O and N (tonne N_2O/tonne N), and GW_{N_2O} is the global warming potential for N_2O (kg CO_2 equivalent/kg N_2O).

The fertilizer application data given in Table 4 and inventory data provided in 'Inventory data for coconut cultivation' are incorporated. As per the equation, the direct N_2O emissions from the utilization of two nitrogen-containing fertilizers (urea and ammonium sulfate) are estimated as 0.00062 kg CO_2 equivalent for 1 MJ of syngas energy production.

For coal gas life cycle, the major emissions are caused by steam generation for gasification of coal, mining, and oceanic transport of the imported coal. The major contributing greenhouse gas to GWP is CO_2, with contributions of 95.9% and 96.2% of the total for producer gas life cycle and coal gas life cycle, respectively, as shown in Table 12. Power requirement for infrastructure and operation of the gasification plant being the same for these two life cycles, it is inferred that the decisive processes are coal mine operation and coal transport for coal gas life cycle.

The most significant contributions for coconut life cycle are from offsetting Indian electricity generation by coconut palm residues for by-product allocation. This process is favorable (GWP is negative) since fossil fuel-based electricity production is offset by the energy content (16.5 kJ/kg) of the residues, as mentioned in 'Allocation procedure'. In addition to this, allocation of the co-product (coconut oil) is also favorable since it replaces the commercial paraffin oil lubricant.

Two options are suggested for reducing the GHG emissions: (1) increasing the domestic mining capacity of coal, which will reduce the oceanic transport power requirement for importing the coal from other countries, as mentioned in 'Coal gas life cycle'; and (2) increasing the share of renewable and hydroelectric energy source contribution to electricity generation. At present, they are contributing only 16% of the total production capacity, as mentioned in 'Supporting process'. Promotion of these two energy sources, especially renewable bioenergy and small hydropower, shall result in reduction in the emissions of greenhouse gases for both the life cycles.

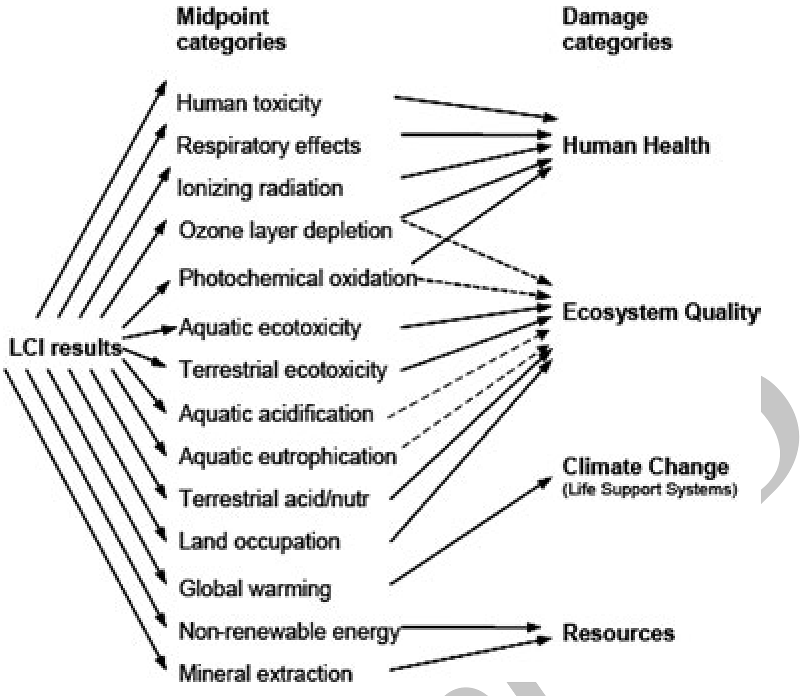

Figure 4 Overall scheme of IMPACT 2002+ framework.

Ozone layer depletion potential

Ozone layer depletion is a situation of serious concern as it will increase the amount of ultraviolet rays from the sun entering the atmosphere. The emissions of stratosphere ozone layer-depleting gases in the two life cycles are given in Table 13. The major gases responsible for the depletion of the ozone layer is CFC-10 (66.26% of ODP) for producer gas life cycle and halon 1301 (66.11% of ODP) for coal gas life cycle. The results provided in Table 9 show that ODP is reduced by 64.1% in the coconut shell-generated producer gas life cycle. The corresponding process contributions are provided in Tables 10 and 11. The by-product and co-product allocations are responsible for the reduction in ODP for producer gas life cycle, as evident from Table 10. Steam generation, fertilizer application, and irrigation are the significant contributors of ozone-depleting gas emissions for producer gas life cycle. Similarly for coal gas life cycle, in addition to steam production for gasifier operation, oceanic transport of coal (especially Australian coal for its large distance) and rail transport of domestic coal are decisive.

