A comparative analysis of the environmental impacts of ceramic plates and biodegradable plates (made of corn starch) using the Life Cycle Assessment tool.

Major Project Report

Submitted by

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For the partial fulfillment of the

Degree of Master of Science in Environmental Studies

Submitted to:

Department of Natural Resources

TERI University

June 2008

DECLARATION

This is to certify that the work that forms the basis of the project work, “A comparative analysis of the environmental impacts of ceramic plates and biodegradable plates (made of corn starch) using the Life Cycle Assessment tool”, is original work carried out by me and has not been submitted anywhere else for the award of any degree.

I certify that all sources of information and data are fully acknowledged in the project report.

Date: May 2008

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CERTIFICATE

This is to certify that Miss Mits Broca has carried out her project in partial fulfillment for the degree of Master of Science in Environmental Studies on the topic “A comparative analysis of the environmental impacts of ceramic plates and biodegradable plates (made of corn starch) using the Life Cycle Assessment tool “ from January 2008 to May 2008. the project was carried out at School of Forestry and Environmental Studies, Yale University.

This report embodies the original work of the candidate to the best of my knowledge.

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ABSTRACT

Life Cycle Assessment (LCA) is a very powerful tool in Industrial Ecology. It is a scientific approach to identify and evaluate the environmental impacts throughout the life cycle of a process or product, right from raw material acquisition ('cradle') through production, use and disposal ('grave'). This study deals with performing a comparative LCA to compare the environmental profiles of two product systems, more specifically the plates made of ceramics and plates made of biodegradable material such as corn-starch. This project was carried out for the Yale Office of Sustainability, which was created in 2005 to facilitate the process of developing and implementing best sustainability practices at Yale. The Office wished to gain an insight into the environmental impacts of the plate ware being used at the residential college canteens so that it could recommend the use of the kind which was least damaging to the environment in the longer run. In order to help them make a well-founded choice between the alternatives, comparative LCA using SimaPro 7.1 software was performed. Developed by PRé Consultants, Netherlands; the software enables users to model and analyze complex life cycles in a systematic and transparent manner.

After defining the goal and scope of the LCA, information was gathered from various sources, and using the software, the environmental impacts of the two kinds of plates were compared. It was found that for the same functional unit, the environmental impact of ceramic plates was 5 times that of the biodegradable plates. However, a minimum number of reuses of the ceramic plate to make the associated environmental impact equal to or smaller than that associated with the single-use biodegradable plate was calculated and was found to be 50. Therefore, the choice from an environmental point of view should be in favour of reusable i.e. ceramic plates.

The limitations of the study and the assumptions made during the analysis are listed.

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LIST OF ABBREVIATIONS

LCA	Life Cycle Assessment
SETAC	The Society of Environmental Toxicology and Chemistry
ISO	International Organisation for Standardisation
PLA	Polylactide

INTRODUCTION

Life Cycle Assessment - History, Concepts and Applications

Traditionally, in attempts to reduce environmental impacts of industrial and human activities, scientists and engineers have resorted to end-of-life measures. Although clean-up technologies do reduce immediate pollution, the use of energy and chemicals and the need to further treat the wastes generated in the clean-up process often lead to additional pollution and cost to the environment. Instead of seeking solutions at a parochial scale, it is essential to adopt a systems approach to consider the whole life cycle of an activity or product. It is now widely accepted that environmentally sustainable solutions can be found only by taking a life cycle approach to environmental systems analysis (Azapagic, 2002). Life Cycle Assessment (LCA) is a very powerful tool in Industrial Ecology. It is a scientific approach to identify and evaluate the environmental impacts throughout the life cycle of a process or product, right from raw material acquisition ('cradle') through production, use and disposal ('grave').

The first LCA study was a study for Coca-Cola conducted in 1969-1970 by the Midwest Research Institute in the US (Guinee 1995; Weidema 1997; Heiskanen 2000). One of the outcomes of the study was the switch from glass to plastic bottles. Around the same time, some of the LCA pioneers began documenting their work on LCA (Boustead 1996; Hunt et al. 1996; Oberbacher et al.1996). LCA started gaining popularity in the 1990s, when it came to be realized that environmental protection should go beyond end-of-pipe strategies and emission control. In several countries, environmental authorities and policy makers started calling for product-oriented environmental strategies in industries. LCA was being viewed as an appealing instrument as it was not just product-oriented but was also quantitative, thus seemingly objective. The 1990s also saw the first scientific conferences on LCA. The Society of Environmental Toxicology and Chemistry (SETAC) is a nonprofit, worldwide professional society comprised of individuals and institutions engaged in the study, analysis and solutions of environmental problems. During early 1990s it started organizing conferences and set up a number of workgroups to develop the methodology of LCA. In parallel, industry representatives organized their own working groups on LCA. This structured approach to discussing LCA helped to establish it as an academic field of study. Guidelines for carrying out LCA studies have been published by SETAC in the 'Code of Practice'. A general methodological framework for LCA has been defined by the International Organisation for Standardisation (ISO) in its 14040 standard. (ISO, 1997). More technical requirements and recommendations for various phases of an LCA are specified in the standards ISO 14041 for goal and scope definition (ISO, 1998), ISO 14042 for life cycle impact assessment (ISO, 2000), ISO 14043 for life cycle interpretation (ISO, 2000). *Figure 1* represents the methodological framework of an LCA (ISO, 1997).

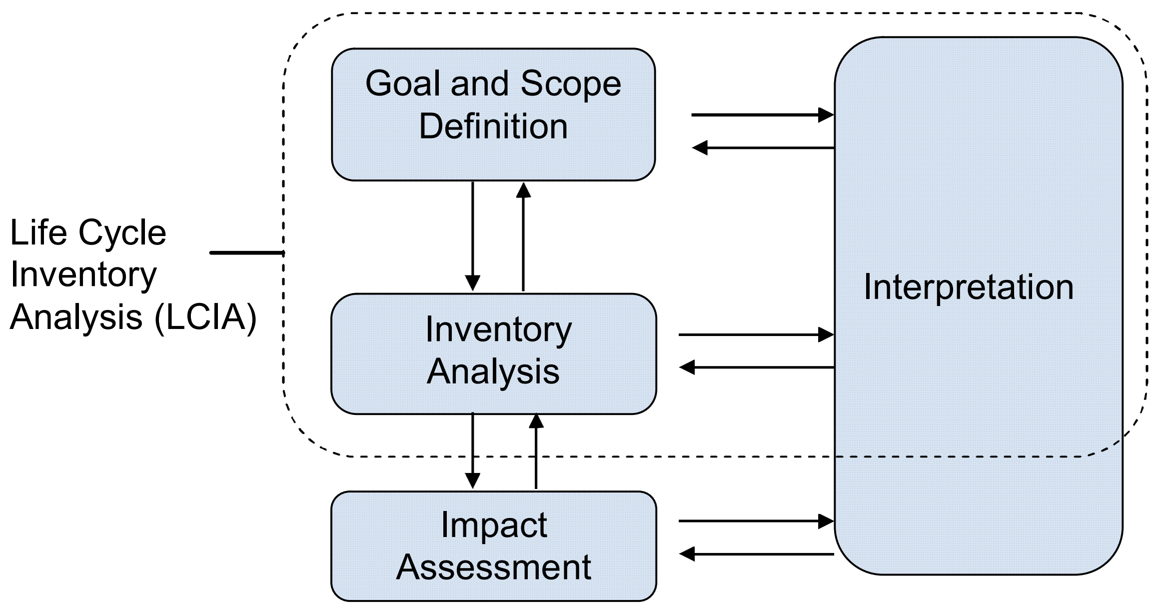

Figure 2: Methodological framework of an LCA (ISO, 1997)

According to ISO 14040 (ISO, 1997), full environmental LCA includes 4 phases:

- Goal and scope definition - the product to study and the purpose of the LCA are specified here. The functional unit[1] and the system boundaries[2] are also defined.

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[1] Functional unit represents a quantitative measure of the output of services which the system/product delivers. It is crucial that the systems are compared on the basis of this equivalent function.

- Inventory analysis - involves data collection and calculation procedures to quantify the inputs and outputs that are associated with the product systems under study.
- Impact assessment - indicates the impacts of the environmental loads quantified in the inventory analysis. Various methods are used and follow the framework[3] given below:
  - classification: assignment of inventory data to impact categories
  - characterization: calculation of category indicator results
  - normalization: calculation of magnitude of category indicator results relative to reference information
  - grouping: sorting and ranking of impact categories
  - weighting: aggregating indicator results across impact categories to a single score.
- Interpretation – identification of major impacts, evaluations of LCA findings and final recommendations.

LCAs have different applications, and according to the applications, different methodologies are used. The following *Table 1* gives some examples of requirements on methodology set by different applications.

*Table 1: Examples of how different applications have different needs for methodology**

Application	**Requirement on methodology**
Decision making, choice between alternative actions/products	Reflection of consequences of contemplated actions
Market communication, e.g. environmental product declaration	Credibility and review process require high transparency
Product development and purchasing (little time and competence of user results)	Results presented with high level of aggregation
Decisions on national level, e.g. on waste treatment strategies	Data representing national averages
Identification of improvement possibilities, own product	Site specific data

* taken from The Hitch Hiker's Guide to LCA-an orientation in the life cycle assessment methodology and application; H.Baumann, A-M.Tillman.

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[2] System boundary includes a statement of which processes will be included and to what level of detail will these processes be studied and evaluations made.
[3] Proposed by ISO 14042 and followed by Eco-indicator method.

About the project

The Office of Sustainability at Yale was created in 2005 to facilitate the process of developing and implementing best sustainability practices at Yale. One of the most important challenges towards the building of a sustainable society, is to develop production and consumption habits that are least damaging to the environment, based on efficient use of natural resources during extraction, transport, processing, use and disposal phases. Among the types of waste generated, plate ware and other containers used in canteens and at functions require major attention because of their volume and the aspects associated with their fabrication and disposal (Garrido et al. 2007).Yale University wanted to gain an insight into the environmental impacts of the plate ware being used at the residential college canteens and as a result of their use in events that take place here. The issue that needed to be looked into was whether cleaning and reusing a food plate was better for the environment than using a disposable one. In this study, the environmental impact of ceramic plates and of plates made from biodegradable material such as corn starch was compared. Some of the obvious concerns with ceramic plates were the energy intensive production process and the environmental impact during washing of the plates. On the other hand using disposable plates would just increase trash volume. Fuel consumption during the transportation of both types of plates from their production site to Yale and then to the disposal site also contributed to the environmental burden. In order to make a well-founded choice between the alternatives, a comparative Life Cycle Assessment (LCA) was done using SimaPro 7.1 software.

SimaPro 7.1 Software

This study deals with performing a comparative LCA of plates made of ceramics versus biodegradable plates and recommend the use of the one that was least damaging to the environment. SimaPro 7.1 is the specialized LCA software that was used in the analysis.

