# Development of a food process sustainability metric based on eco-efficiency

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# Dedication

To my Parents and most importantly to Trinity

To my beloved Sisters.

## Preface and contribution of authors

This thesis has been written in accordance with the McGill University guidelines for thesis preparation. Specifically, the manuscript-based format was adopted for the thesis. It contains six chapters, some of which are published or being prepared for publication as shown below:

- John I., E.M. Kwofie, M. Ngadi. "Two decades of eco-efficiency research: A bibliometric Analysis." Environmental Sustainability 3, 155–168 (2020). https://doi.org/10.1007/s42398-020-00105-1.
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Izuchukwu John (main author) conducted the literature review, collected the data, did all the result analysis, and wrote all the manuscripts. The research work was majorly conducted in the Food Engineering laboratory, Department of Bioresource Engineering, Macdonald Campus of McGill University, Montreal.

Dr Michael Ngadi (co-author), James McGill Professor at the Bioresource Engineering department, McGill University, Macdonald Campus, Sainte-Anne-de-Bellevue, Quebec, supervised the research, provided technical advice, helped to review and revise the manuscripts. Dr Ebenezer Kwofie a research associate in the Department of Bioresource Engineering helped in organizing and revising the review articles for publication, assisted in data collection and provided scientific inputs in the course of the research.

Signed: Izuchukwu John

Date: March 2020

# Abstract

Global food sustainability has been a topical issue over the last few decades requiring both effective assessment mechanism and strategies for meeting the challenge. Eco-efficiency lends itself as an interdisciplinary sustainability technique that can be applied to provide both environmental and economic insights across the food value chain. The study aims at enhancing eco-efficiency assessment technique by inclusion of data envelopment analysis to measure not only the economic and environmental performance but also the operational efficiency of potential alternatives to improve the overall sustainability of agro enterprises. In the first phase of the study, life cycle assessment (LCA) and life cycle costing (LCC) were used to conduct environmental and economic assessment for a fruit juice processing plant. The study presents a gate to gate system boundary. A functional unit of one tonne of fruit juice (lime, tamarind and passion fruit) was used to evaluate the impact of processing. Characterized and normalized results of the impacts were presented. Electricity usage, wastewater and fruit waste were found to be the major contributors to the environmental changes. The LCA results show that these processes contribute to global warming potential, acidification, eutrophication potential, human toxicity (cancer and non-cancer), resources and ecotoxicity. The normalized results expressed in person-equivalent shows that tamarind had the lowest normalized results signifying a good environmental performance when compared to lime and passion fruit. A life cycle costing shows that for a small-scale fruit juice enterprise, the raw material cost may be the most significant cost component accounting for more than two-thirds of the total cost.

In the second phase of the study, a new eco-efficiency sustainability model which combines analysis of environmental, economic and operational performances was developed. The new model quantifies the various performances into a single eco-efficiency score (EES). The primary benefit of the model is its ability to provide economic, environmental, and operational efficiency data on current and proposed improvement/alternatives for informed enterprise decision. The model was applied to measure the sustainability performance of a small-scale fruit processing enterprise. In this case study, six decision-making units (DMUs) were evaluated including the current process. An index was generated from an Eco-Enviro assessment to estimate the EES. The proposed model may be applied to both product and process-based food assessments for a wider and all-inclusive assessment, and to make informed decisions for enhanced food system sustainability.

# Résumé

La durabilité alimentaire mondiale a été un sujet d'actualité au cours des dernières décennies, nécessitant à la fois un mécanisme d'évaluation efficace et des stratégies pour relever le défi. L'éco-efficacité se prête comme une technique de durabilité interdisciplinaire qui peut être appliquée pour fournir des perspectives environnementales et économiques à travers la chaîne de valeur alimentaire. L'étude vise à améliorer la technique d'évaluation de l'éco-efficacité en incluant l'analyse d'enveloppement des données pour mesurer non seulement la performance économique et environnementale, mais aussi l'efficacité opérationnelle d'alternatives potentielles pour améliorer la durabilité globale des agro-entreprises. Dans la première phase de l'étude, l'évaluation du cycle de vie (ACV) et le coût du cycle de vie (CCV) ont été utilisés pour réaliser l'évaluation environnementale et économique actuelle d'une usine de transformation de jus de fruit. L'étude présente les aspects du système an amont qu'en aval. Une unité fonctionnelle d'une tonne de jus de fruits a été utilisée pour évaluer l'impact de la transformation des fruits de la passion, du tamarin et de la chaux. Des résultats caractérisés et normalisés des impacts ont été présentés. La consommation d'électricité, les eaux usées et les déchets de fruits ont été les principaux contributeurs aux dommages environnementaux. Les résultats de l'ACV montrent que ces processus contribuent au potentiel de réchauffement planétaire, à l'acidification, à l'eutrophisation, à la toxicité humaine (cancer et non cancéreux), aux ressources et à l'écotoxicité. Les résultats normalisés exprimés en équivalent-personne montrent que le tamarin a les résultats normalisés les plus faibles, ce qui signifie une bonne performance environnementale par rapport au chaux et aux fruits de la passion. Un coût du cycle de vie montre que pour une petite entreprise de jus de fruits, le coût des matières premières peut être la composante de coût la plus importante, représentant plus des deux tiers du coût total.

