CHAPTER 3

LIFE CYCLE ASSESSMENT FRAMEWORK AND METHODS

This chapter describes the methods used in the scientific work underlying the thesis, both in general and detail. The methodological framework is of an interdisciplinary approach with focus on assessment of environmental impact and energy usage while producing biofuels. The thesis is based on the concept of system analysis in all the four studies, which states that it is not a method rather it is an approach to handle problems/or answer query from an interdisciplinary point of view [174]. A system is a set of objects connected to each other by different processes and together forming an entity in the form of the product and defined by a system boundary. There are two types of systems (i) natural system, created by nature, e.g. ecological systems and (ii) artificial system, created by humans, e.g. technical, social and economic systems. In this thesis, technical systems and their effect on environment are studied and described in Chapter 4, 5, 6 and 7. In addition to LCA, life cycle costing (LCC) of ethanol has been performed and described in greater details in Chapter 6.

3.1 LIFE CYCLE ASSESSMENT (LCA) CONCEPT

The concept of LCA was evolved in the 1960s and several efforts have been made to develop LCA methodology since then [175]. Later in 1990s a significant attention was given to LCA by individuals in environmental sciences and the concept was promoted, sponsored and adopted by the various national and international organizations such as United States Environmental Protection Agency (USEPA), European Union Renewable Energy Directive (EU RED), International Organization for Standardization (ISO) [176-181]. LCA is described in the ISO standards 14040 [182]. It is one of the several methods for calculation of environmental impacts caused by the product or any process and service. The other methods which are partly based on the LCA approach include carbon footprint [183] to calculate green house gas (GHG) emissions, standard methodology to calculate GHG emissions of biofuels as described in the RED of EU [184] or national methods such as PAS 2050 method developed especially for analysis of biofuels in UK [81]. LCA is the most recommended approach for calculating the environmental impact and certification standards of the biofuels [185-188]. LCA is based on the concept that environmental impacts not only result from the production of a product, but additionally from the upstream and downstream activities involved throughout the product life cycle. The life cycle of a product begins with the acquisition of the raw materials and ends at the disposal phase of product. Figure 3.1 shows the typical life cycle stages of any product, along with account of input and output from the process.

There is a variation in the approach of conducting LCA, varying from simplified matrix to comprehensive tool. There are different kinds of variants in LCA which are mainly classified as [189]:

- **Cradle to grave:** Assessment starting from resource extraction (cradle) to use and disposal phase of product (grave).
- **Cradle to gate:** Assessment of life cycle from resource extraction (*cradle*) to the production phase (gate of factory).
- **Cradle to cradle:** Extended form of cradle to grave LCA where end product is recycled.

- **Gate to gate:** Partial LCA analyzing only single process in the entire production chain.
- **Well to wheel:** LCA used only for analyzing transportation fuels.