It is developed and marketed by PRé Consultants, founded in 1990, in Netherlands. PRé Consultants specializes in environmental Life Cycle Assessment solutions. It offers global consultancy and assists in assessing, improving and managing the environmental performance of products and services with the help of professional tools like SimaPro 7.1. Following the ISO 14040 series recommendations, the software enables users to model and analyze complex life cycles in a systematic and transparent manner. It includes the following features:

- Modelling of complex life cycles and complex products.
- Advanced analytical features.
- Includes inventory (LCI) database and impact assessment methods.
- Ecoinvent database included, optional for educational versions.
- Available in a range of versions (single/multi user) and in different languages like French, German, Italian, Spanish, Japanese, Swedish, Korean, Dutch and English.

Previous work done in the area

The issue of reusable versus disposable plates is an important one and has been addressed in a number of studies. Some studies suggest that to wash and reuse a container is better for the environment in the longer run than to dispose it (Eijk et al. 1992; To et al. 2006). Other studies suggest that disposables have certain environmental and public health advantages over reusables (BUWAL study, 1994; Institut Fresenius, 1990). Most of these investigations were conducted in Germany, Switzerland, Netherlands but a few have been carried out in the United States (Hunt et al. 1996; Menke et al. 1996; Owens, 1997; To et al. 2006). Many of these used the evolving methodology of LCA to provide overall environmental comparisons of certain reusable and disposable ware. Some investigations included economic issues related to packaging (Brisson, 1995; Alles et al. 1995). A review of the relevant investigations indicates that neither disposables nor reusables have a consistent environmental advantage over the other. The relative environmental impacts e.g., water use, waste water generation, air pollution, solid waste disposal and energy usage do not uniformly favour either type of plate ware in all aspects. The selection of reusable or disposable plates and containers is a complex one which should be viewed carefully. The decision should be based upon the type of foodservice establishment, geographic location, health issues and environmental factors.

OBJECTIVES

- To understand the concept of LCA and its applications; data collection, impact assessment and interpretation of LCA results using SimaPro software.
- To study the current selection of plate ware being used at cafeterias across Yale and their pattern of utilization in terms of the type and number of dishwasher runs.
- To compare the environmental impact of ceramic plates and plates made from a biodegradable material such as corn starch.
- To find the minimum number of reuse cycles, using the given dishwasher specifications, so that the impact of using ceramic plates is smaller than that of single use biodegradable plates.

METHODOLOGY

To perform the environmental evaluations and comparison of both types of plates, the SimaPro software was used. The environmental impacts during the life cycle of a reusable ceramic plate was compared with that of a single-use disposable plate made of corn starch using the LCA methodology (ISO 14040 series).

1. Goal and scope of the LCA:

Goal

a) To compare the environmental impact of ceramic plates and plates made from biodegradable material like corn starch.

b) To find the minimum number of reuse cycles so that the impact of using ceramic plates is smaller than that of single use biodegradable plates.

Scope

a) Functional unit- the number of ceramic plates that are loaded in the dishwasher at one time i.e. 2960 plates. The analysis is done for an equivalent number of biodegradable plates.

b) System boundary-The following chart depicts the phases in the life cycle of a product.

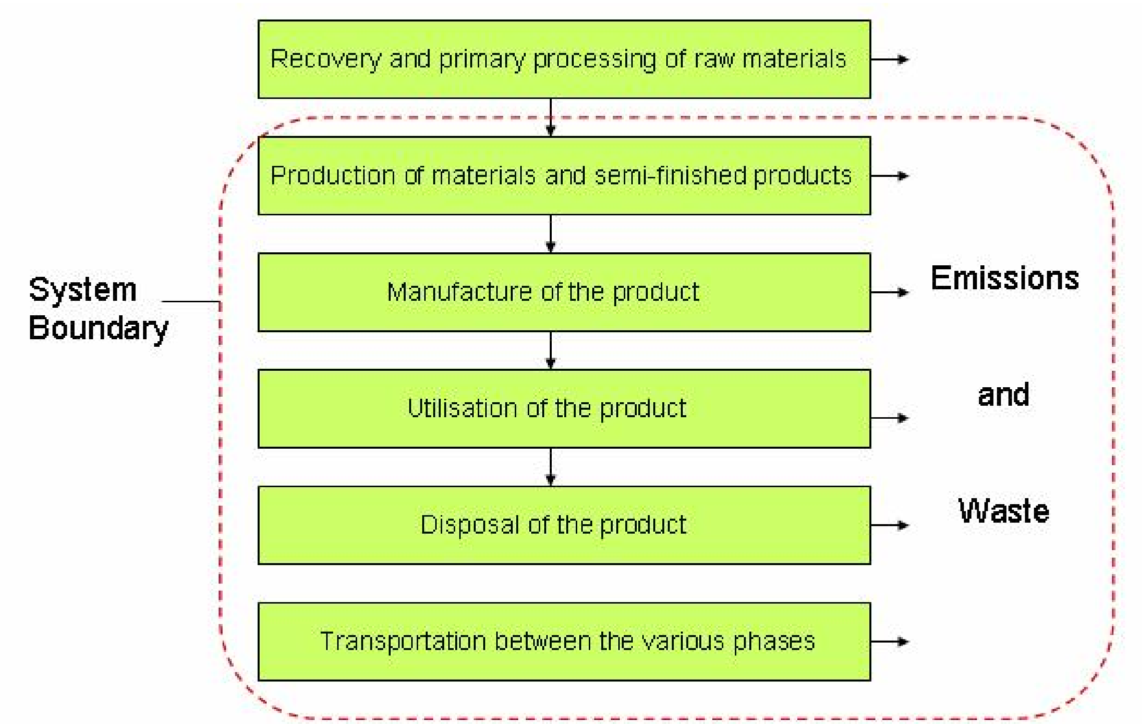


Figure 3: Life cycle of a product

- In *Figure 2*, the stages within the dotted line are included in the system boundary. This study does not consider the environmental impacts associated with the recovery and primary processing of the raw materials. The transportation of raw materials to the site of manufacture is also excluded from the study.
- Accidental pollution and environmental impacts caused by personnel at the site of production are neglected.
- The consumption of water for washing the reusable plates is taken into account together with the impact of the detergent.

Details of the specific stages involved in the manufacture of the ceramic plate and the biodegradable plate are given in the Observation section, (point 2)

2. Inventory Analysis:

- Data needed in order to meet the goal of the study was identified and the level of detail decided.
- All the relevant input (consumption of energy and raw materials) and output (emissions to air, water, soil) data was gathered.
- To gather the required data, the following procedures were applied:

  Inquiry: Manufacturers of plates, suppliers, event organizers, waste collection and waste treatment organizations were contacted. Data was collected based on telephonic and personal interviews. For the ceramic plates, data collection began with contacting Yale Procurement division and getting details of the suppliers of ceramic plate ware to Yale. Interviews were conducted with the Yale Dining Services and Caterers and necessary information was extracted. Discussions with concerned people led to the identification of the manufactures who were contacted for detailed information. Data regarding main stages and methods of production of plates, raw material acquisition, amount of fuel, energy and water consumption required during various stages of manufacture, amounts of wastes and emissions associated with production was collected from concerned departments. Dining halls all over the campus were visited and the pattern of use of plates was observed. Companies manufacturing biodegradable plates were contacted. The manufacturing processes involved in the making of corn starch plates were thoroughly studied and detailed discussions and clarifications with officials held to gather company specific data.

  - Simultaneously literature sources discussing similar issues were reviewed.

  - For aspects where no specific or published data was available, assumptions were made based on well-founded arguments. Details of the data and the sources are listed in Chapter 4, Observation section. A list of all organizations and people approached for the information is included in Annexure 4.

- Life cycle inventory was prepared in the software by feeding in the data step wise carefully, verifying and checking at each stage for errors. Databases in the software were studied and relevant data was filtered and added to the inventor

3. Impact assessment:

The Eco-Indicator 99 methodology was used in this study. This method is one of the more scientifically sound and accepted methods as it allows expressing the environmental burden of a product system as one aggregate figure. The pre-calculated set of indicator values can be used as a quick tool to gauge the broad environmental performance of a product. This is essentially used for internal use in companies and is not suitable to use in public comparisons, marketing and ecolabelling as it lacks the necessary transparency.

4. Interpretation of results:

The results generated by the software were carefully studied and interpreted. The environmental impact of ceramic plates and plates made from biodegradable material like corn starch. The minimum number of reuse cycles was calculated so that the impact of using ceramic plates is smaller than that of single use biodegradable plates.

OBSERVATION AND ANALYSIS

1. Current selection of plate ware being used at cafeterias across Yale:

Cafeterias across Yale largely used porcelain plates. Yale dining services also used china for most of their events. The plates were manufactured in Syracuse, New York, and purchased from suppliers at Bridgeport, Connecticut. Several types of dishwashers were used across the campus. Therefore, an average machine type, rated 148 racks per hour capacity, was considered in this analysis. Yale procurement recently contacted suppliers of biodegradable plate ware. There was no composting facility present at Yale. The closest incinerator was at Bridgeport, 27.353 km from the campus at New Haven.

2. Details of the specific stages involved in the manufacture of the ceramic plate and the biodegradable plate:

Figure 3 is a diagram of the various stages of the life cycle of porcelain plates.