Au cours de la deuxième phase de l'étude, un nouveau modèle d'éco-efficacité durable combinant l'analyse des performances environnementales, économiques et opérationnelles a été développé. Le nouveau modèle quantifie les différentes performances en un seul score d'éco-efficacité (EES). Le principal avantage du modèle est sa capacité de fournir des données sur l'efficacité économique, environnementale et opérationnelle sur les améliorations actuelles ou proposées pour une décision éclairée de l'entreprise. Le modèle a été appliqué pour évaluer le rendement durable d'une petite entreprise de transformation de fruit. Le modèle proposé peut être appliqué à la fois aux évaluations

des produits et des processus alimentaires pour une évaluation plus large et exhaustive, et pour prendre des décisions éclairées en vue d’améliorer la durabilité du système alimentaire.

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# Abbreviations

| *Abbreviations* | *Full form* |
|---|---|
| AHP | Analytical Hierarchy Process |
| AP | Acidification Potential |
| CF | Characterization factor |
| CPC | Central Product Classification |
| CRS | Constant Returns to Scale |
| CSR | Corporate social responsibility |
| CVA | Cost and Value Assessment |
| DfE | Design for Environment |
| DMU | Decision Making Units |
| EEA | European Environment Agency |
| EEI | Eco-enviro Index |
| EES | Eco-efficiency scores |
| EP | Eutrophication Potential |
| EPE | Environmental Performance Evaluation |
| FAO | Food and Agriculture Organization |
| FEM | Fuzzy Evaluation Method |
| FLW | Food Loss and Waste |
| GaBi | Ganzheitlichen Bilanzierung |
| GHG | Green house gas |
| GWP | Global Warming Potential |
| IRR | Internal Rate of Return |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCC | Life cycle cost |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |

| | |
|---|---|
| LP | Linear program |
| NPV | Net Present Value |
| OECD | Organization for Economic Cooperation and Development |
| PPS | Production possibility set |
| SA | Social Accountability |
| SDG | Sustainable Development Goal |
| SFS | Sustainable Food System |
| SFVC | Sustainable food value chain |
| S-LCA | Social Life Cycle Assessment |
| SMEs | Small and medium enterprises |
| TRACI | Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts |
| VRS | Variable Returns to Scale |
| WCED | World Commission on Environment and Development |
| WRAPS | Waste and Resource Action Programme |

# 1 Introduction

## *1.1 Background*

The food industry comprises chain of activities targeted at satisfying the global food demands. It is a major part of the manufacturing industry constituting approximately 25% of the private economy in industrialized countries and a bigger percentage in developing countries (Josling, 2002). In Canada, the food and beverage processing industry has 16.4% of the total gross domestic product of the manufacturing sector making it the largest manufacturing industry (Sam et al., 2017). While the activities of the food sector has always provided food for the human race and contributed considerably to total gross domestic products of many economies, they have a corresponding environmental, economic and social implications with associated challenges (Béné et al., 2019).

The challenges of food and agricultural industry comes in different forms and with varying level of difficulty. Key among them is the issue of food loss and waste which occurs in two forms, planned (unavoidable) and unplanned (avoidable) (Martin et al., 2019). A considerable amount of food produced globally are either lost or wasted which has huge implications for global food security. (Gustavsson et al., 2011; Timmermans et al., 2014). This is particularly important because addressing it could provide a solution to the 'inability to feed the world in the years ahead' narrative. In addition to limiting food availability, Food loss and waste influences the production cost with an associated environmental impact, thus contributing about eight percent of the global anthropogenic greenhouse gas (GHG) emissions (Daviron et al., 2011; Stuart, 2009; Wieben, 2017).

The challenge of food waste and losses seems to cut across all stages along the value chain – from production to consumption, although, the focus has primarily been within the production stage. Several experts (FAO, 2016; Global Panel, 2016; IPES, 2016) have suggested that food systems are failing us not only in food security but also in nutrition security, small-scale actors, natural resources, agrobiodiversity, and energy-water-carbon efficiency (Béné et al., 2019). To shift from this current unsustainable state, there is a need for a more sustainable food system aimed to deliver food security and nutrition in an economically, socially and environmentally friendly manner (Timmermans et al., 2014). This task of achieving a sustainable food system certainly requires a multi-component assessment tool.