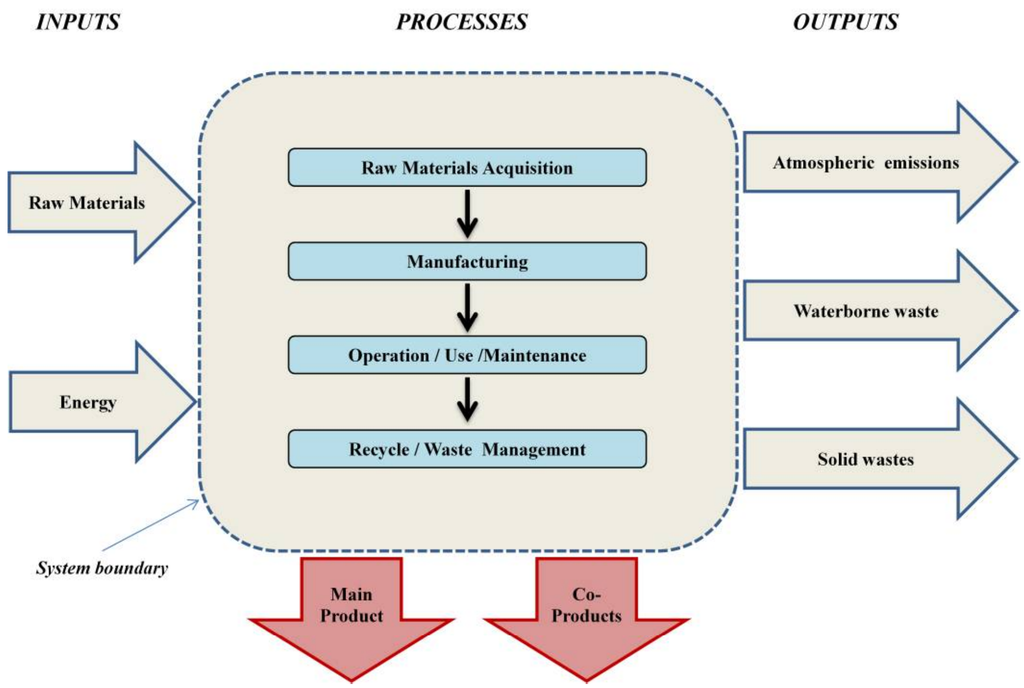

Figure 3.1 Typical life cycle of product/process [190]

3.1.1 TYPES OF LCA: ATTRIBUTIONAL OR CONSEQUENTIAL

In general there are two types of LCA, attributional LCA (ALCA) and consequential LCA (CLCA). An attributional LCA gives a description of environmental impact that are directly related to the production and use of a product [191]. Consequential LCA (CLCA) depicts what environmental effects a change in the production of a product leads to [192] [193]. The difference between these two approaches can be demonstrated clearly by a study performed by the Nuffield Council on Bioethics [194], which raised the following questions with regard to the environmental assessment of biofuel supply chains:

- ALCA: "What are the factors in biofuels production that contributes to net change in emissions?"
- CLCA: "What is the effect of emissions on a policy that promotes the production of biofuels?"

Depending on the type of LCA, different methodological choices are available and accordingly requirement of data is fulfilled. This highlights the fact that there is an element of responsibility which should be taken into consideration while choosing a method to estimate emissions from biofuels. It is recommended that biofuels are mainly certified according to an ALCA approach, because it calculates total direct emissions from a product [195], and process emissions are directly analyzed by the producer [194]. This approach is also useful for identifying opportunities and scope of improvement for reducing emission within the life cycle. Chapter 4, 5 and 6 of the thesis are based on concept of ALCA and identifies life cycle GHG emissions and energy use in production chain of 1G and 2G ethanol. The detailed research methodology used is discussed in each chapter.

A CLCA approach investigates emissions due to changes in outputs of a product, e.g. overall impacts of biofuel use are analyzed at global level both by producer and user [196]. A CLCA approach is considered to be the appropriate method for policy makers [196]. In summary, the goal and scope of a given LCA will depend on whether it is based on ALCA or CLCA and it is reasonable that the methodological approaches will vary in these different LCA [197]. Chapter 7 is related with CLCA which identifies the best utilization practice of rice straw in India from environment perspective.

3.1.2 IMPLICATIONS OF LCA

LCA has emerged an important tool for authorities, industries and individuals to assess environmental profile of product and process. Moreover, it can help policy makers to make firm and informed decision. LCA can solve the following purpose [198]

- Design and improvement of process
- Publishing product details and information
- Eco-labeling of product
- Designing and formulating policy
- Guide to investors
- Economic profile of product/process

3.2 LCA FRAMEWORK

ISO 14040 and 14044 standards defines the framework to conduct LCA in four different phases as shown in the Figure 3.2 [182]. These phases are: defining goal and scope, inventory analysis, impact assessment and interpretation. These four phases are interlinked and as a result one phase guide another phase to proceed further. The detail description of each phase is given below:

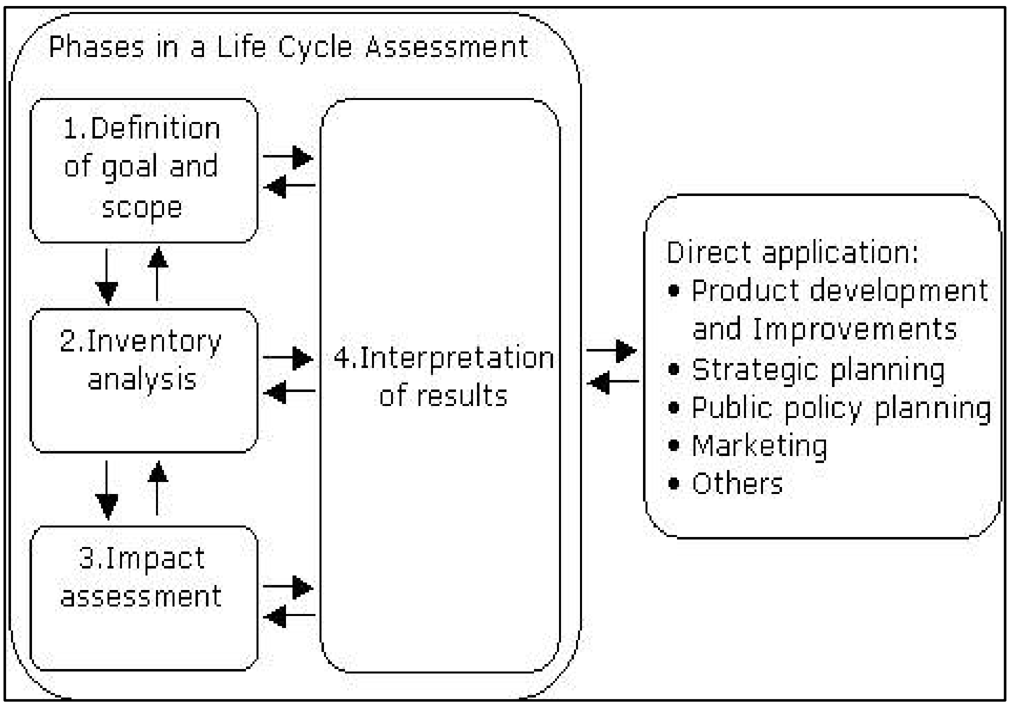

Figure 3.2 Life cycle assessment framework [198]

3.2.1 DEFINING GOAL AND SCOPE

Goal and scope definition is the first and important step in performing a LCA. This phase defines the purpose of the study, functional unit (FU), system boundaries, assumptions, allocation used in study and to whom the results need to be communicated. This is an important step as the proceeding steps are dependent on the decisions made in this phase [198]. The technical details of this phase are discussed in following paragraphs:

3.2.1.1 Functional Unit (FU)

The FU in LCA is the reference unit to which input and output flows are normalized. It is a relevant measure of the function provided by the product and should be chosen in such a way that a fair comparison between different systems can be made [182]. In LCA of energy systems, the FU is often represented in energy terms, e.g. 1MJ fuel or 1kWh electricity. The choice of FU on energy basis is the most widely used practice and represents a fair comparison based on the lower heating value of fuels [136]. Another way to compare transportation fuel could be the distance, e.g. 1 km driven by car. This FU gives a good comparison between functionality of different fuels and is recommended by some researchers. However, the results may then be dependent upon other factors too such as the type of vehicle, type of engine and the speed of vehicle apart from fuel use as such.

For a multifunctional system like biorefineries, the choice of FU must be considered with care. Since, along with main product several byproducts and co-products are also produced. This can be handled by choosing a FU related to the amount of biomass input. Another option is to use multiple FUs where production system consists of several independent sub-systems providing different functions [199].

In Chapter 4, LCA is conducted for fuel ethanol from sugarcane molasses in two different regions of India using 1 ton of ethanol as a FU. In Chapter 5, LCA of second generation ethanol from rice straw is conducted for 1 MJ ethanol as FU and comparison is made with 1 MJ gasoline. In Chapter 6, comparative analysis of modified and conventional pretreatment method is done for 1L ethanol as the FU. In Chapter 7, different rice straw utilization practices are compared based on 1 ton processing of dry rice straw.