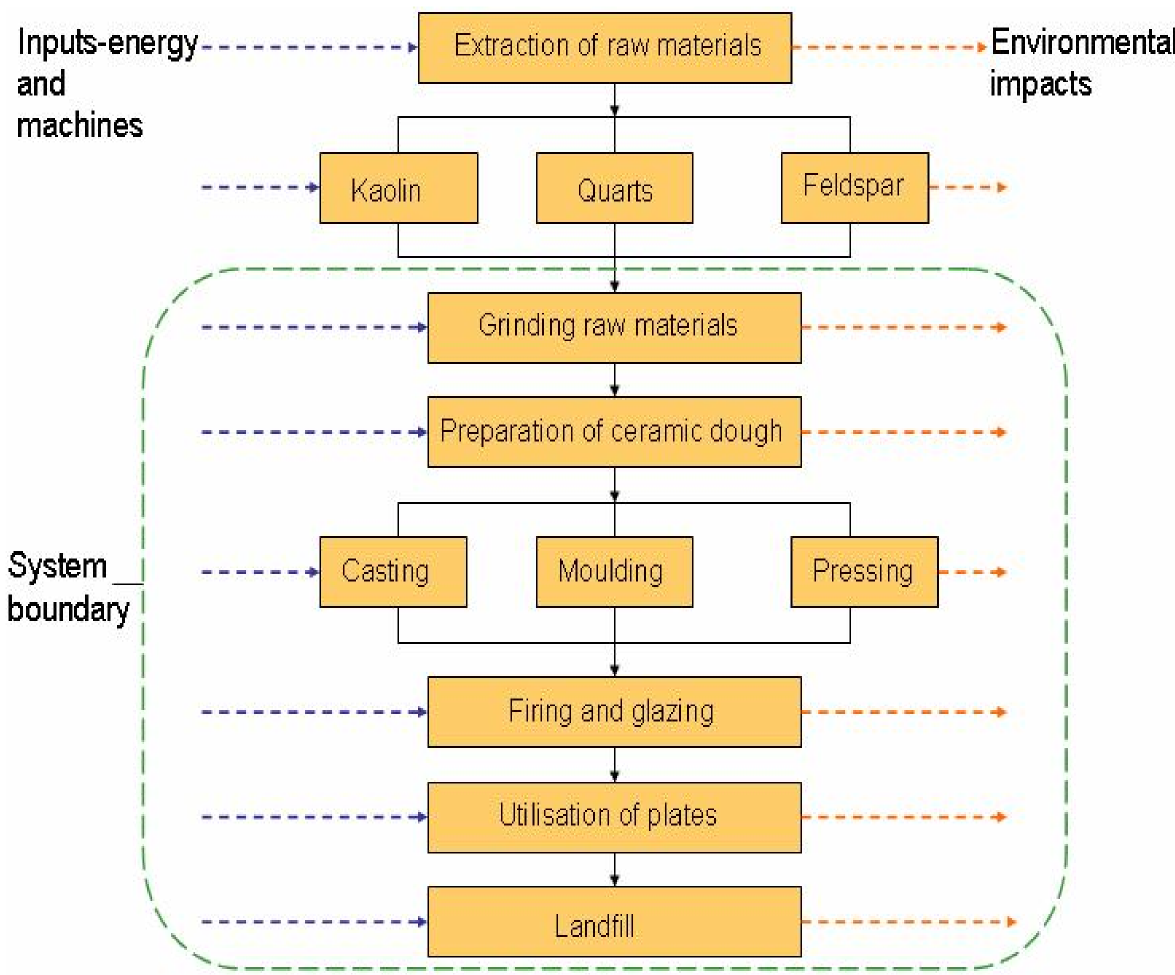
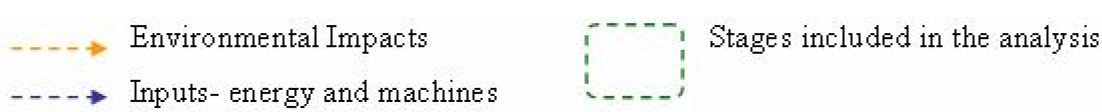


Figure 4: Stages in the Life cycle of Ceramic Plates



As the recovery of raw materials (which in this case were kaolin, feldspar and quartz) was not included in the system boundary, the analysis begins with the preparation of the dough at the manufacturing site at Syracuse, New York. The ground clay minerals were mixed with water to prepare the dough. The dough was then subjected to casting, moulding and pressing using machines. It was then fired in a kiln at 1260˚C. This porous porcelain, (referred to as biscuit) after cooling, was given a coat of glaze by spraying. The glazed biscuit was fired once again in the kiln. The finished plates were then packed in corrugated cardboard boxes and transported to the suppliers at Bridgeport through trucks. The inputs and the emissions generated at every stage are listed in *Annexure 1.* With regard to the utilization phase of ceramic plates, the amount of water used in one wash cycle, energy requirement and impact of using detergents is taken into account. Details of the dishwasher and information concerning the environmental impact during the utilization phase are given in *Table A5* of *Annexure 1.*

Ceramic ware is usually discarded when it is damaged to such an extent that it can no longer be used. As ceramic plates are subjected to very high temperatures while firing and glazing, they are heat resistant. Therefore, few or no emissions occur when they are dumped in an incinerator. The plates are eventually removed from the incinerator and dumped in the landfill. In this study, it was assumed that the ceramic plates were dumped in the closest landfill.

3. Cataloguing the environmental impacts of ceramic plates at different stages:

- In Annexure 1, *Tables A1, A2, A3, A4, A5, A6* list the raw material consumption, energy consumption and emissions to air and water during- the preparation of ceramic dough; casting, moulding and pressing; firing of plates; packaging and transportation; utilization of plates and disposal of plates respectively.
- Raw materials kaolitite, feldspar and quartz were mixed in the ratio 2:1:1 to prepare the raw mixture (Eijk et al 1992).
- Casting, moulding, pressing stage accounted for 78% of the total electricity consumption and 22% of heat requirement, while firing and drying accounted for 22% of total electricity consumption and 78% of heat requirement. (To et al, 2006).
- Approximately 1050ml of water was consumed to create a 9"commercial dinner plate. (interview with engineers at the manufacturing site, Syracuse, New York)

- Firing and drying processes caused approximately 78% of the emissions to air, the rest caused during casting, moulding and pressing. (To et al, 2006)
- Emissions to water were attributed to the casting, molding and pressing stages (To et al, 2006)
- One corrugated cardboard case fitted a pack of 12 plates. (interview with Yale University Dining Services)
- It was assumed that the type of transport used for delivery of both types of plates is the same.
- It was assumed that the racks of the dishwasher were stacked only with plates and no other crockery for ease in calculations.

Figure 4 is a diagram of the various stages of the life cycle of biodegradable plates (made of corn starch).

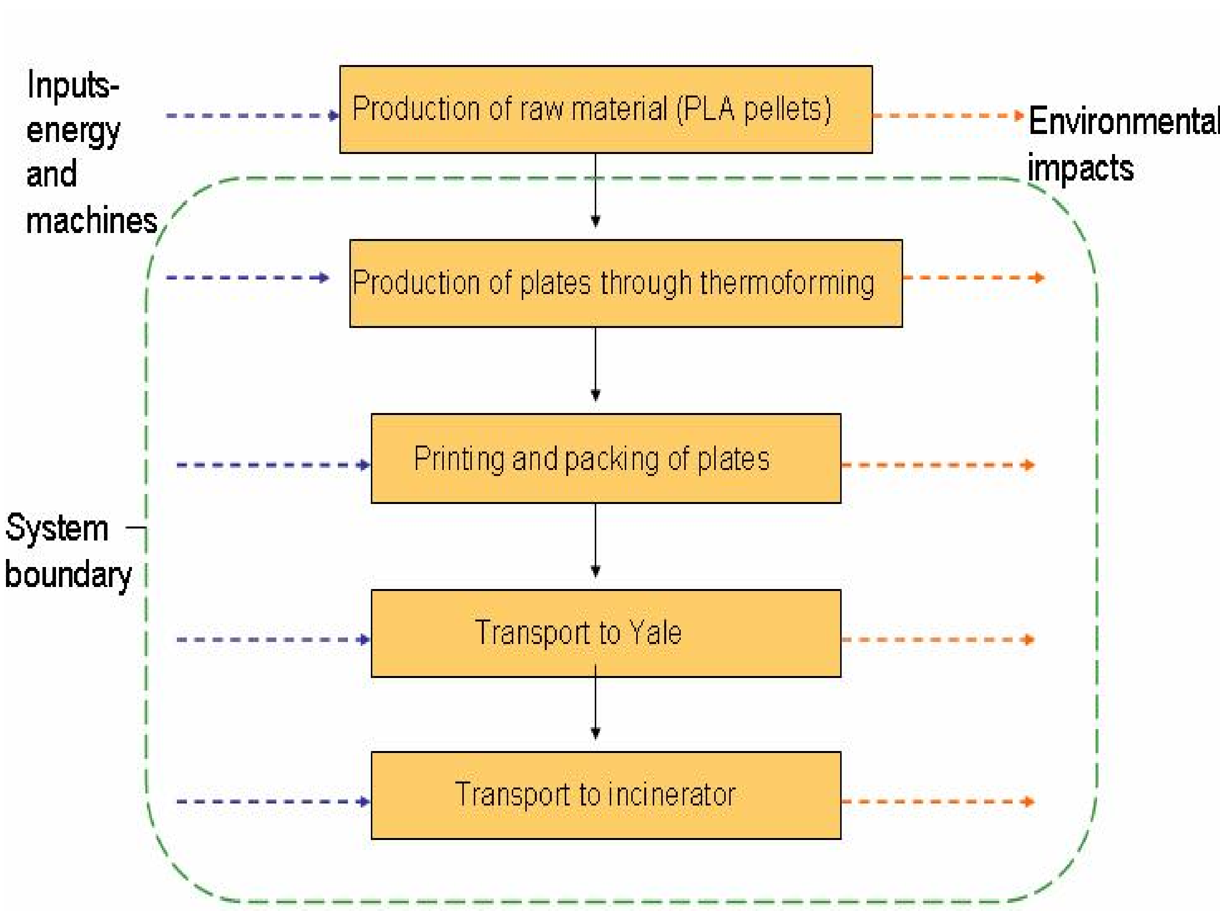
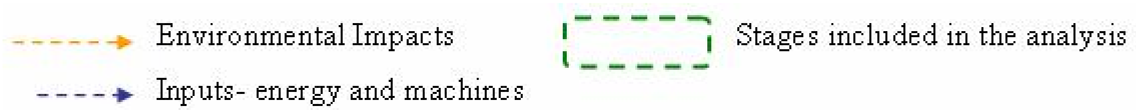


Figure 5: Stages in the Life cycle of PLA plates



The production process of PLA (polylactide) starts with corn. The starch after being separated was subjected to a number of fermentation and polymerization reactions. The preparation of PLA pellets was not included in this study. The starting point for this study was the production of plates using the PLA pellets. The PLA production facility and the manufacturing site for the plates were located near Blair Nebraska. The plates were produced by means of thermoforming.[4] They were then printed, packed in a polyethylene film and transported in cardboard boxes. In this study, it was assumed that these plates were being transported to Yale University campus and the associated environmental impacts of introducing such plates in the cafeterias were studied. (In case the University decides to do so in the near future). The environmental profiles of ceramic plates and biodegradable plates were compared so that an informed choice could be made between using reusable or biodegradable plate ware. There was no composting facility at Yale currently. So the plates would be burnt at the closest incinerator located at Bridgeport, Connecticut.

4. Cataloguing the environmental impacts of corn-starch plates at different stages:

- In Annexure 2, *tables A1, A2* list the raw material consumption, energy consumption and emissions to air and water during- the production of corn-starch plates from PLA pellets, and the manufacture and transport of finished plates to Yale.
- Mix of company specific and SimaPro 7.1 data was used.
- 238.109g of PLA waste was produced during the thermoforming process in the manufacture of 2960 plates. (Vaes, 2006).

[4] Thermoforming: The PLA sheet or film is heated between natural gas heaters to its forming temperature. Then it is stretched over or into a temperature-controlled, single-surface mold. The sheet is held against the mold surface unit until cooled. The formed part is then trimmed from the sheet.