A sustainable food system defined as value-added agro-activities that transforms raw materials into finished goods in a way that is economically and environmentally sustainable in addition to efficient resource utilization (Neven, 2014). As addressed in the Sustainable Development Goal (SDG) 12, a sustainable food system, should produce, process and consume food in a sustainable manner (UN, 2020). This view of sustainable food system should address food waste and losses using technological improvement that promotes renewable energy sources and integrating energy and resource efficiency measures (Kroll, 2015; Wieben, 2017).

The food industry has adopted several practices like food loss and waste protocols, Food Waste Audit, and WRAPS (Waste and Resource Action Programme) to meet the sustainability challenge, these tools do not incorporate resource management with the sustainability components (Strotmann et al., 2017). Therefore, some experts have proposed the use of a resource-based approach like eco-efficiency which could provide the necessary information to improve product economic value as well as decrease the environmental impact (Koskela and Vehmas, 2012; Mickwitz et al., 2006).

Eco-efficiency as a multi-disciplinary "environmental impact assessment index" that synergises the environmental and economic aspects of a product (Pang et al., 2016). It has been applied in many industries outside the food industry to address the issues of sustainability. The concept of eco-efficiency is based on resource use approach to produces economic benefit (Hukkinen, 2001). When the concept is applied, it has the potential to provide users a competitive advantage, improve their product quality and reduce environmental impacts (Mickwitz et al., 2006; Prasaja, 2018). In manufacturing, eco-efficiency could be applied to energy management, reduction in material intensity, efficient use of renewable resources, and improved production patterns. Its techniques allow users to evaluate the use of such resources in all the life cycle stages (Pang et al., 2016).

Recently, several eco-efficiency evaluation techniques like Life Cycle Assessment (LCA), Data Envelopment Analysis (DEA), the Analytical Hierarchy Process, the neural network, the Fuzzy Evaluation Method have been used in different sectors either singly or in combination (Pang et al., 2016). Many authors have used the different techniques in assessing one of more of the sustainability components (social, economic and environment). For instance, Kicherer et al. (2007) applied a combination of LCA and Life Cycle Cost (LCC) to assess the economic and environmental aspects of eco-efficiency using a normalization approach. Other authors like Huang and Hua (2018) studied Eco-efficiency Convergence and Green Urban Growth in China. Niklaß et al. (2018) studied the implementation of eco-efficient procedures to reduce the climate impact of non-$CO_2$ effects. Similarly, DEA based eco-efficiency approach has been applied widely in many sectors such as agriculture, industrial production and electronics both for short- and long-term (Barba-Gutiérrez et al., 2009; Kuosmanen and Kortelainen, 2005; Wu et al., 2016; Zhang et al., 2008). However, only few studies have applied the concept of eco-efficiency in the food industry. In these studies, they were applied to assess environmental or/and economic efficiency of the food system.

Given that food system is complex, with the complexity expected to increase with increasing global population, and increasing food demands, the application of eco-efficiency evaluation techniques and model coupled with mathematical process optimization methodologies like DEA would be useful for providing a decision-making framework and for designing a model for a sustainable eco-efficient food system. This may fulfil the Food and Agriculture Organization of the United Nations vision for achieving a sustainable food system that gives the world access to nutritious food with efficient resource use that has a low environmental impact.

### *1.2 Rationale*

Sustainability studies, with and/or without models, have addressed environmental and/or economic components of products and processes. However, studies on improving these processes are lacking. These previous studies only assess the current sustainability of the food firms but did not provide and assess a potential improvement option for these firms.

It is necessary to drive the sustainability of the food product/process using novel approaches that involve resource use management, a measure of operational performances and sustainability components. By doing this, one can easily compare all the performances of these unit processes, choose a process that offers a better resource use efficiency as well as an associated environmental and economic performance.

Agro-sustainability assessment has primarily been focused on production and hence looking into local agro processing units that are recipient of most local products and their impact on environment is necessary. To enhance their sustainability, it is necessary to look beyond their environmental stewardship and consider their economic performance as well as the operational efficiency.

Organizations would adopt a sustainability approach that does not only have an environmental benefit but also an accompanying economical benefit. Hence, driving both sustainability components requires a resource use management approach and operational efficiency. Eco-efficiency concept focuses mainly on resource efficiency and technological improvement which offers a better production pattern, operational excellence, product quality, waste management and the associated reduction in the emission of pollutants to the environment. Resource management has been suggested in literature to have an underlying economic benefit. Similarly, technological improvement, despite having a high initial cost, may improve the resource usage, energy usage, product quality and safety, and reduces waste. Hence, if eco-efficiency techniques and models are adopted largely by the food industry, it could be possible to assess the sustainability of a product/process.