The major source of ozone-depleting gas emissions in both the cycles is the steam generation. The fossil fuel-based (natural gas and coal) electricity production for steam generation contributes 33% of the total ozone-depleting gas emissions. On analyzing the sub-processes, it is traced that 83% of the ODP of steam generation is attributed to the transport and storage of liquefied natural gas onshore and offshore for utilization in power plants. The liquefaction of natural gas is accomplished by cryogenic treatment, which is responsible for the emission of three gases, halon 1301, CFC 10, and CFC 114, to the atmosphere which deplete the ozone layer in the stratosphere. The remaining 17% is contributed by the utilization of diesel for the transport of hard coal to power plant locations. The diesel production stage (crude oil refining) involves many low-temperature extraction processes utilizing refrigerants, which emit ozone-depleting gases. It may also be noted that the other two major processes in producer gas life cycle are fertilizer production and irrigation, while transport of the coal through large distance (e.g., oceanic transport of

Table 9 Impact assessment of the two life cycles

Impact	Unit	Coal gas life cycle	Coconut shell-derived producer gas life cycle	Percentage of decrease for producer gas life cycle
GWP due to GHG emissions	kg CO_2 equivalent/MJ energy	0.133	0.108	18.3
Emissions causing ODP	kg CFC 11 equivalent/MJ energy	2.39E−8	8.6E−9	64.1
FDP	MJ energy surplus/MJ energy	4.19	1.4	71.5

Table 10 Process contributions for producer gas life cycle

Contributing life cycle process	GWP (kg CO_2equivalent/ MJ energy)	ODP (kg CFC 11 equivalent/ MJ energy)	FDP (MJ energy surplus/ MJ energy)
Gasification of coconut shell	1.21E−6	0	0
Electricity production and supply for gasification	6.2E−3	4.82E−10	0.0806
Steam production and supply for gasification	0.2068	8.3E−9	1.30
Compressed-air generation and supply for gasification	8.56E−3	6.64E−10	0.1116
Gasifier infrastructure establishment	8.06E−5	7.4E−12	1.15E−3
Crushing coconut in machine	4.16E−6	2.0E−12	6.58E−5
Electricity for crushing mill operation	2.45E−4	1.9E−11	3.18E−3
Crude coconut oil production (co-product allocation)	−0.098	−1.35E−9	−0.24
Fertilization machinery	2.53E−3	3.68E−10	0.04105
Irrigation	0.098	5.0E−9	0.98
Fertilizers	0.1009	1.19E−8	1.75
Coconut plantation (seedling, tillage, and compost)	2.89E−4	3.29E−11	3.6E−3
Electrical energy to main grid (by-product allocation)	−0.324	−9.46E09	−2.89
Furnace for gasifier operation	3.8E−6	2.46E−13	1.07E−4
Bed material, catalysts, etc.	1.86E−3	1.88E−10	0.034
Transport and maintenance of all the vehicle transport infrastructure	1.57E−3	2.6E−10	0.02701
Disposal of ash and sewage treatment	4.24E−5	1.006E−12	1.37E−6

the imported coal) is prominent for coal gas life cycle. The share of natural gas in electricity production and fueling (diesel) transport contributes ozone-harmful gases to these three sub-processes also.

Fossil fuel depletion potential or utilization of nonrenewable energy

Syngas produced from gasification of biomass feedstock is often cited as an effective alternative to fossil fuels, thus reducing the dependence on fossil fuel reserves. The utilization of nonrenewable energy or fossil fuel depletion potential (FDP) is expressed in megajoules of energy surplus. The FDP values for the two life cycles are shown in Table 9. The results show that a reduction of 71.5% is possible regarding fossil fuel consumption for coconut shell-produced gas life cycle, compared to coal gas life cycle. This significant reduction is attributed to two reasons: (1) utilization of renewable biomass (coconut shell) instead of fossil fuel (coal) and (2) allocation of coconut residues for offsetting fossil fuel-based power production capacity. The process contributions of both life cycles are given in Tables 10 and 11. Source-wise fossil fuel consumption is represented in Table 14 for both life cycles. The major fossil fuel is coal, with contributions of 84.96% and 77.62% for the life cycles, as shown in the table. For coal gas life cycle, the coal is utilized for electricity production (Indian electricity mix) and also as the feedstock in coal gasifier.

Contribution of life cycle stages to the impact emissions

Based on the impact values provided in Tables 10 and 11, the percentage share of major stages in the two life cycles to the impact emissions is shown in Tables 15 and 16. For producer gas life cycle, the major sources of life cycle emissions are generation of gasification agents (superheated steam and compressed air), production and utilization of synthetic fertilizers, and coconut cultivation and husbandry practices, as shown in Table 15. Utilization of fossil fuel-based electricity is used for the generation of steam and compressed air. This is responsible for the substantial share (38.97%, 32.58%, and 33.98% respectively to GWP, ODP, and FDP) of the stage (generation and supply of gasification agents) to the impacts. Nitrogen-containing fertilizer production and application is another life cycle stage which contributes 34.92%, 44.58%, and 40.52% respectively to GWP, ODP, and FDP. Considering these two factors, some improvement measures to the life cycle emissions are also discussed separately ('Sensitivity analysis').

For coal gas life cycle, the production of gasification agents and production and transport of domestic coal are the major contributors, as shown in Table 16. More than 85% of GWP and FDP is contributed by these two coal gas life cycle stages. Life cycle emissions from domestic coal production and transport dominate that of the corresponding imported coal since 85% of Indian coal is produced by domestic mining from open and underground mines, as mentioned in 'Coal gas life cycle'.