3.2.1.2 System Boundary

The choice of system boundary is decided while defining the goal and scope of the system to be studied [199]. The system boundaries include all the technical details of system and have a major impact on the outcome of study. Therefore, a judicious decision needs to be taken in consultation with the researchers working on the process and on the basis of the literature available as the outcome of the study could give misleading results. System boundaries can also be related to geography or concerning time. LCA can be of different types and that is well defined by the system boundary e.g. it can be cradle to grave, cradle to gate, gate to gate or well to pump. Cradle to grave study as described in Chapter 4 includes all the processes from the extraction of raw materials till the end use and disposal phase of the product. However, the manufacturing of machinery used in agriculture and capital investment is not included in the studies. In systems utilizing an agricultural residue or waste as a raw material, it is recommended to exclude the agricultural phase as the waste products should not be burdened with the emissions from cultivation. Therefore, system boundary in Chapter 5, 6 and 7 starts with harvesting followed by collection, transport, processing and end use. If the aim of the study is to find the best utilization practice or production pathway for a product it is always recommended to choose a cradle to grave or cradle to gate LCA.

3.2.1.3 Allocation of Environmental Impact

Allocation refers to the division of environmental impact to main and by-product in a production system [200, 201]. Allocation is a simple, yet a critical issue in LCA, as it has a major impact on the results. The allocation can be conducted using mass, energy and economic/market price approaches. The overall results of LCA are highly sensitive based on the choice of allocation method [202]. The issue of allocation is thus of particular importance in assessing LCA of bioenergy systems [82, 83].

The ISO standard recommends avoiding allocation by using system expansion or sub-division [182]. Sub-division is rarely used as it can be applied only to those systems that consist of sub-processes that are fully independent. In system expansion, the system boundaries are expanded to include the assessment of the displaced product [174]. System expansion requires detailed inventory data on the production of the displaced product and to find such data might be a difficult task. Sometimes, the data is not available for such an alternative systems. System expansion is a good option to use in conducting LCA of bioenergy systems e.g. bio-electricity or biofuels displacing fossil electricity and fuels respectively [64]. If, however, two production pathways are compared for a single product then system expansion is not the method of choice.

If system expansion is not applicable, allocation may be based on the physical properties such as mass and energy content. The mass and energy content of a material is readily available consistent over time and can be easily interpreted [104]. The allocation by mass is not recommended in biofuel studies as there is a possibility of creating a large quantity of a low value co-product and thus attributing higher emissions to the co-product [104]. Some studies on biofuels show that allocation by energy content provides the most favorable results [82]. However, disadvantage of choosing energy content for allocation is that not everything has a similar energy content e.g. in a biorefinery system. Allocation by price is a good representative of what drives business decision-making, and it is usually assumed that price drives production, though in reality, policy may be the main driver [203]. A limitation of allocating by price is that the economic value of products is not constant and economic values do not represent the environmental dimensions of economic activity [204]. Therefore, either all allocation approach can be applied and results may be displayed as a comparative statement or a judicious decision need to be taken before applying the single approach and should be logically justified.

3.2.2 LIFE CYCLE INVENTORY (LCI)

The data used for the assessment is collected in Life Cycle Inventory (LCI). The main steps in inventory analysis include collection of data, relating data to specific unit process of system boundaries and validation of data [200]. The production systems rarely involve single producers; therefore, data may need to be collected from a number of developers and partners. The quality of data is an important parameter to be kept in mind while collecting data from the aggregated source and therefore, this phase is the most challenging in LCA.

The following stages are performed while conducting the inventory data collection:

1. *Scoping the supply chain:* the supply chain should be defined according to the system boundaries of the study determined in the goal and scope. For example, in biofuel production, this may include the cultivation of crop or may directly start with the collection in case of agricultural residue to convert into biofuels for the combustion in a vehicle.
2. *Identifying the mass and energy flow:* involves quantifying the inputs in form of material, energy and outputs in the form of product, co-product and by-product at each phase of the supply chain. This should also include an account of the condition or quality of the material at each point, such as moisture content or energy content.
3. *Identifying emission factors:* emission factors are multipliers which translate units of materials equivalent to GHG emissions and energy use.