- 500 corn-starch plates, wrapped in polyethylene film (0.1562 kg), packed in a corrugated carton would be transported to Yale. (company specific data; Vaes, 2006)
- It was assumed that the type of transport used for delivery of both types of plates is the same.
- Since there was no composting facility at present, used plates would be collected and transported to the nearest incinerator.

5. Analyses:

The data collected was fed into the software to generate results. The various outputs have been discussed step wise in this section:

1. Generation of Life cycle flowcharts of ceramic plates and corn starch plates:
Products were defined in a so called assembly. An assembly contained the list of materials and production processes, as well as transport processes. Assemblies did not contain environmental data. The assemblies were then linked to the use and the waste disposal scenarios to generate the entire life cycle of the product. Using the Eco-indicator 99 impact assessment methodology, the environmental impacts got linked to each process and were represented in the flowchart as small red thermometers showing the contribution of each process to the total environmental impact score. *Figure 5* represents the life cycle of ceramic plates that was generated using the SimaPro 7.1 software.

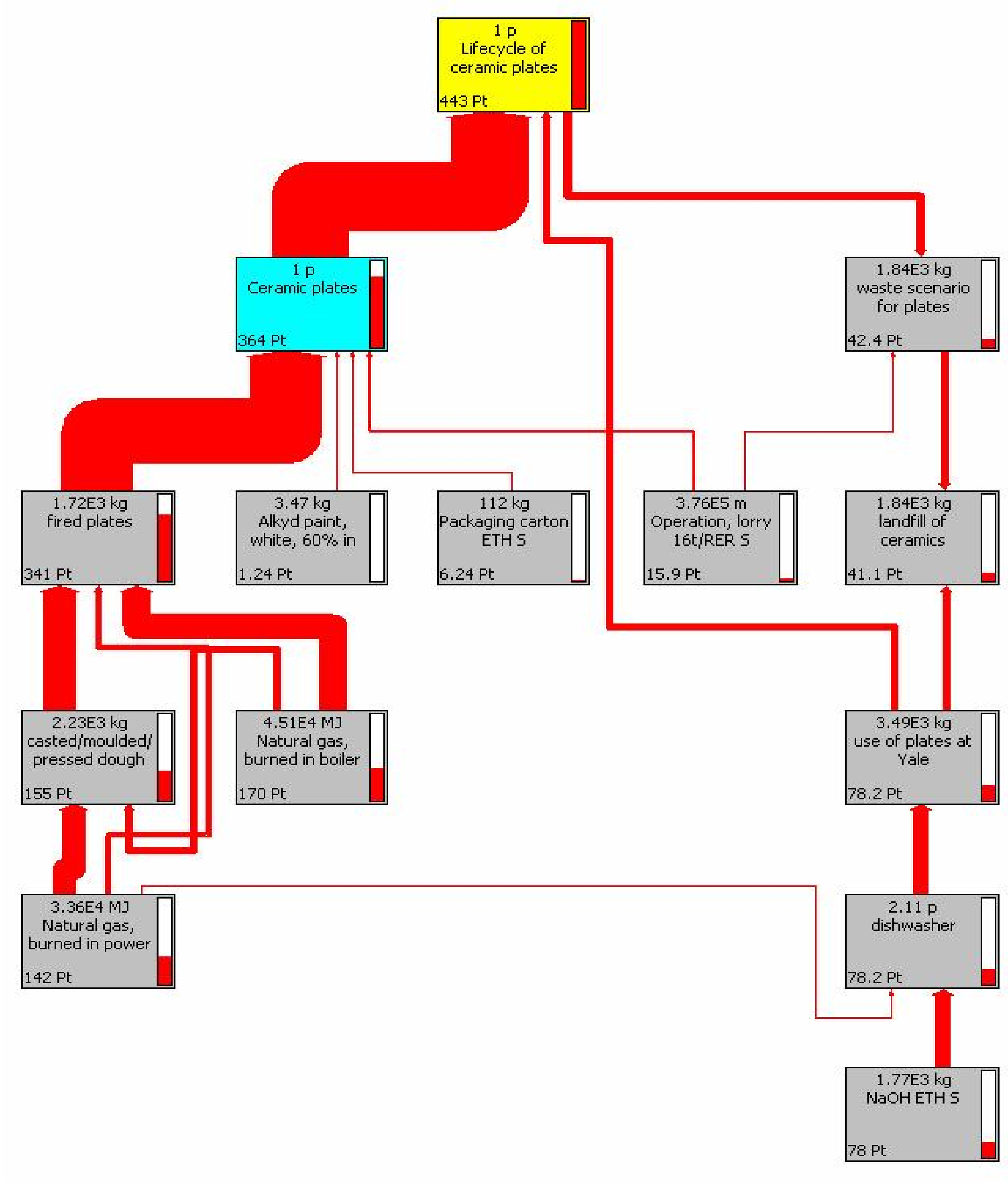


Figure 6: Life cycle of ceramic plates

As the flowchart clearly shows, the firing stage contributes the most to the environmental impact in the life cycle of ceramic plates (~82% of the total). The energy consumption required for the preparation of ceramic plates is largely determined by the amount of gas and electricity required to fire the crockery. *Figure 6* represents the life cycle of biodegradable plates made from corn-starch that was generated using the SimaPro 7.1 software.

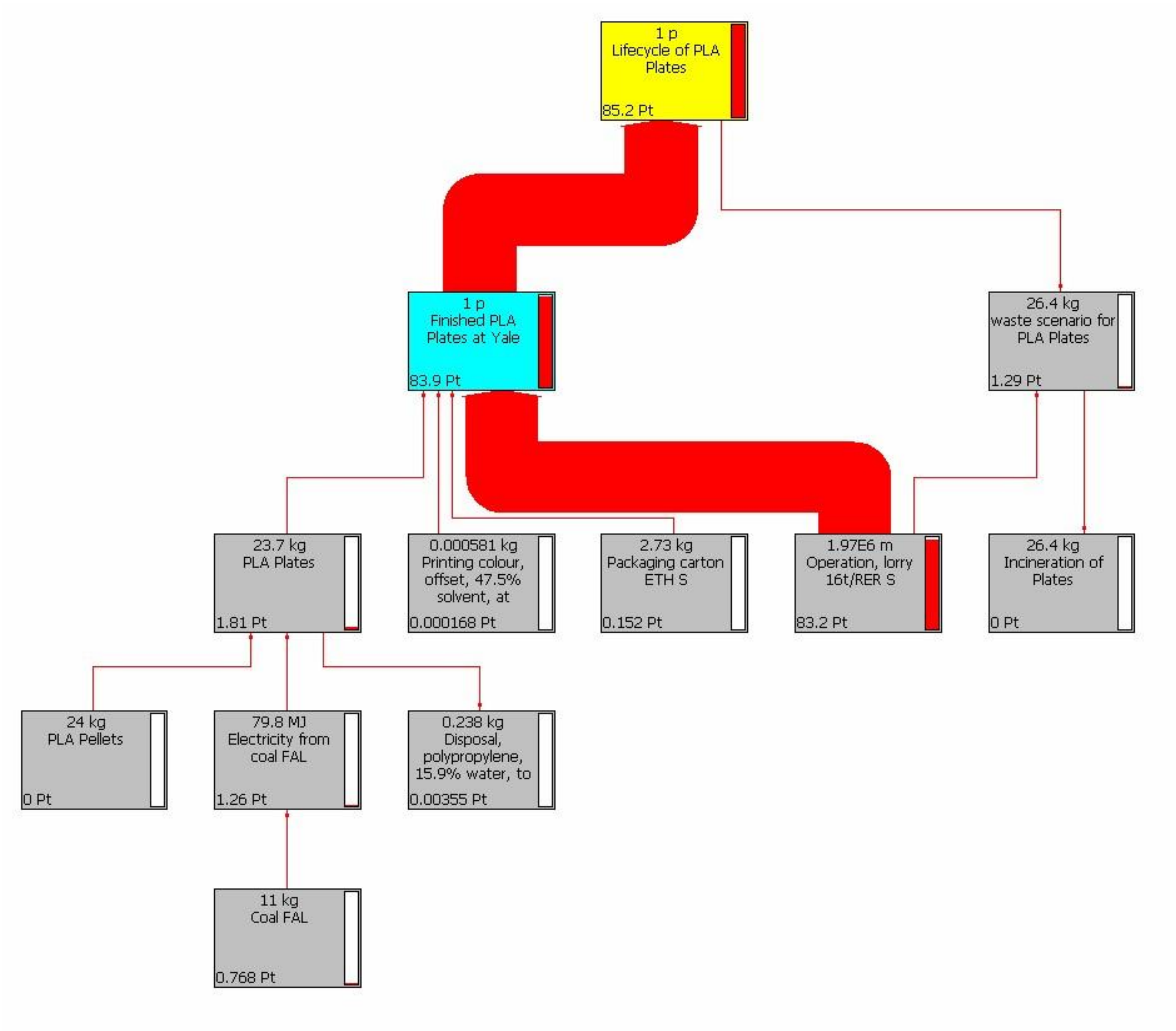


Figure 7: Life cycle of biodegradable plates made of corn-starch

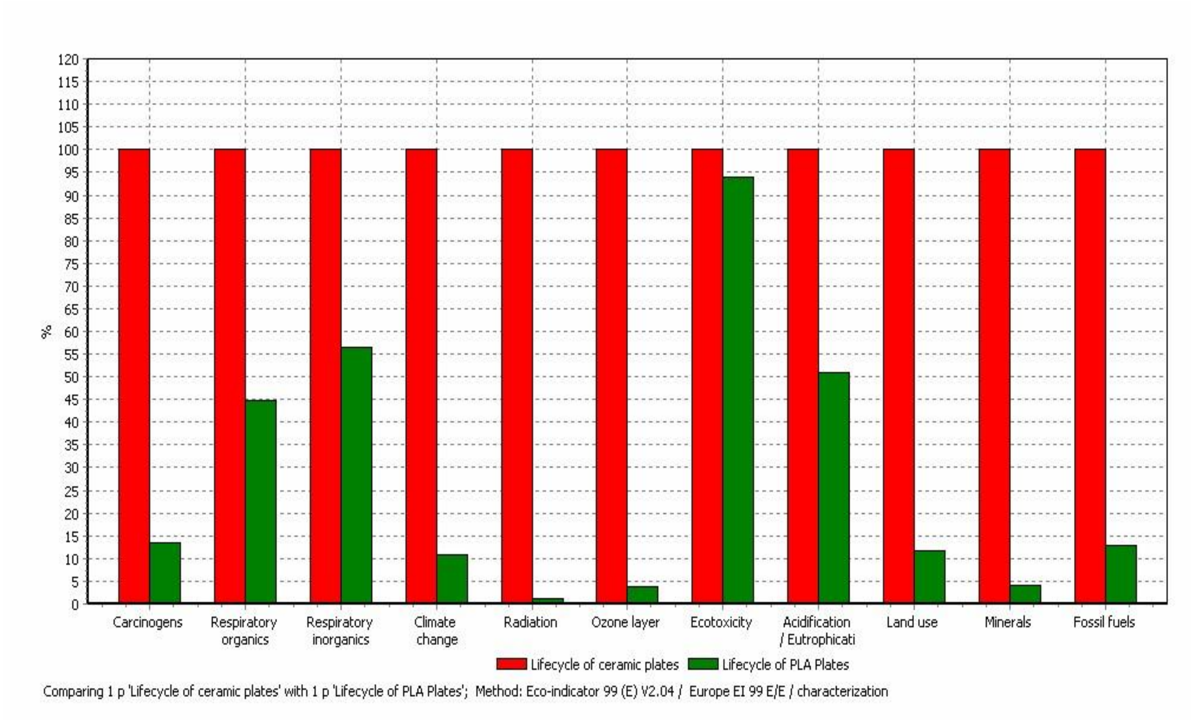
In the life cycle of Plates made of corn-starch, transportation clearly appears top have the most significant influence on the total environmental impact (~97%).