Table 11 Process contributions for coal gas life cycle

Contributing life cycle process	GWP (kg CO_2equivalent/ MJ energy)	ODP (kg CFC 11 equivalent/ MJ energy)	FDP (MJ energy surplus/ MJ energy)
Gasification of coal	1.09E−6	0	0
Electricity production and supply for gasification	5.58E−3	4.338E−10	0.07254
Steam production and supply for gasification	0.09612	7.47E−09	1.251
Compressed-air generation and supply for gasification	7.70E−3	5.976E−10	0.1004
Gasifier infrastructure establishment	7.25E−5	6.66E−12	1.04E−3
Imported coal			
Road transport	9.54E−5	1.53E−10	1.701E−3
Rail transport	1.13E−3	9.18E−10	0.021474
Electricity	5.02E−5	2.23E−11	1.152E−3
AU coal (production and ocean transport)	3.6E−3	4.482E−09	0.3092
SAf. coal (production and ocean transport)	3.29E−4	3.33E−10	0.04338
SAm. coal (production and ocean transport)	5.45E−4	6.89E−10	0.0779
Domestic coal (open mine and underground mine)			
Coal transport (road)	1.08E−3	1.735E−9	0.019278
Coal transport (rail)	6.82E−3	5.63E−9	0.130
Electricity	6.43E−4	5.04E−11	8.33E−3
Coal stock and infrastructure for mining	5.67E−3	9.34E−10	2.0898
Furnace for gasifier operation	3.42E−6	2.214E−13	9.61E−5
Bed material, catalysts, etc.	1.67E−3	1.692E−10	0.0306
Transport and maintenance of all the vehicle transport infrastructure	1.42E03	2.34E−10	0.0243
Disposal of ash and sewage treatment	4.07E−5	9.05E−13	1.23E−6

Electricity supply is a supporting process for many processes such as steam generation, fertilizer production, compressed-air production, furnace operation, crushing of coconut shell, infrastructure establishment for coal mining, etc. in the two life cycles. Fossil fuel-based electricity production is the major contributing process to the impacts for the life cycle stages mentioned. Table 17 lists the contribution of electricity production and supply to the emissions of the life cycles stages mentioned in Tables 15 and 16. From Table 17, it is evident that fossil fuel-based Indian electricity production almost completely controls the impacts from the stages coconut shell crushing (C) and gasification agent generation (D) in the producer gas life cycle. Similar is the case with stage 'C1' for the coal gas life cycle. Substantial electricity-consuming equipments such as crushing mill, boiler, and air compressor are responsible for this. It may also be noted that the emissions associated with coal transport dominates in the production and transport stage of the imported (A1) and domestic (B1) coal.

In short, it can be estimated from Tables 15 and 17 that the contribution of Indian electricity production and utilization to GWP, ODP, and FDP are 68.8%, 51.4%, and 56.3%, respectively, for the life cycle of producer gas. This is due to the fact that 82% of Indian electricity generation is a combination of coal and natural gas, as mentioned in 'Supporting process'. This fact necessitates switching over from fossil fuel-based electricity to renewable-based green electricity (discussed in 'Sensitivity analysis').

Other impact categories

In addition to the discussed impact categories of GWP, ODP, and FDP, IMPACT 2002+ links all types of LCI

Table 12 Major GHG emissions causing global warming

Producer gas life cycle			Coal gas life cycle		
Gas	GWP (kg CO_2equivalent)	% of total GWP	Gas	GWP (kg CO_2equivalent)	% of total GWP
CO_2	0.10473	95.96	CO_2	0.128	96.20
CH_4	0.00233	2.15	CH_4	0.0391	2.98
Dinitrogen monoxide	0.00062	1.52			
CO	0.0000217	0.02			

Table 13 Major gas emissions causing ozone layer depletion

Producer gas life cycle			Coal gas life cycle		
Gas	**ODP (kg CFC 11 equivalent)**	**% of total ODP**	**Gas**	**ODP (kg CFC 11 equivalent)**	**% of total ODP**
CFC 10	5.87E−9	66.26	Halon 1301	1.58E−8	66.11
Halon 1211	1.59E−9	18.49	CFC 10	5.95E−9	24.89
CFC 114	1.27E−9	14.76	Halon 1211	1.69E−9	7.10
			CFC 114	9.85E−10	1.90

results to four damage categories: human health, ecosystem quality, climatic change, and resource depletion. Under these damage categories, another eleven impact categories (brief description is provided in the Appendix) are also identified, and the life cycles are compared in terms of these categories also, as shown in Figure 5. The comparison is related to coal gas life cycle which is assumed to be having 100% impact. As evident from the figure, all the impact categories calculated show an edge for producer gas life cycle over coal gas life cycle. Major sources of the emissions responsible for these impacts are represented in Table 18. The difference in the impacts caused by these emissions is due to the contribution of electricity to the grid by coconut palm residues. This is because many of these emissions are resulting from the stack gas from fossil fuel-based power plants. The processes responsible for the emissions of these gases and ions are mentioned briefly for each of these impacts, as given below.

Carcinogenic and non-carcinogenic emission potential

The major source is the stack gas emissions from coal and natural gas power plants. Utilization of zeolite for various purposes in these plants makes carcinogenic emissions of elements like arsenic ion and PAH and non-carcinogenic emissions such as selenium. Infrastructure requirement for the power plant operation also contributes (<15%) to these emissions. However, the major emissions for coal gas life cycle are attributed to the tailing of coal in landfill from coal gasification plant (72%).