3.2.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

It aims at associating flow of material and energy used in LCI with the environmental impact defined as Life cycle impact assessment (LCIA). In order to compare different emissions, the inventory results are assigned to different impact categories, based on their kind of impacts on the environment. The impact assessment phase establishes a relationship between the product and its impacts on the environment [182, 200]. There are numerous environmental impacts that can be monitored and evaluated but the aim of study determines selection of category. This phase consists of the following elements: classification, characterization, normalization and valuation [198]. Classification is the process of assignment and initial aggregation of LCI data into common impact groups. Characterization is the assessment of the magnitude of potential impacts of each inventory flow to its corresponding environmental impact (e.g., modeling the impacts of CO_2 and CH_4 on GWP). The LCI results within each category are compared directly using characterization factors. Normalization expresses the potential impacts in ways that can be compared. Impact categories include global effects (global warming, ozone depletion etc.); regional effects (eutrophication, acidification, photo-oxidant formation etc.) [198].

A common framework consisting 'midpoint' and 'endpoint' approach is desirable in this phase because both approaches have their specific strengths and weakness. The total impact for an environmental category is known as the 'Midpoint' result [205]. For example, greenhouse gases are placed into the category which has impact on climate change. Within this category, the greenhouse gases are weighted according to their relative effect and characterized as global warming potentials (GWP) in terms of kgCO_2eq. The total quantity of CO_2 equivalents (eq.) released due to the production of a product is the midpoint result for the environmental category GWP. For conducting LCA, various environmental categories have been identified and their associated impacts are described in Figure 3.3. However, in this thesis, the most commonly studied categories are global warming potential (GWP), eutrophication potential (EP), acidification potential (AP) and photo chemical oxidation creation potential (POCP) at midpoint level. GWP over a 100 year time horizon, expressed as kg CO_2 eq. includes the CO_2 (fossil origin), CH_4 and N_2O emissions. EP includes the impact of nitrogen and phosphorus emissions and is expressed as kgPO_4eq. The impacts of acidifying pollutants such as SO_2 and NOx emissions are measured in AP and expressed as kgSO_2eq.. The impact of NOx, CO, CH_4 and particles matter are measured in POCP and expressed as kgC_2H_4eq.. The characterization factors used in thesis to calculate GWP, EP, AP and POCP are given in Table 3.1 [198].