The Graphs in Annexure 3 depicted environmental impacts of ceramic plates and PLA plates separately. The contribution of each stage in their respective life cycles was also reflected in the graphs.

2. Comparison of the environmental impacts of ceramic plates and biodegradable plates made of corn-starch.

Characterization:

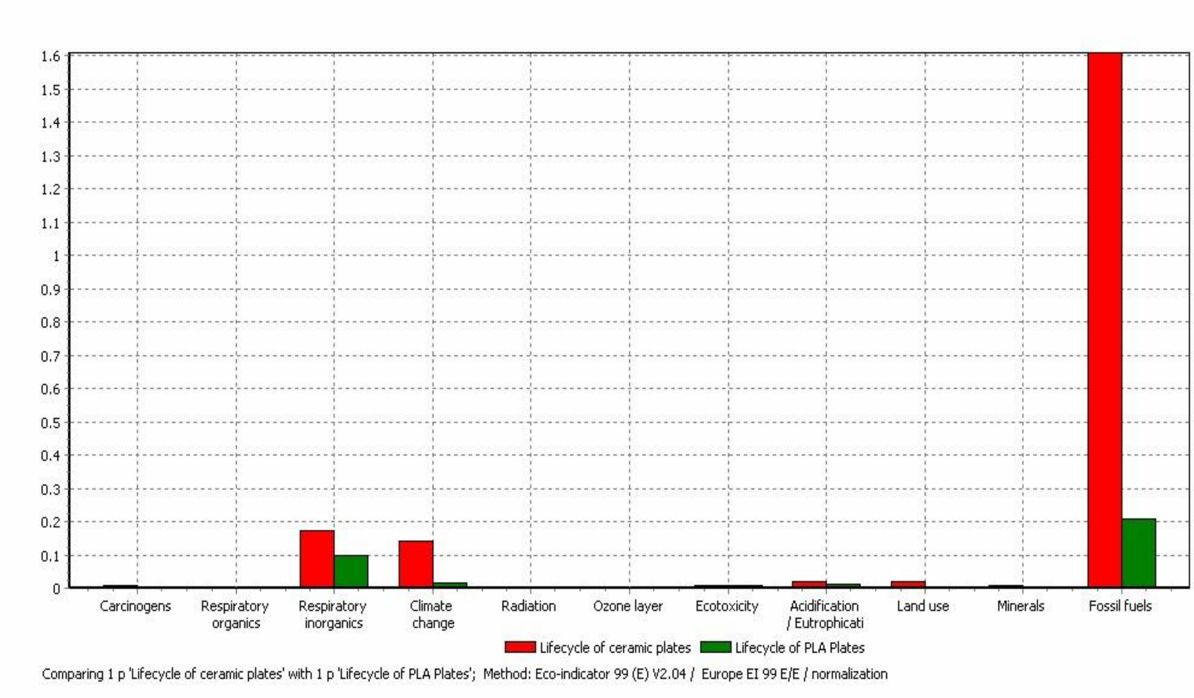
Using the Eco-indicator 99 methodology, the environmental impacts were calculated from the inventory results and categorised into various classes e.g. carcinogens, respiratory organics and inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, fossil fuels. Taking into consideration the entire life cycle of both types of plates, *graph 1* was obtained in which the contribution (in percentage) to every impact category of each plate could be seen. It was observed that the magnitude of environmental impacts of ceramic plates was greater than that of biodegradable plates across all impact categories.



Graph 1: Damage categories and comparison of environmental impacts of ceramic plates and biodegradable plates made of corn-starch

Normalization and Weighting:

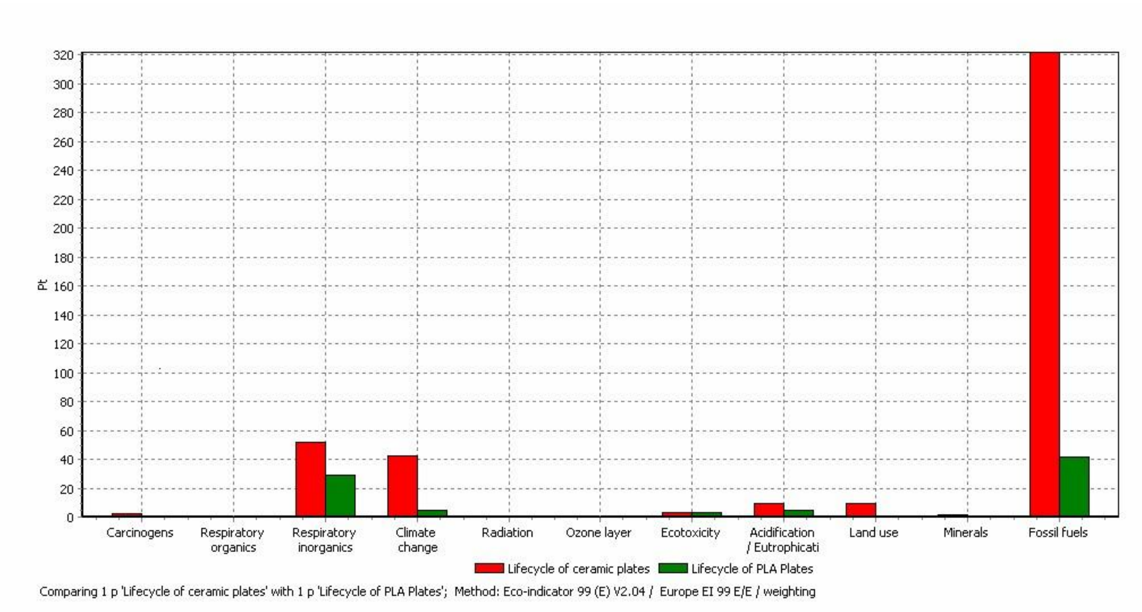
The relative contribution of the calculated damages to the total damage caused was determined in normalization. Eco-indicator 99 normalised the results using a unifying parameter, which was, the environmental effect caused by one European person in one year. Therefore, normalization revealed which effects were large or small in relative terms. To study the relative importance of these effects, the normalised data was weighted using internal weighting factors of the methodology used. *Graph 2* was obtained in the normalization stage and depicted that the most significant impact categories were those due to the consumption of fossil fuels, climate change and effects of respiratory inorganics.



Graph 2: Comparison of normalization of the LCA for the ceramic and PLA plates

Graph 3, which was obtained for weighting of the LCA of both plates, brought out the same observation that the most severe damage category was the depletion of fossil fuel resources and its associated impacts. The consumption of fossil fuels during the life cycle of ceramic plates was approximately 8 times more than that of the biodegradable plates.

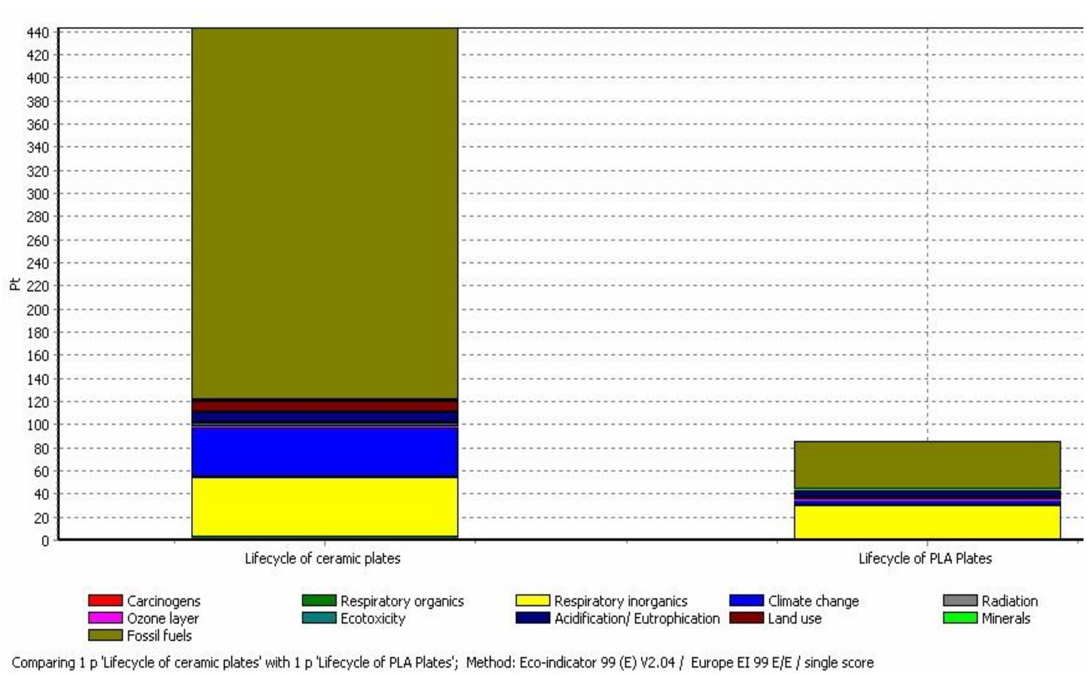
(for the processes included in the system boundary).