Respiratory organics emissions potential

A percentage of 91.2 of this impact is contributed by coal power plant emissions of volatile organic compounds and xylene. Emissions from the diesel-fueled vehicles and natural gas power plant emissions are also responsible for less than 8%. For coal gas life cycle, in addition to the 77% contribution from coal power plants and coal gasification plants, the oceanic freighter for coal transport is a critical entity emitting large proportions of methane and pentane.

Ionizing potential

Emission of species such as radon 222 and carbon 14 by nuclear power plants amounts to 73% of this impact. In the remaining, less than 21% is contributed by the emissions of radon 222 and cesium from coal-fired plants. Uranium enrichment process for fueling the nuclear power plant is also responsible for the emissions of radon 222.

Aquatic ecotoxicity potential

The major sources of this impact for both life cycles are the utilization of zeolite powder at natural gas and coal-fired power plants (52%), contamination of metals like Al and Cu in hot water released into the sea by the coal power plant (41%), and utilization of water for various processes in the life cycles (4%).

Terrestrial ecotoxicity potential

For producer gas life cycle, 93% of terrestrial ecotoxic emissions and 94.5% of terrestrial acidic emissions are contributed by solid waste emissions to the soil by coal-fired power plants to landfill. In the case of coal gas life cycle, the transport fuel (diesel) emissions are also responsible as its utilization is much larger than that for producer gas life cycle.

Land occupation

For producer gas life cycle, the occupation of arable land by coal power plant, hydroelectric power plant, and gasification plant share this impact in the ratio of 76%:14%:11%. However, for coal gas life cycle, land for open mines and

Table 14 Major nonrenewable energy sources causing fossil fuel depletion

Producer gas life cycle			Coal gas life cycle		
Material	**MJ energy surplus**	**% of total FDP**	**Material**	**MJ energy surplus**	**% of total FDP**
Coal	1.0867	77.62	Coal	3.56	84.96
Natural gas	0.2113	15.09	Natural gas	0.2416	5.77
Oil	0.04485	3.20	Oil	0.234	5.58
Uranium	0.0533	3.81			

Table 15 Percentage share of producer gas life cycle stages to GWP, ODP, and FDP

Stage in life cycle	Percentage contribution to the environmental impacts		
	GWP	ODP	FDP
Coconut cultivation and husbandry practices	22.73	18.32	22.25
Fertilizer production and application	34.92	44.58	40.52
Coconut shell production and crushing	0.09	0.09	0.08
Generation and supply of gasification agents	38.97	32.58	33.98
Coconut shell gasification in gasifier including infrastructure development and waste disposal	3.29	4.43	3.17

land for rail and road (for coal transport) are prominent (total 69%), leaving land utilization for power plant contributing less than 20%.

Aquatic acidification potential

The presence of sulfur-containing compounds in the stack emissions from coal-fired power plants and the nitrous oxide emissions from fertilizers for coconut cultivation are the major contributors to impact caused by aquatic acidifying emissions.

Aquatic eutrophication potential

Utilization of single super phosphate as fertilizer for coconut cultivation emits P_2O_5. For coal gas life cycle, coal tailing, emissions from coal power plant, and crude oil production are the major sources of aquatic eutrophication. In coal gas life cycle, the transport of imported coal by oceanic tanker also is a contributor since the emissions from transport fuel is very high.

Mineral extraction

Infrastructure for electricity production for each of the power plant and emissions from the utilization of zeolite powder are responsible for the extraction of minerals like Al and Cu. In addition, iron ore from mines are also responsible for the impact caused by mineral extraction for coal gas life cycle.

Energy and exergy consumption

The energy and exergy consumptions of the two life cycles in terms of renewable and nonrenewable energy sources are given in Table 19. The reason for the negative values of cumulative energy demand (CED) and cumulative exergy demand (CExD) for renewable biomass source is accounted when allocating the by-product coconut palm residues for electrical energy contribution to the main grid. Exclusion of this by-product increases the CED for producer gas life cycle to 2.3 MJ equivalents. In such case, the renewable fraction in total energy demand is 62.9%, while it is only 2.8% for coal gas life cycle. Substantial improvement in renewable fraction can be achieved by increasing the share of renewable fraction in total power production capacity of the country. To assess this, different scenarios are generated for the share of electricity production, and the results are given in Table 20. As expected, substantial increase in the renewable fraction of the cumulative energy consumption can be achieved by increasing the share of renewable energy in the Indian electric grid.

Sensitivity analysis

Sensitivity analysis is a systematic evaluation process for describing the effect of input variations in a system on the output [6]. The life cycle emissions of the producer gas are broadly divided into five contributors (A to E), as given below.

A. Coconut cultivation and husbandry practices (seedling, bed preparation, tillage, plowing, and irrigation)
B. Fertilizer production and application
C. Coconut shell production and crushing
D. Generation and supply of gasification agents (air and steam)
E. Coconut shell gasification in a gasifier including infrastructure development and waste disposal

Table 16 Percentage share of coal gas life cycle stages to GWP, ODP, and FDP

Stage in life cycle	Percentage contribution to the environmental impacts		
	GWP	ODP	FDP
Imported coal production and transport	4.33	27.62	10.86
Domestic coal production and transport	10.67	34.94	53.63
Generation and supply of gasification agents	76.12	33.76	32.25
Coal gasification in gasifier including infrastructure development and waste disposal	8.88	3.68	3.26

Table 17 Percentage share of electricity production and supply to the emissions of the life cycle stages