### *1.3 Hypothesis*

Most current techniques used in local small-scale enterprises are not efficient and pose threats to the communities in which they operate. Hence, an eco-efficiency assessment could reveal the potential areas requiring improvement and their associated economic and environmental implications.

Previous studies cited in literature suggest that there could be a strong link between resource use management, operational efficiency, productivity and sustainability. It is herein hypothesized that

1. it is possible to use eco-efficiency techniques to measure the current economic, environmental and operational efficiency of a small-scale food processing firm.
2. It is possible to suggest alternative process options that could provide a better efficiency for this firm.
3. It is also possible to develop an eco-efficiency-based model to assess the efficiency of the current process and the potential improvement options. The efficiency of these potential options serves as a basis for decision and improvement in this firm.

### *1.4 Research objectives*

The overall objective is to apply the concept of eco-efficiency in evaluating the performance of a small-scale food system (using a fruit juice plant in Honduras as a case study). This objective comprises of the following sub-objectives:

1. To perform a techno-environmental assessment of a fruit processing plant using Life Cycle Assessment and Life Cycle Cost.
2. To develop an integrated food system eco-efficiency model that allows evaluation of economic, environmental and operational performance.

## Connecting text

Having discussed the background of study and highlighted the objectives in the previous chapter, in the next part of this work, I will be exploring the trend and extent of eco-efficiency research in the last two decades spanning from 1998 to 2018. A bibliometric analysis is used to identify the research keywords, growth trend, major research areas, countries, institutions and authors within the eco-efficiency research space.

# 2 Two decades of eco-efficiency research: A Bibliometric Analysis

**Abstract**

Sustainability has been a global focus in recent decades. It has been viewed in various forms and measured across many fields. One of the critical assessment tools that measure both environmental sustainability and economics is eco-efficiency. In this paper, the trend of eco-efficiency research over the last two decades (1998 – 2018) has been evaluated based on 5,582 scientific publications on the Web of Science using bibliometric analysis. The result provides a detailed analysis of the number of papers, authors, journals, institutes, countries, citations, co-citations, bibliographic coupling, and the general eco-efficiency research growth trend. The analysis shows that keywords such as life cycle analysis and data envelopment analysis alongside other concepts have been frequently applied in eco-efficiency research. Furthermore, the eco-efficiency concept and its approaches have been applied across a wide range of sectors. The result indicates besides engineering, and environmental science, the concept is also trending in the business economics sector. The study also reveals an increasing growth trend in its application in industrial and environmental sustainability, recording 576 publications in 2017. Following the analysis, pathways for future research have been suggested.

**Keywords:** Eco-efficiency, bibliometric analysis, sustainability

## *2.1 Introduction*

Eco-efficiency is an indispensable concept for the analysis of industrial sustainability (Zhang et al., 2008). It can be seen as a transformation tool that relates to improved production processes, economic cost, and environmental value (Mickwitz et al., 2006). Eco-efficiency as an environmental concept has four variants as described by Huppes and Ishikawa (2005). These variants are environmental productivity; the environmental intensity of production; environmental improvement cost; and environmental cost-effectiveness. By implementation of the concept of eco-efficiency, the food system uses several approaches to achieve the envisaged industrial and environmental sustainability (Gómez et al., 2018). The term "eco" used in the eco-efficiency concept denotes both economic and ecological aspects (Yin et al., 2014). These two aspects have been the basis of eco-efficiency evaluating techniques (Li et al., 2012). Thus, one of the primary advantages of this tool over other environmental sustainability tools is its ability to evaluate both environmental and economic dimensions of sustainability. Some eco-efficiency techniques include life cycle analysis (ISO, 2006), data envelopment analysis (Cooper et al., 2011; Ji, 2013), stochastic frontier analysis (Baráth and Fertő, 2015) and indexes system method (Meng et al., 2008). Overall, eco-efficiency has been recognized as a technique which focuses on creating more value with less input while ensuring a minimal environmental impact. It has gained more ground both in science/engineering and business economics to addresses adverse environmental impacts caused by industrial and human activities (Mickwitz et al., 2006). As sustainability concerns increase, it is essential to provide not only data on current techniques for eco-efficiency research but also to track its application in various fields, identify leading institutions, pioneers and current leading authors, and identify current gaps.