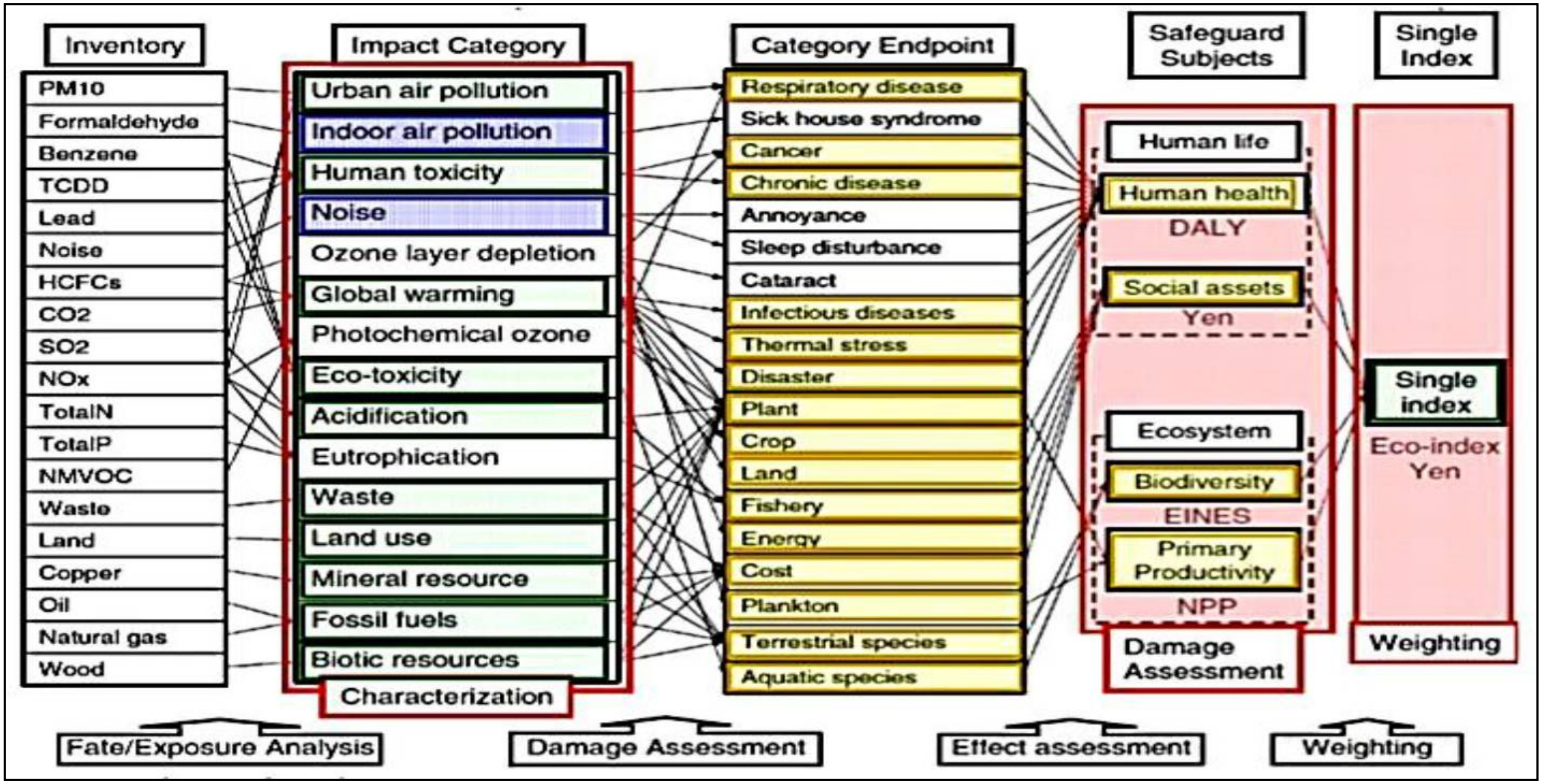

Figure 3.3 Environmental impact categories used in LCA studies [205]

Table 3.1 Characterization factors for different emissions

	GWP	EP	AP	POCP
	$kgCO_2eq.$	**$kgPO_4eq.$**	**$kgSO_2eq.$**	**$kgC_2H_2eq.$**
CO_2	1	-	-	-
CO	-	-	-	0.032
NOx	-	0.13	0.7	-
SO_2	-	-	1	-
HC	-	-	-	0.42
CH_4	25	-	-	0.007
N_2O	298	-	-	-
NO_3	-	0.1	-	-
NH_3	-	0.35	1.88	-

In the case of current renewable energy policies, the main driver has been for regulation of GHG emissions impacting the climate change globally; hence, this is the most studied impact category in the thesis. The study is therefore 'selective' as only selected environmental impacts are analyzed. In this thesis, midpoint analysis solves the purpose because the GHG emissions from biofuels are being directly compared to those of gasoline or the product displaced. Impact assessment relies on the use of emission factors of various inputs consumed during the production chain. There are databases and software's that can provide a short cut to estimate the GHG emissions from a process but the results are not representative to specific country. As in case of India, the emission factors specific to India are not available in the libraries such as Ecoinvent, GREET model, Simapro and in the literature available in the public domain. Therefore, all the studies have been performed in excel based programme so as to have emission factors specific to India.

3.2.4 LIFE CYCLE INTERPRETATION

Life cycle interpretation is a systematic technique to identify, quantify, check and evaluate information from the results of the LCI and LCIA. ISO has defined the following two objectives of life cycle interpretation [182]:

1. Analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and to report the results in a transparent manner.

2. Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with goal and scope of study.

In this section, contribution, uncertainty and sensitivity analysis is performed.