Graph 3: Comparison of weighting of the LCA for the ceramic and PLA plates

Single score:

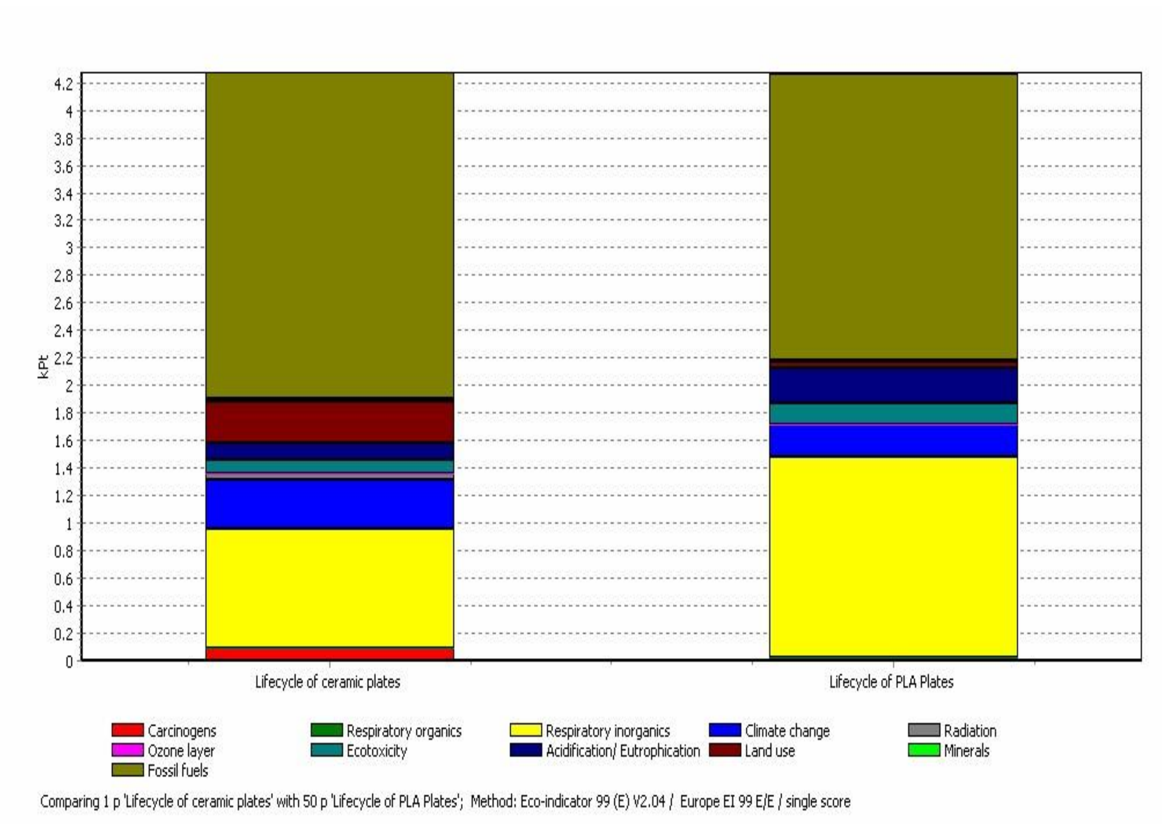
In the last stage, the software was used to add up all the weighted sores to give a total, single impact score for each product. *Graph 4* was thus generated.



Graph 4: Single score graph comparing the overall impact of both plates.

3. Calculation of minimum number of reuse cycles, using the given dishwasher specifications, so that the impact of using ceramic plates is smaller than that of single use biodegradable plates:

When the reuse cycles of ceramic plates was increased by 50 times, the environmental impact was almost the same as that caused by the manufacture, use and disposal of 50 biodegradable plates. With each use of the ceramic plate, the impact due to the washing of the plate in the dishwasher was doubled (assuming that the plate was washed after each use). *Graph 5* thus obtained depicted this break-even number.



Graph 5: Comparison of environmental impacts of a ceramic plate reused 50 times and 50 biodegradable plates (single score graph)

CONCLUSION

Major findings:

After analyzing the life cycles of ceramic plates and biodegradable plates made of corn-starch, the following conclusions stood out as most important.

- For the same functional unit, the environmental impact of ceramic plates was 5 times that of the biodegradable plates (from the single score graph).
- The most severe damage category was the depletion of fossil fuel resources. The consumption of fossil fuels during the life cycle of ceramic plates was approximately 8 times more than that of the biodegradable plates.
- The minimum number of reuses of the ceramic plate to make the associated environmental impact equal to or smaller than that associated with the single-use biodegradable plate was found to be 50. As the number of uses of the plate increased, the environmental impact decreased.

Recommendations:

- From the environmental point of view, each ceramic plate must be used at least 50 times to have less impact than a single use biodegradable plate.
- PLA fibers degrade at high temperatures and must be collected and composted in a well designed compost facility, which currently does not exist at Yale University campus. Therefore, the advantages of plates made of corn starch are not dramatic enough to recommend them as a replacement for the plates that are currently being used, i.e. ceramic plates.

Limitations of the study:

- Life cycle assessments, being extremely comprehensive studies require detailed technical information regarding the energy and raw material consumption at every stage along with the associated emissions to air, water and soil. If the system boundary is not clearly defined then conducting an LCA becomes highly complicated and problematic as gathering data can become an unending task.

- The impact assessment methodology used (Eco-indicator), reflects European standards. Emissions and damages are assumed to occur within Europe except those that occur on a global scale. The normalization and weighting factors are also Europe based.
- Data collection had its limitations as the manufacturers that were approached had proprietary issues and could not let out detailed information. Some of the data that was borrowed from the database of the software is Euro-centric.
- The single-score comparison of environmental impact must not be used in public comparisons, marketing and ecolabelling as it is an approximate result based on factors that may not necessarily apply to that particular region.
- Although many different types of issues and problems can be explored with LCA, it is not an all-purpose tool. It should be seen in comparison with other environmental tools like cost-benefit analysis, ecological risk assessment for sound decision making.

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Annexure 1

Details of ceramic plates under study:-

Size: 9" dinner plate

Weight: 0.5681 kg/plate

Functional Unit: 2960 plates

The following tables set out the raw material consumption, energy consumption and emissions to air and water in the following stages during the production, utilization and disposal of 2690 ceramic plates;

1. Preparation of ceramic dough
2. Casting, moulding and pressing
3. Firing of plates
4. Packaging and transportation
5. Utilization of plates
6. Disposal of plates

The data was compiled from a number of sources including a report containing results of a product comparison on crockery, carried of within the framework of Netherlands's environmental policy (Eijk et al, 1992). Some bits of information have also been borrowed from a recent life cycle assessment carried out for Barn restaurant in 2006. (To et al, 2006). It is also based on personal communication with the concerned manufacturers and vendors.

1. Preparation of ceramic dough:

Quantity of ceramic dough required to make 2960 plates-4765.6 kg

Inputs	**Quantity** In kg/2960 plates
Kaolinite	840
Silicon	420
Feldspar	420
Water	3108

Table A1: Inputs into the making of ceramic dough

Source: Eijk et al, 1992; To et al, 2006; interview with the official at the manufacturing site.

2. Casting, moulding and pressing:

Quantity of casted, moulded and pressed dough- 2228.457143kg

Inputs	**Quantity** Per 2960 plates
Ceramic dough	4765.6 kg
Natural gas (heat)	9915.6288 MJ
Electricity	26208 MJ
Emissions to air	In kg/2960 plates
Carbon dioxide	6.47×10^{2}
Carbon monoxide	2.00×10^{-1}
Nitrogen dioxide	1.19×10^{0}
Sulphur dioxide	7.76×10^{-1}
Hydrocarbons	7.54×10^{-1}
Particulates	6.28×10^{-2}
Aldehydes	7.98×10^{-4}
Organic compounds	1.44×10^{-3}
Ammonia	1.51×10^{-4}
Fluoride	1.23×10^{-2}
Emissions to water	in kg/2960 plates
Suspended substances	2.07×10^{-4}
COD	6.23×10^{-4}
Oils	6.62×10^{-3}
Metallic ions	4.20×10^{-6}
Fluoride	1.86×10^{-3}
Ammonia	8.67×10^{-4}
Sulphate	3.95×10^{-4}
Nitrate	4.42×10^{-4}
Chloride	2.39×10^{-5}
Sodium ion	3.06×10^{-4}

Table A2: Raw material consumption, energy consumption and emissions during casting, moulding and pressing of ceramic dough.

Source: Eijk et al, 1992; To et al, 2006

3. Firing of plates:

Quantity of fired plates-1721.028952 kg

Inputs	**Quantity** Per 2960 plates
Casted, moulded, pressed dough	2228.457312 kg
Natural gas (heat)	35155.4112 MJ
Electricity	7392 MJ
Emissions to air	In kg/2960 plates
Carbon dioxide	2.29×10^{3}
Carbon monoxide	7.08×10^{-1}
Nitrogen dioxide	4.23×10^{0}
Sulphur dioxide	2.75×10^{0}
Hydrocarbons	2.67×10^{0}
Particulates	2.23×10^{-1}
Aldehydes	2.83×10^{-3}
Organic compounds	5.11×10^{-3}
Ammonia	5.35×10^{-4}
Fluoride	4.36×10^{-2}

Table A3: Raw material consumption, energy consumption and emissions during firing of plates

Source: Eijk et al, 1992 ; To et al, 2006

4. Packaging and transportation of finished ceramic plates:

Inputs	**Quantity** In kg/2960 plates
Fired plates	1721.028952
Paint	3.47008
Packaging carton	112
Transportation by truck	346 km

Table A4: Inputs into the packaging and transportation of ceramic plates

Source: Eijk et al, 1992; primary data through interviews and discussions

5. Utilisation of ceramic plates:

Details of the average dishwasher type considered in the analysis are as follows. The water, electricity and detergent consumption are for one washing cycle:

Details	**Quantities**
Model name	Model 66 DRWSPW-champion company
Capacity	148 racks/hr
Water consumption	302.5298 kg
Detergent dosage	840.64 kg
Electricity consumption	16 MJ

Table A5: Details of the dishwasher

Source: Eijk et al, 1992, Yale dining services, Dishwasher Company.