	Producer gas life cycle stage					Coal gas life cycle stage			
	A	**B**	**C**	**D**	**E**	**A1**	**B1**	**C1**	**D1**
GWP	57.6	26.8	93.8	99.8	1.6	2.1	29.3	93.8	1.5
ODP	61.1	17.1	98.1	99.3	2.3	0.8	7.2	98.1	2.3
FDP	63.1	19.9	99.5	99.7	7.9	0.2	0.03	99.5	7.9

A, coconut cultivation and husbandry practices; B, fertilizer production and application; C, coconut shell production and crushing; D, generation and supply of gasification agents; E, coconut shell gasification in gasifier including infrastructure development and waste disposal; A1,imported coal production and transport; B1,domestic coal production and transport; C1,generation and supply of gasification agents; D1,coal gasification in gasifier including infrastructure development and waste disposal.

Summary of GWP, ODP, and FDP of the life cycle in terms of these broad contributors (A to E) are illustrated in Figure 6 (Table 15 shows the corresponding percentage values). The contributions from by-product and co-product allocation are not represented. The existing fertilization practice (type and schedule) for coconut cultivation in the region and the utilization of gasifying agents for FB gasification of coconut shell are the major contributors to the discussed environmental impacts for the producer gas life cycle. The major reasons attributed to the higher sensitivity of these processes towards GWP are the utilization of fossil fuel-based electricity (68.8%) and the presence of nitrogen content in synthetic fertilizers (25.6%). Out of the 34.92% share of synthetic fertilizer production and utilization (Table 15) to total GWP, 26.8% is contributed by electricity from the grid (Table 17).

Scenario generation approach, which is widely used [38-40] in LCA studies for suggesting improvement options to environmental impacts, is adopted here to address the GHG emission savings. In the background of the information provided by the data presented in Tables 15 and 17, three scenarios were analyzed to account for their sensitivity on the base case GWP: (1) green electricity, (2) organic farming, and (3) catalytic gasification.

Green electricity

Complete replacement of fossil fuel-based electricity by renewable energy-based (green) electricity is not feasible in India in the near future, on behalf of the negligible current share (1%) of green electricity. Thus, generation of gasifying agents (air and steam) for gasification is taken as accomplished by energy source contribution in the following ratio: coal 50%, biomass 20%, hydropower 16%, natural gas 12%, and nuclear 2%. This means that the 20% share of fossil fuel is replaced by biomass in the Indian electric grid. A reduction of 11.1% in GHG emissions from the base case (GWP = 108 g CO_2 equivalent) was estimated. The GHG emission savings over coal gas case is 27.7%.

Organic farming

Application of synthetic fertilizers containing nitrogen emits nitrous oxides. A case in which 50% weight of synthetic fertilizers (ammonium sulfate, urea) replaced by organic fertilizers for coconut cultivation is generated. This results in improvement in GHG emissions by 5.2% from the green electricity-applied base case. The combined GWP improvement over coal gas is 31.5%.

Catalytic gasification

The lower heating value of syngas generated from steam-assisted AFB gasification of biomass ranges from 6 to 9 MJ/Nm^3 [41]. LHV depends on several factors such as design of the gasifier, temperature of steam and air, and particle size of the crushed biomass. In the present study, LHV is taken as 7 MJ/Nm^3. It was reported by Sutton et al. [42] that application of catalysts helps to improve the yield of hydrogen by 20% to 40% (depending

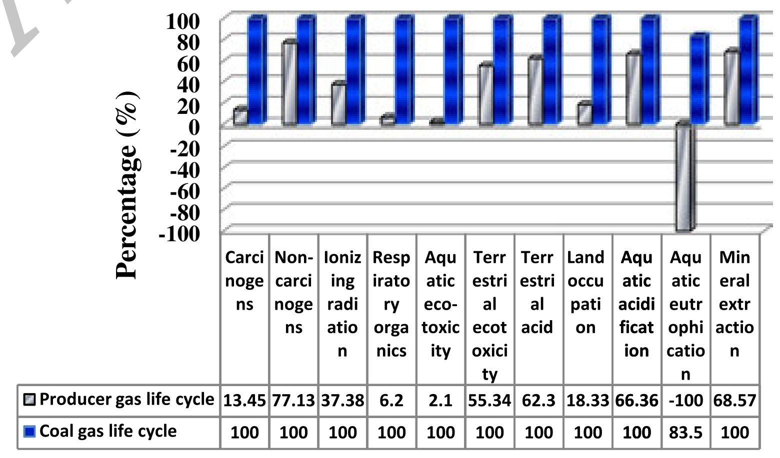

Figure 5 Percentage comparisons of the life cycles based on various emissions.