Bibliometric analysis as a research methodology applies quantitative analysis and a statistical approach to the evaluation of research interest (Li and Zhao, 2015). The bibliometric analysis of eco-efficiency will provide the current scope of research and report associated topics of current interest in eco-efficiency research. This is important for the sustainability research community and could lead to useful collaboration and multi-disciplinary research. The overall objective of this component of the thesis is to track the trends in eco-efficiency research over the last 20 years (1998-2018) with a primary focus on life cycle assessment and data envelopment analysis. The paper will evaluate growth trends and publications, as well as perform analysis of keyword, citations, countries, institutions, and journals using the VOSviewer (version 1.6.9.0, Leiden

University's Centre for Science and Technology Studies, Rapenburg, Leiden, Netherlands) software. Additionally, we will provide an insight into the direction for future studies to further grow the knowledge base of eco-efficiency as a sustainability concept.

### *2.2 Materials and methods*

The bibliometric analysis methodology used in this study was adapted from (Li et al., 2018). The data was collected in February 2019 from the Web of Science database (Institute for Scientific Information, Thomson Reuters, Clarivate Analytics (Firm), Philadelphia, PA; accessed from McGill University Library, Canada). The analysis was made with data from this single database. The keywords used in the search were “Eco-efficiency” or “Life-cycle analysis” (LCA) or “Data Envelopment Analysis” (DEA) on a “title” basis for which a total of 5582 articles were obtained. The search on a “title” basis means that only records of articles having any of the keywords in their title will be displayed. It was a one-time search of entering the keywords together in the database. The three keywords represent the concept (eco-efficiency) and the two eco-efficiency techniques (LCA and DEA). All the articles and their cited references were downloaded and used as the primary material for this review. The VOSviewer was used for the map analysis while the SigmaPlot 12.0 graphical/statistical software (Systat Software Inc.), San Jose, USA was used to plot the graphs. The record content of the files (author, title, source, abstract, year of publication, journal names) were downloaded from the Web of Science in a text file (*.txt) format. The downloaded text files were used in the VOSviewer software for analysis. From the Web of Science, the information obtained includes the publication years, Web of Science categories, document types, organizations, authors, journals and citation reports. The relationship between organizations, keywords, journals, countries, citations referred to as network collaboration were also analyzed using VOSviewer. The publication records, citation records, journal records, research areas and Web of Science category records were gotten from the Web of Science result analysis page, collated and plotted using the SigmaPlot.

The bibliometric analysis focused on categories and journal analysis; basic growth trend analysis; author’s analysis, countries and institution analysis, and keyword analysis. For the keyword analysis, category and journal analysis, a threshold of ten appearance was used (Li et al., 2018). A threshold simply refers to the minimum number of occurrences. The partnership between the different countries or institutions is called collaboration network or collaborative relationship.

### 2.3 ***Results and Discussion***

The 5582 materials cited were not mutually exclusive, so the total appearance was 5908. The distribution of the records (number of materials, percentage) are shown in Fig. 2.1. Articles (4093, 73.3%), proceedings papers (1275, 22.8%), book chapters (183, 3.3 %), editorial materials (96, 1.7%), reviews (116, 2.1 %), meeting abstracts (61, 1.1%), letters (11, 0.2 %), book reviews (25, 0.4%), books (19, 0.3%), and others (29, 0.5%). These records may likely change in a later date due to updating of the database and uploading more documents by the institution managing the database.