6. Disposal of ceramic plates:

Distance from Yale campus to the landfill at Bridgeport – 27.353 km

Annexure 2

Details of biodegradable corn-starch/PLA plates under study:-

Size: 9" dinner plate

Weight: 8g /plate

Functional Unit: 2960 plates

The following tables set out the raw material consumption, energy consumption and emissions to air and water in the following stages during the production, utilization and disposal of 2960 corn-starch plates:

1. Production of corn-starch plates using PLA pellets
2. Finished plates at Yale
3. Disposal of plates

The data for was collected from a number of published studies. The main source of reference was a comparative LCA of four types of drinking cups, done by the Public waste Agency for the Flemish region (Vaes et al, 2006). Eco-profiles for current and near-future NatureWorks polylactide were also consulted (Vink et al, 2007)

1. Production of corn-starch plates using PLA pellets:

   Weight of 2960 plates- 23.680 kg

Inputs	**Quantity Per 2960 plates**
PLA pellets	24.04906988 kg
Electricity	22.16250 kWh
Emissions to air	In kg/2960 plates
Particulates	1.861×10^{-3}
Carbon monoxide	1.202×10^{-1}
Sulphur dioxide	5.928×10^{-2}
Nitrogen dioxide	1.858×10^{-1}
Hydrogen chloride	2.164×10^{-4}
Hydrocarbons	3.032×10^{-2}
Nitrogen oxides	8.777×10^{-3}
Hydrogen	3.414×10^{-3}
Methane	3.330×10^{-1}
VOC	7.623×10^{-3}

Emissions to water	In kg/2960 plates
COD	1.419×10^{-1}
BOD	2.587×10^{-2}
Sodium ion	1.755×10^{-2}
Nitrogen oxides	2.900×10^{-2}
Chloride	3.915×10^{-2}
Suspended solids	7.440×10^{-2}
Phosphorous compounds	2.881×10^{-4}
Nitrogen	2.031×10^{-3}
Sulphate	3.318×10^{-3}
Calcium compounds	3.061×10^{-3}
TOC	3.770×10^{-2}
Calcium ion	5.956×10^{-3}
Solid waste	In kg/2960 plates
Plastics	2.404×10^{-2}
Unspecified waste	2.404×10^{-2}
Mineral waste	4.425×10^{-1}
Slags and ashes	2.195×10^{-2}
Chemical waste, regulated	1.049×10^{-1}
Chemical waste, unregulated	2.404×10^{-2}
Waste returned to mine	7.844×10^{-2}
Mineral waste from mining	2.339×10^{-1}
PLA waste generated	2.381×10^{-1}

Table A6: Raw material consumption, energy consumption and emissions during the production of corn-starch plates from PLA pellets.

Source: Vaes et al, 2006; Vink et al, 2007

2. Finished corn-starch plates at Yale:

Weight of finished plates- 23.680 kg

Inputs	Quantity In kg/2960 plates
PLA plates	23.680
Paint	5.861×10^{-4}
Packaging carton	2.727
Transportation by truck	1940 km

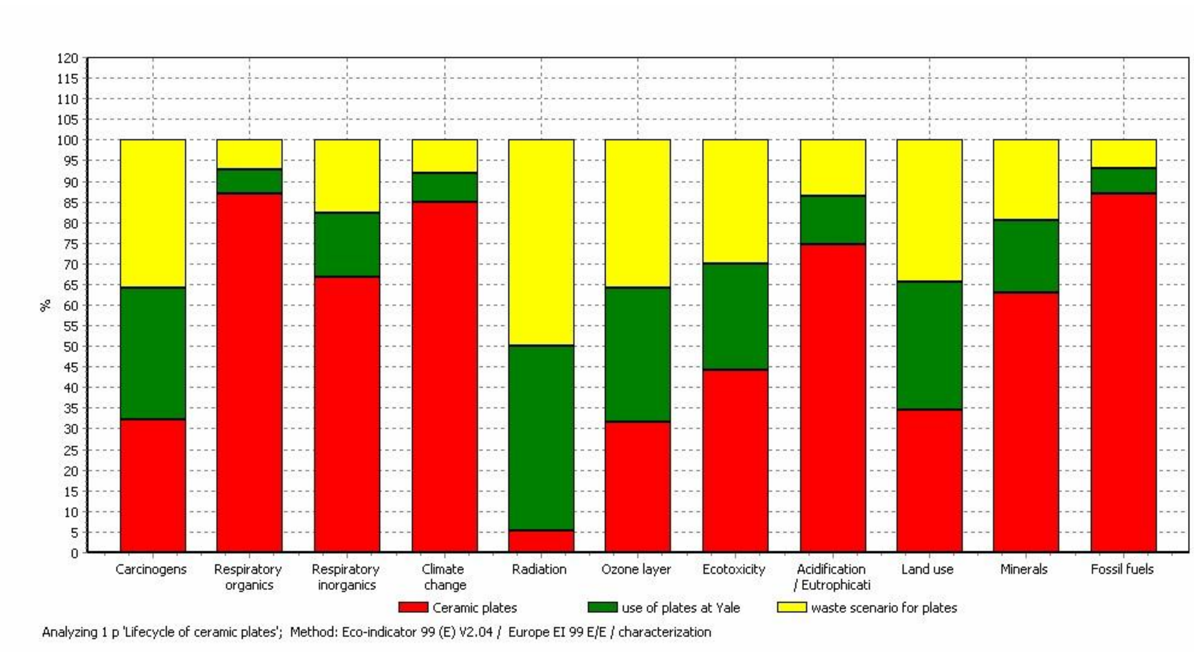
Table A7: Emissions during manufacture and transport of finished corn-starch plates to Yale

Source: Vaes et al, 2006; Vink et al, 2007

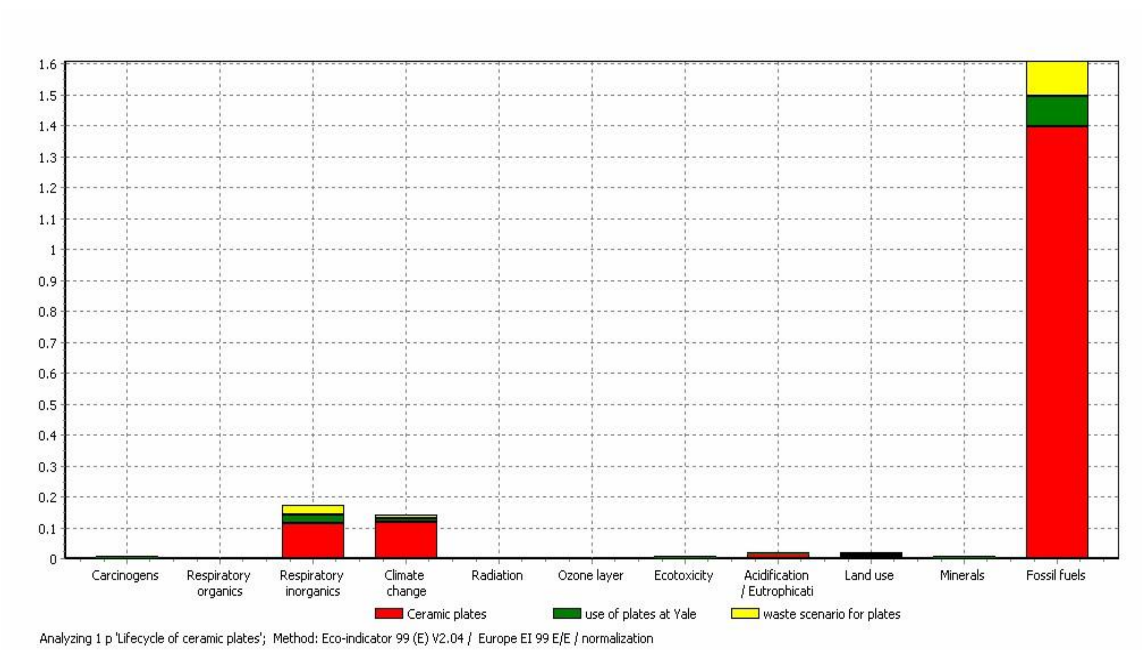
3. Disposal of corn-starch plates:

Distance from Yale campus to the incinerator at Bridgeport – 27.353 km

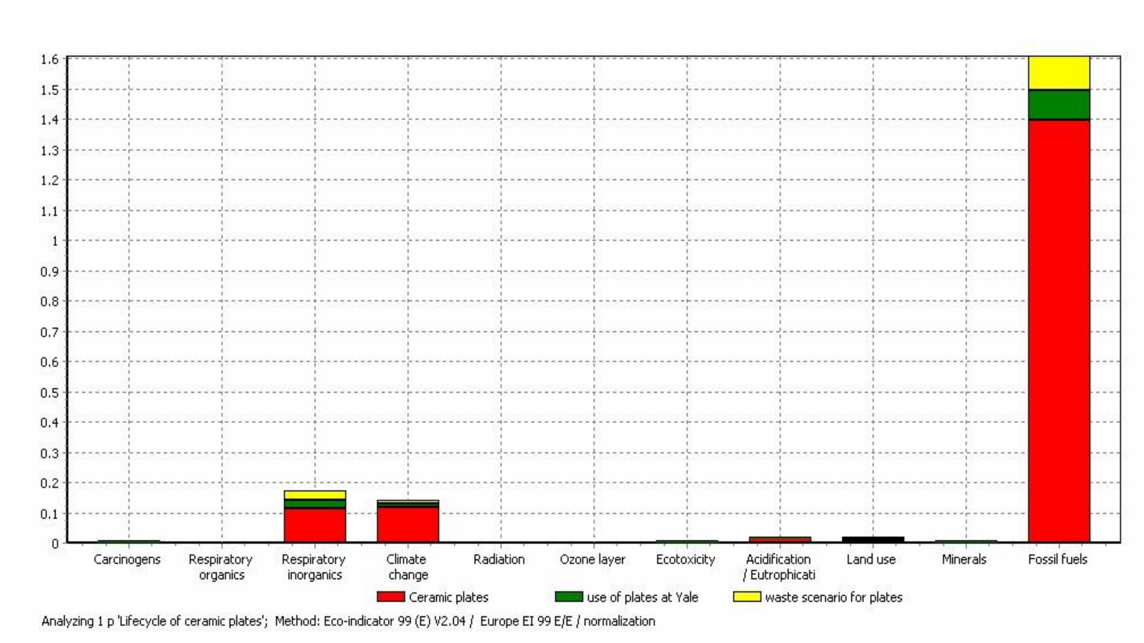
Annexure 3



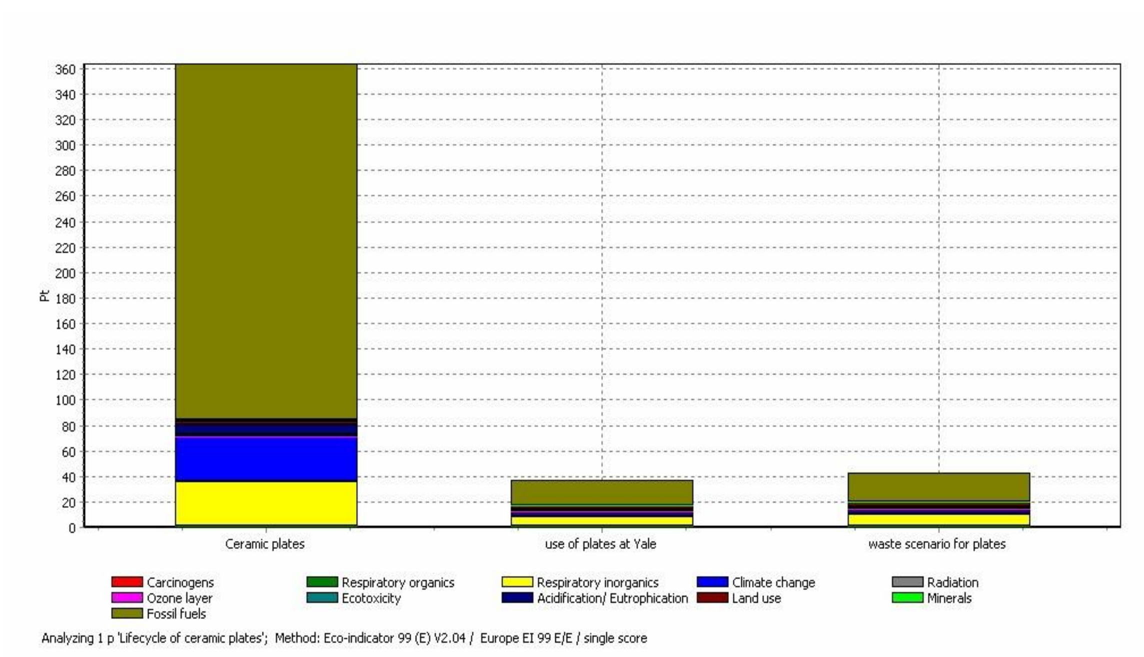
Graph A1: Characterization results for life cycle of ceramic plates