Table 18 Major emission/substances responsible for various impact categories and their contribution

Emissions	Producer gas life cycle		Coal gas life cycle	
	Emissions/substance	Percentage of total	Emissions/substance	Percentage of total
Carcinogens	Arsenic ion in water	41.46	Arsenic ion in water	62.87
	Tetrachlorodibenzene-dioxine	27.40	Aromatic hydrocarbons in air	21.41
	Aromatic hydrocarbons in air and water	25.01		
	Polyaromatic hydrocarbons	5.93		
Non-carcinogens (causing human diseases other than cancer)	Arsenic ion in water	73.16	Arsenic ion in water	63.59
	Tetrachlorodibenzene-dioxine	23.51	Selenium	13.06
			Barium	11.42
			Aluminum	5.75
			Tetrachlorodibenzene-dioxine	3.13
Ionizing radiation	Radon 222	66.96	Radon 222	76.51
	Carbon-14	26.86	Carbon-14	17.78
	Cesium −137	4.52	Cesium −137	4.97
Respiratory organics	Non-methane volatile organic compounds	26.41	Non-methane volatile organic compounds	85.50
	Xylene	46.08	Methane	3.78
	Pentane	9.47	Xylene	3.52
			Pentane	2.01
Aquatic ecotoxicity	Aluminum	97.03	Aluminum	95.03
	Copper ion	0.47	Copper ion	2.70
Terrestrial ecotoxicity	Aluminum	97.85	Aluminum	69.43
	Zinc	2.11	Copper	14.48
			Zinc	10.93
Terrestrial acid	Nitrogen oxides	76.54	Nitrogen oxides	79.61
	Sulfur dioxide	19.14	Sulfur dioxide	13.11
Land occupation	Occupation forest	40.43	Occupation forest	0.000237
	Occupation industrial area	51.43	Occupation industrial area	0.000133
Aquatic acidification	Sulfur dioxide	62.37	Sulfur dioxide	45.53
	Nitrogen oxides	31.7	Nitrogen oxides	35.24
Aquatic eutrophication	Phosphate	1.38	Phosphate	94.65
	Chemical oxygen demand	95.75	Chemical oxygen demand	4.19
Mineral extraction	Copper	79.94	Copper	79.22
	Aluminum	12.56	Aluminum	12.23

on the type of catalyst used), increasing the heating value correspondingly. Assuming a 30% improvement with catalyst application, the volume of syngas to be generated for 1 MJ of energy content (reference functional unit) could be reduced correspondingly. Incorporating this case (when all the three scenarios are implemented at the same time), 43.4% reduction in GHG emissions from the corresponding fossil coal gas case can be achieved. As reported by Singh et al. [39], this reduction in GWP ensures the sustainability of coconut shell-derived producer gas as a biofuel up to 2017, as defined by the EU renewable energy directive [43]. Figure 7 illustrates the GWP improvement accomplished under the scenarios discussed.

Comparison of the results with similar studies

Several studies reported on the comparative LCA of biofuels and their utilization systems with respect to fossil fuel-based systems. Some of the recent studies reported on LCA of biomass-derived syngas (or its utilization system) and are given in Table 21. Major relevant results drawn from these studies are also mentioned. According to Singh et al. [6], differences in approaches and assumptions taken under consideration in various LCA studies can lead to significant variations in the environmental impacts. It may be noted that direct comparison between the results is not recommended. This is because scaling of LCA balances to geographical scale may not be

Table 19 Energy and exergy consumption

Cumulative energy demand (MJ equivalent)			Cumulative exergy demand (MJ equivalent)		
Impact category	**Coal gas life cycle**	**Producer gas life cycle**	**Impact category**	**Coal gas life cycle**	**Producer gas life cycle**
Nonrenewable, fossil	4.235	1.37	Nonrenewable, fossil	4.08	1.36
Nonrenewable, nuclear	0.0632	0.0492	Nonrenewable, nuclear	0.127	0.0533
Renewable, kinetic	0.00322	0.00294	Renewable, biomass	0.00607	−1.98
Renewable, solar	0.00254	0.00248	Renewable wind, solar, geothermal	0.00595	0.0056
Renewable, potential	0.11	0.0978	Renewable, water	0.11	0.0978
Nonrenewable, primary	3.87E−7	9.12E−7			
Renewable, biomass	0.00638	−2.08			
Renewable, water	1.8	0.483			
Renewable, metals	0.00406	−0.00644			
Nonrenewable, minerals	0.00167	0.000704			

appropriate due to the variability in topography, soil and climatic conditions, and factors (economical and political) influencing land use [44,45].

Prospect of coconut shell in electrifying India

The purpose of any LCA study is to assess the system in the relevant and selected perspective, and hence, the suggestions and results hold good mostly in the selected system boundary only. The present study is applicable to India, which is the third largest coconut-producing country, behind the Philippines and Malaysia, having an area of about 1.78 million ha under the crop. Annual production is about 7,562 million nuts with an average of 5,295 nuts/ha. The state of Kerala, where the study pertains to, tops in production accounting 39% of the total production in the country. Coconut farming provides employment to nearly 10 million people and makes a contribution of nearly INR 70 billion to gross domestic product. The electricity sector in India had an installed capacity of 205.34 GW as of June 2012, the world's fifth largest [46]. In terms of fuel, coal-fired plants account for 70% (143 GW) of India's installed electricity capacity [47,48]. As per the data from the local agricultural university (as given in 'Life cycle inventory analysis'), 3.1 numbers of husked nuts are required to produce 1 kg of coconut shell. The average calorific value (LHV) of coconut shell ranges from 16.5 to 18 MJ/kg. Thus, based on the above mentioned annual production of nuts, by allocating 100% of the coconut shell for the production of power by converting it into syngas (producer gas), 40.25 to 43.9 GW of power could be produced. This is 19.6% to 21.4% of the total energy demand in the country, offsetting almost 35% to 38% of coal consumption. Careful planning and long-term policies on coconut cultivation encouragement, effective utilization of energy from coconut residues, and coconut shell gasification practice will definitely help to build an effective alternative fuel sector in India.