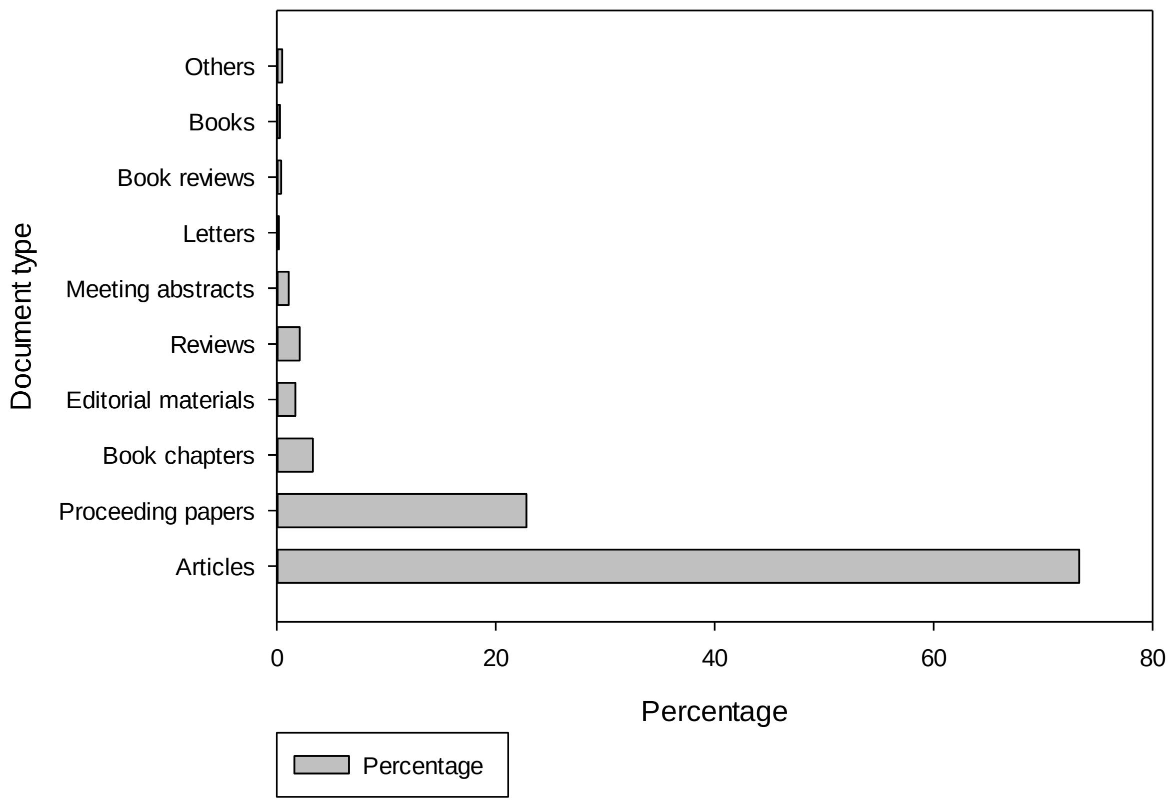


Fig. 2.1. The percentage distribution of the publications across different types of document

#### *2.3.1 Categories and journals analysis*

##### *2.3.1.1 Categories analysis*

The categories analysis was based on two categories namely “research area” and “Web of Science categories.” The research areas and Web of Science categories were displayed on the Web of Science result analysis page. The ten highest research areas and Web of Science categories are shown in Fig.2.2 and Fig. 2.3, respectively. The term ‘research area’ represents a broad field of study, for instance, engineering. The Web of Science category is the database-specific subject categorisation and the category sub-fields. Preliminary results identified 185 Web of Science categories out of which 90 met the threshold of at least ten publications. Overall, 114 research areas were identified from the Web of Science records out of which 54 had ten or more publications. The data collected shows that eco-efficiency studies have been more intense in the engineering field with a substantial record of 2,100 representing 36.6% of the total publication. Business economics and environmental sciences ecology are ranked second and third with records of 1,274 and 1076, respectively. These three areas constitute 79.7% of the total research records in the period under review. The Web of Science categorisation shows environmental sciences had the highest record of 959, followed by operations research management science and management with records of 894 and 715, respectively. Although the research areas and Web of Science categories showed engineering, management, and environmental science as the primary research field, the full records show there is eco-efficiency research in almost all the major fields of study.