- **Contribution analysis:** Identifies the process that has greatest contribution on the impact indicator.
- **Uncertainty analysis:** Describes the variability of the LCIA data to determine the significance of the impact indicator results.
- **Sensitivity analysis:** Measures the extent that changes in the LCI results effect impact indicator results.

3.3 GENERAL RESEARCH METHODOLOGY

The key objective of a LCA study is to provide complete portrait of energy, environmental, social impacts and economic viability of the product and process. The thesis is based on assessing the energy and environmental benefits of biofuels production and use in India using LCA. The generalized research methodology used in thesis is shown in Figure 3.4.

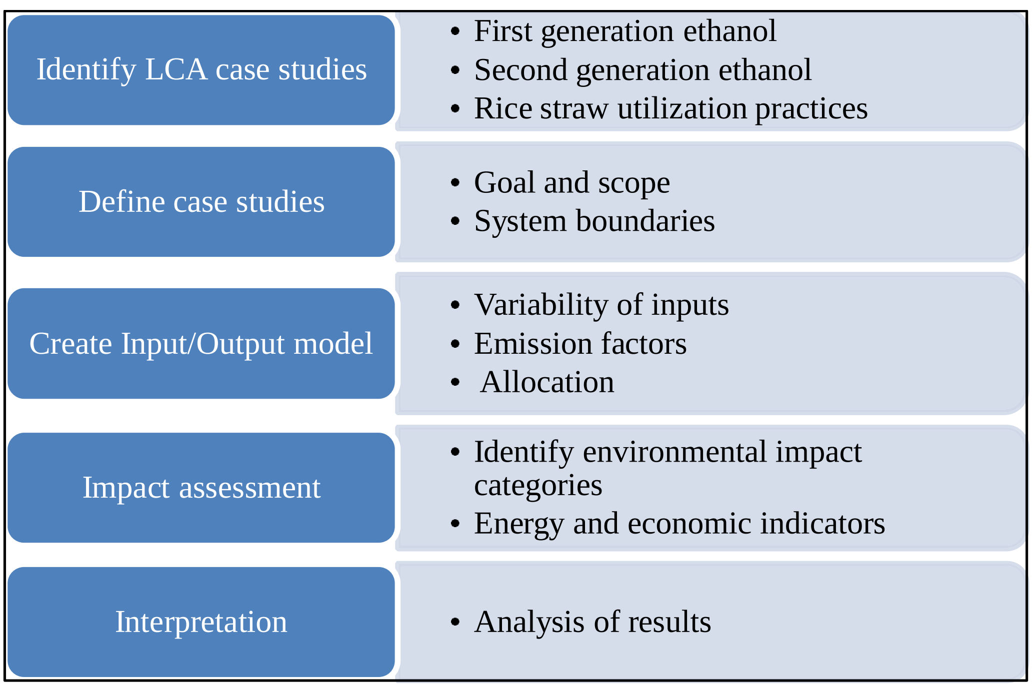

Figure 3.4 General research methodology used in thesis

LCA is used to estimate net energy consumption, GHG emissions, identify the hotspots and suggest possible recommendations to improve the production process. Economic analysis is performed only in case of second generation ethanol. Cost analysis along with the estimation of GHG emissions and energy use broadens the process of making sound decisions in commercializing cellulosic ethanol. Finally, the results are interpreted to make useful to the stakeholder, environmental activist and policy makers, which may help investor and policy makers decision to draw more investment in the bioenergy sector. The outcome of LCA studies hence, enable effective planning for a sustainable society. The novel information generated in this study would be useful to researchers, investors and policy makers which might help India compete economically and technologically in the world ethanol markets. This thesis is specific to Indian context and specific novel information generated by this thesis is as follow:

- Information on impact of regional differences on LCA of sugarcane molasses in India.
- Identified the impact of EBP on GHG emissions and energy use.
- Information on sustainability assessment of 2G ethanol in India.
- Information on methods for lowering down the cost of 2G ethanol production in India.
- Identified the environmental benefits in utilizing rice straw instead of burning