Conclusions

Two gaseous fuels (coconut shell-derived producer gas and coal gas) were compared in terms of their environmental impacts by conducting a LCA study with respect to Indian conditions. The environmental impacts are quantified as 18.3% lower GWP, 64.1% lower ODP, and 71.5% lower FDP, indicating better environmental performance of producer gas life cycle. In addition to this, comparisons based on several other impact categories also confirmed the edge of producer gas life cycle. Steam and compressed-air generation for gasifier operation and fertilizer production and application for coconut cultivation are the major contributors to the environmental impacts for producer gas life cycle. Substantial contribution

Table 20 Renewable fraction of CED for various electricity production scenarios

Share of total electricity production (%)					Renewable fraction of cumulative energy demand (%)	
Coal	**Natural gas**	**Hydroelectric**	**Nuclear**	**Renewable**	**Coal gas life cycle**	**Producer gas life cycle**
70	12	15	2	1	2.8	62.9
60	12	25	2	1	5.2	69.4
56	12	25	2	5	10.7	76.3
56	18	19	2	5	8.5	71.2
35	20	25	0	20	18.9	84.5

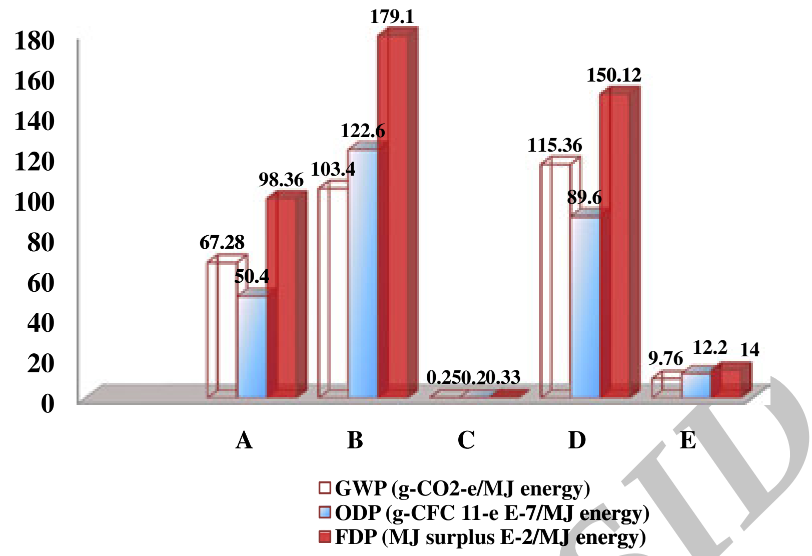

Figure 6 Major contributors to the life cycle impacts of producer gas. **A**, coconut cultivation and husbandry practices; **B**, fertilizer production and application; **C**, coconut shell production and crushing; **D**, generation and supply of gasification agents; **E**, coconut shell gasification in a gasifier including infrastructure development and waste disposal.

of the by-product allocation is the major factor responsible for lower emissions for the producer gas life cycle. Based on the existing fertilizing practice and the utilization of electricity from the Indian electric grid, substantial GHG emission savings cannot be achieved for producer gas life cycle. However, the green electricity-aided catalytic gasification of coconut shell produced by organic farming can result in 43.4% reduction in GHG emissions from fossil coal gas, meeting the EU renewable energy directive.

Appendix

Impact assessment methods and indicators

SimaPro contains several methods for the assessment of impacts of process and product stages. In these methods, multiple damage categories are taken into account, such as resource depletion, land use, climate change, and ecotoxicity. IMPACT 2002+ methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14

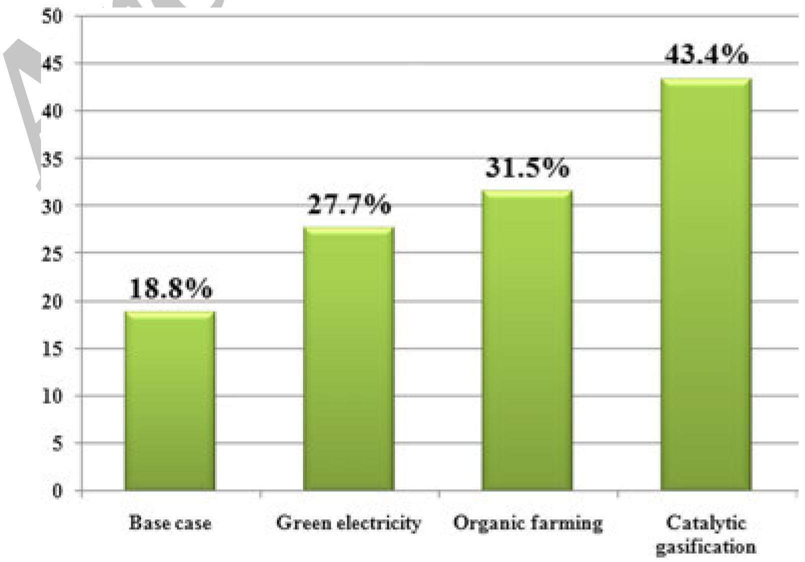

Figure 7 Percentage of GHG emission savings for producer gas life cycle under various scenarios. The scenarios are combined from left to right.