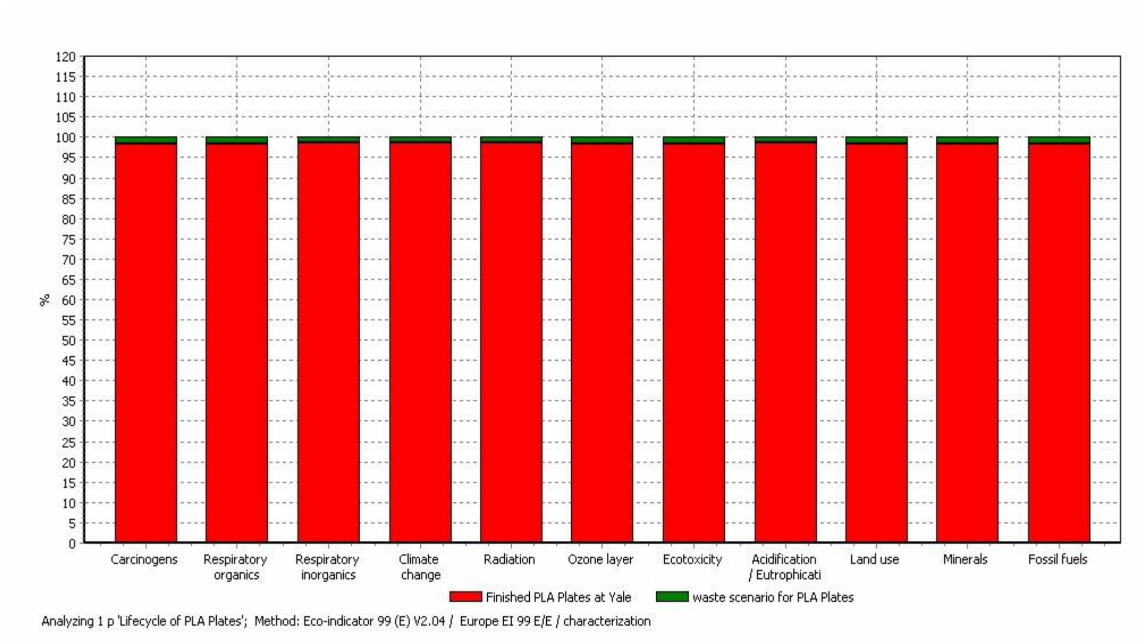
Graph A2: Normalisation results for the life cycle of ceramic plates



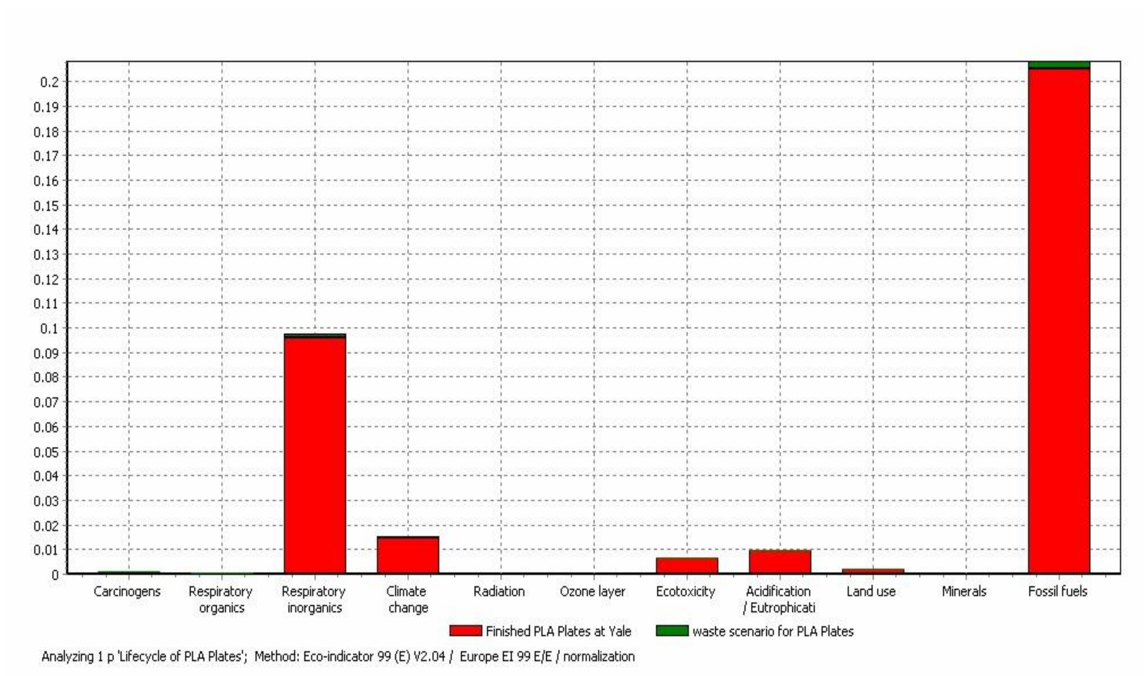
Graph A3: Weighting results for the life cycle of ceramic plates



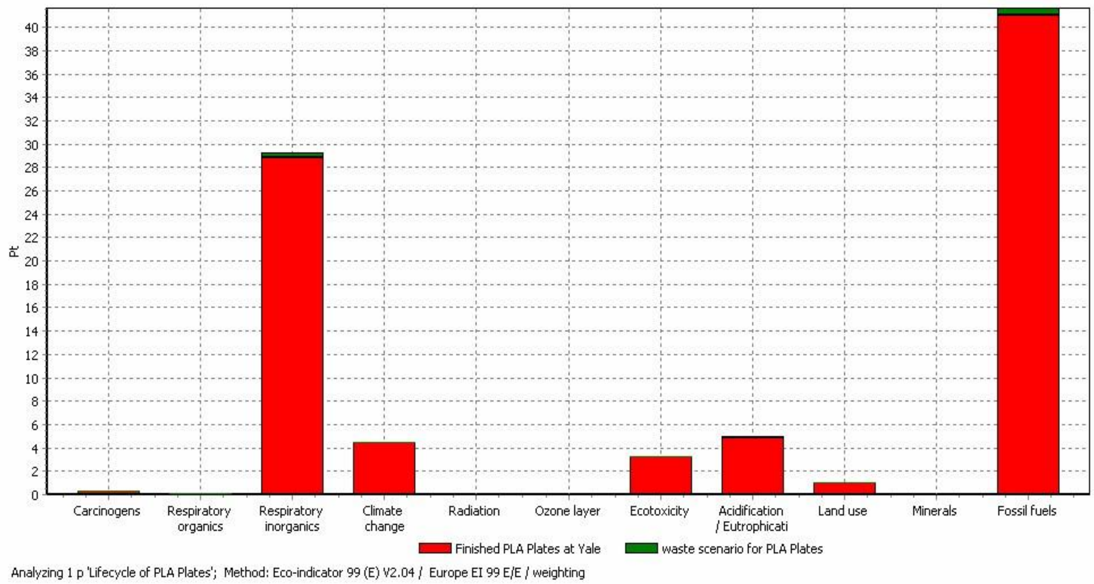
Graph A4: Single score impacts during the life cycle of ceramic plates



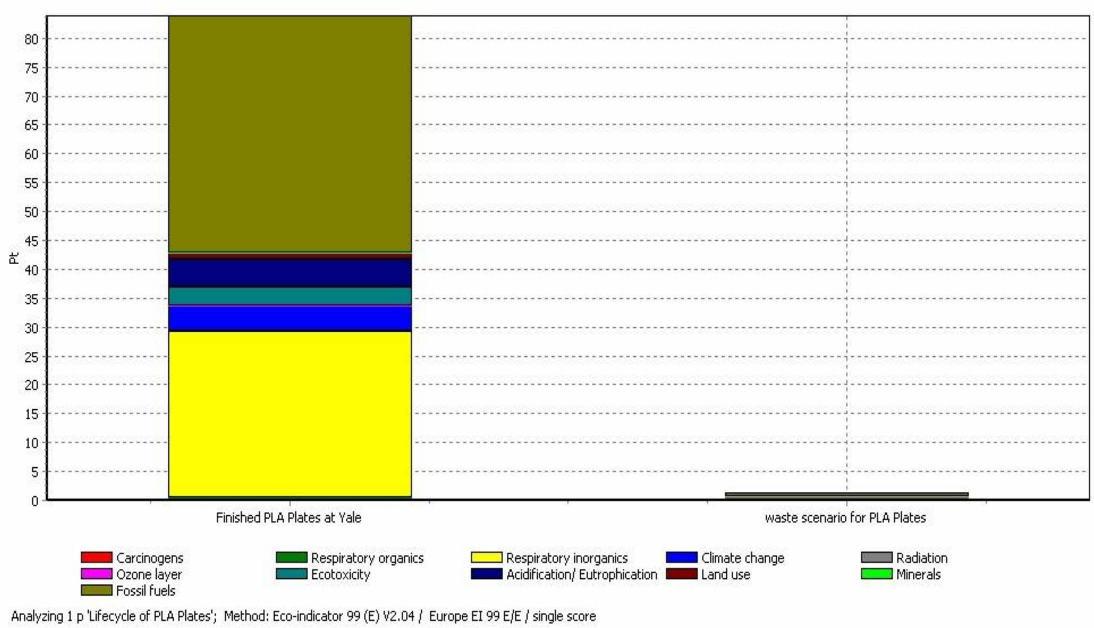
Graph A5: Characterization results for life cycle of PLA plates



Graph A6: Normalization results for the life cycle of PLA plates



Graph A7: Weighting results for the life cycle of PLA plates



Graph A8: Single score impacts during the life cycle of PLA plates

Annexure 4

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