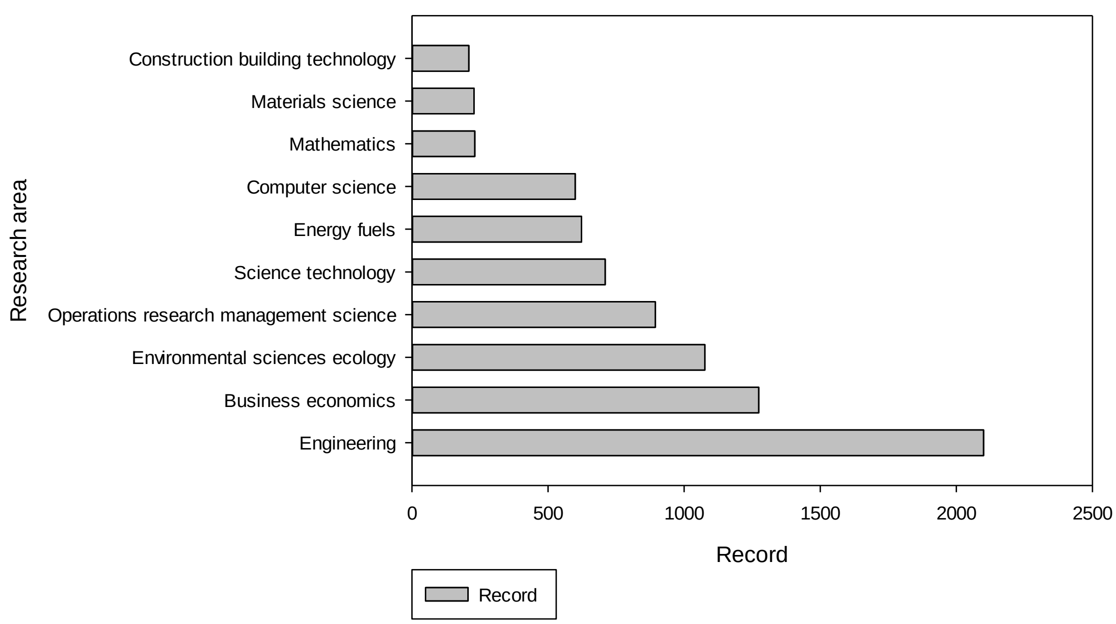


Fig 2.2: The top 10 research areas

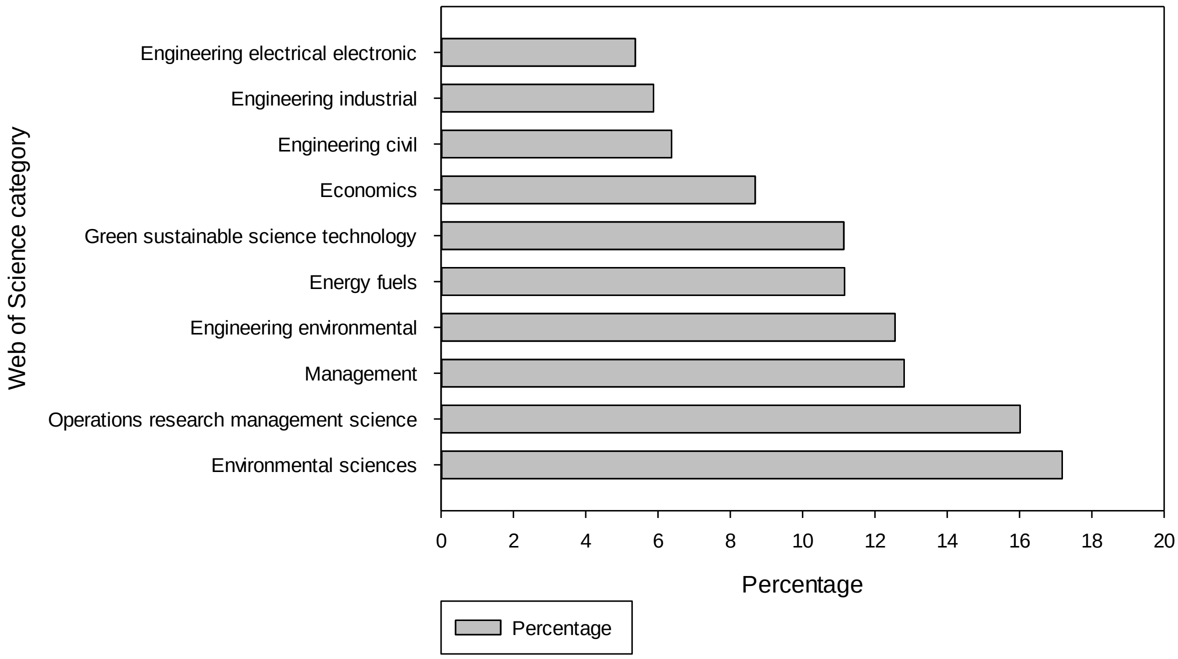


Fig 2.3: The top 10 Web of Science categories

#### *2.3.1.2 Journal analysis*

This analysis was to identify the leading journals publishing eco-efficiency research. This reveals the main area of application of eco-efficiency research. The Web of Science records shows that 2,614 journals had publications on eco-efficiency during the period under review. Seventy-seven (77) of these journals had at least ten publication records. Table 2.1 shows the 20 most productive journals. From the analysis, the Journal of Cleaner Production - a journal that focuses on science, technology, engineering, environment, and sustainability has the highest number of records. It has a record of 270 representing 4.84% of the total number of publications. Also, European Journal of Operational Research, a journal that focuses on management and operational research is the second most productive journal with a record of 165 representing 2.96% of the total number of publications. Other journals on the list are mainly related to sustainability, environment, engineering, management, science and technology.

A bibliometric coupling between the journals is presented in Fig. 2.4. Bibliometric coupling occurs when journals reference a common work in their bibliographies (OECD, 2016). The partnership between the different journals is called network collaboration or collaborative relationship. Each curve represents the collaborative relationship while the size of the circle denotes the number of publications as shown in Fig. 2.4. The link thickness/number of links shows the strength of their collaborations while the different colours depicts the affiliation of different journals (Li et al., 2018). For the map analysis in Fig. 2.4, the threshold (minimum number of documents from a source) was five. An overall record of 157 journals met the threshold. The journals are represented by circles and connected to each other with curves. There seem to be no variation in the size of the links which shows that the difference in the collaboration strength is minimal. It could be seen that one journal can be linked to many other different journals. The different areas are differentiated by specific colours; green - environmental science journals, red – business economics, blue – engineering and grey – transportation. As seen from the map, the Journal of Cleaner Production has the biggest circle in green while European Journal of Operational Research has the biggest circle in red. This implies that both journals have the highest records in their respective areas or affiliations.