Table 21 Some recent studies on LCA of syngas generated by gasification of biomass

Criteria	Siegl et al. [1]	Roedl [14]	Guest [16]	Pa et al. [17]	Puy et al. [19]
Location	Austria	Norway	British Columbia	Barcelona metropolitan area	Sweden
Biomass material	Energy crops, manure, organic residues, wood chips	Forest residues	Wood wastes, wood pellets	Post-consumer wood, forest residues	Municipal solid waste
Reference functional unit	Kilowatt hour electricity generation in power plant which utilizes the syngas	Production of 1 MJ of thermal energy and 1 MJ of electrical energy in CHP plants	1 MJ of heat output	1,000 MJ of energy	1 ton of biomass
Impacts analyzed	GWP, ACD, TE, ET, ODP, ADP, PO, HT	GWP, PO, HT, AD	GWP, combined effect of the impact categories on human health	AD, GWP, ODP, HT, ACD, ET	AD, ACD, ET, GWP, ODP, HT, AE, TE, PO
Reference system	Anaerobic digestion power plant	Various capacity (micro, small, medium) gasification-CHP plants	Natural gas-based district heating system	Comparison between the two biomass life cycles	Sanitary land fill, incineration
Major relevant results[a]	64% to 83% reduction in GWP and 40% to 50% reduction in ODP	84% to 98% contribution of GWP from small- and medium-scale plants (for electricity)	82% and 83% reduction in GWP for wood wastes and wood pellets, respectively	34% reduction in GWP and 66% reduction in ODP for post-consumer wood biomass	3% reduction in GWP and 26% increase in ODP with respect to incineration
		59% to 72% contribution of ODP from small- and medium-scale plants (for electricity)			44% reduction in GWP and 46% reduction in ODP with respect to landfill

[a] Relevant in the context of the present study. AD, abiotic depletion potential; ACD, acidification potential; ET, eutrophication potential; GWP, global warming potential; ODP, ozone layer depletion potential; HT, human toxicity potential; AE, aquatic ecotoxicity potential; TE, terrestrial ecotoxicity potential; PO, photochemical oxidation potential; CHP, combined heat and power.

midpoint categories to four damage categories, as shown in Figure 4 [49].

For the assessment of the impact of GHG emissions, global warming potential of the greenhouse gases are expressed in terms of kilograms of CO_2 equivalent as per the IPCC fourth assessment report [50].

Ozone depletion potential values have been established mainly for hydrocarbons containing combined bromine, fluorine and chlorine, or CFCs. Here, one of the substances (CFC-11) has been adopted as the reference.

For assessment of the resource depletion using fossil fuel consumption, a term 'surplus energy' is employed in IMPACT 2002+. Mankind will always extract the best resources first, leaving the lower-quality resources for future extraction. The damage of resources will be experienced by future generations as they will have to use more effort to extract the remaining resources. This extra effort is expressed as surplus energy. Thus, fossil fuel depletion is expressed as surplus energy per extracted megajoule fossil fuel as a result of lower-quality resources.

Emission of carcinogenic substance causing human cancer is expressed as kilograms of C_2H_3Cl (vinyl chloride) equivalent. The normalization is based on the probability of the number of people from a group of 1 million who will develop cancer with the exposure to vinyl chloride. Impacts depend on the amount of the substance that will be transferred to water, air, or soil, each having different acceptable levels for the carcinogenic vinyl chloride.

Other midpoint impact categories in IMPACT 2002+ leading to the mentioned four damage categories are listed below [49] in terms of the equivalent units of known factors contributing to the corresponding impact:

1. Non-carcinogens: Human toxicity is stated in non-carcinogenic effects of equivalent mass of C_2H_3Cl (vinyl chloride).
2. Respiratory inorganics: Respiratory health effects are stated in equivalent units of inorganic particulate matter smaller than 2.5 microns.
3. Respiratory organics: Respiratory health effects are stated in equivalent mass of ethylene.
4. Ionizing radiation: Irradiating impacts are stated in equivalent units of becquerels of carbon-14.
5. Aquatic ecotoxicity: Freshwater ecotoxicity is stated in equivalent mass of triethylene glycol released into water (streams and lakes).
6. Terrestrial ecotoxicity: Land-based ecotoxicity is stated in equivalent mass of triethylene glycol released into the soil.
7. Terrestrial acidification/nitrification: Land-based acidification and nitrification are stated in equivalent mass of sulfur dioxide (SO_2) released into the air.

8. Land occupation: Units for land occupation are stated in square meters of arable land.
9. Aquatic acidification: Units are the same as for land-based acidification.
10. Aquatic eutrophication: Aquatic eutrophication is stated in equivalent mass of phosphate.
11. Mineral extraction: Mineral extraction impacts are stated in megajoules of surplus energy per kilogram of extracted substance.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

CCS conducted the life cycle assessment and drafted the manuscript. CM conducted the comparison between the life cycles, supervised the work and corrected the manuscript. AP performed the inventory collection, co-supervised the work and helped in drafting the manuscript. All authors read and approved the final manuscript.

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**Received: 6 August 2012 Accepted: 30 December 2012
Published: 11 February 2013**

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doi:10.1186/2251-6832-4-8
Cite this article as: Sreejith *et al.*: **Life cycle assessment of producer gas derived from coconut shell and its comparison with coal gas: an Indian perspective.** *International Journal of Energy and Environmental Engineering* 2013 **4**:8.