Table 2.1: Top 20 eco-efficiency or "life cycle assessment" or "data envelopment analysis" journals

| Rank | Source title | Records | Percentage of publication records |
|---|---|---|---|
| 1 | Journal of Cleaner Production | 270 | 4.84 |
| 2 | European Journal of Operational Research | 165 | 2.96 |
| 3 | International Journal of Life Cycle Assessment | 79 | 1.42 |
| 4 | Journal of the Operational Research Society | 76 | 1.36 |
| 5 | Sustainability | 74 | 1.33 |
| 6 | Expert Systems with Applications | 60 | 1.08 |
| 7 | Journal of Industrial Ecology | 58 | 1.04 |
| 8 | Omega International Journal of Management Science | 57 | 1.02 |
| 9 | Applied Energy | 56 | 1.00 |
| 10 | Computers Industrial Engineering | 54 | 0.97 |
| 11 | Energy | 54 | 0.97 |
| 12 | Annals of Operations Research | 43 | 0.77 |
| 13 | Energy and Buildings | 43 | 0.77 |
| 14 | International Series in Operations Research Management Science | 42 | 0.75 |
| 15 | Advanced Materials Research | 41 | 0.74 |
| 16 | Renewable Sustainable Energy Reviews | 41 | 0.74 |
| 17 | Transportation Research Record | 39 | 0.70 |
| 18 | Environmental Science Technology | 38 | 0.68 |
| 19 | Journal of Productivity Analysis | 34 | 0.61 |
| 20 | Energy Policy | 33 | 0.59 |

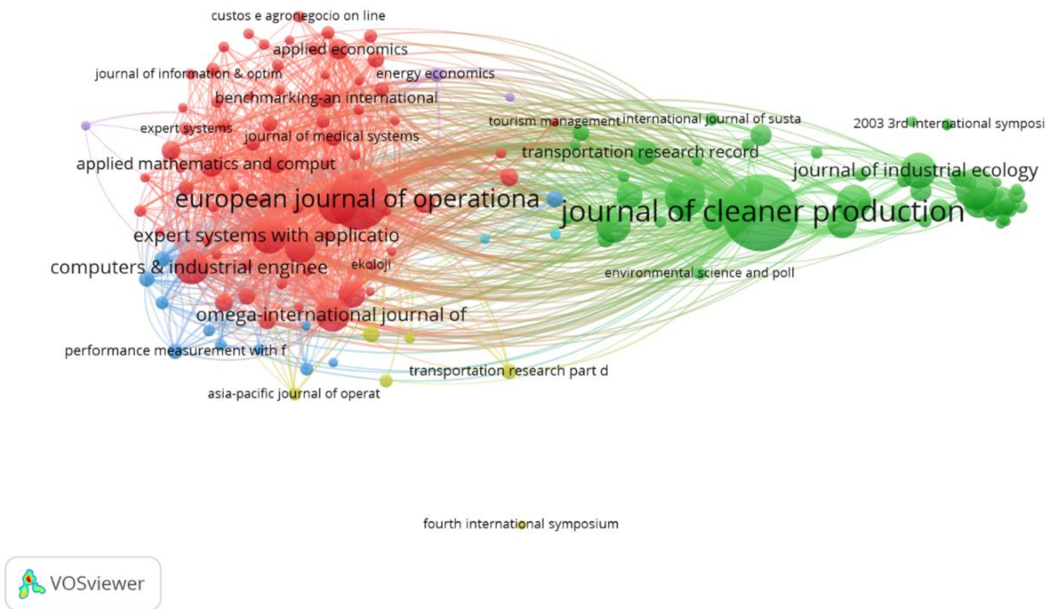


Fig. 2.4: Bibliographic coupling between journals

### 2.3.2 Basic growth trend analysis

The growth trend analysis presents the rate of increase or decrease of eco-efficiency research. From the results, it could be seen that there has been an increase in the research in the years under review from a record of 60 publications in 1998 to 504 publications in 2018. Eco-efficiency research seems to follow an exponential growth curve with a peak in 2017 with a record 9.6 times higher than 1998 when the lowest number of publications were recorded. This increase could be attributed to the relevance of the subject. This could also be due to the increasing global concern in environmental degradation, sustainability and resource management (Caiado et al., 2017; Lupan and Cozorici, 2015). Comparing this analysis with other bibliometric studies on other subjects like ceramic membranes, there was also an increase in research publications. For the ceramic membrane, the publication records increased from 188 in 1998 to 331 in 2016 (Li et al., 2018). This is low compared to this eco-efficiency research records that increased from 60 in 1998 to 504 in 2018. Table 2.2 provides a summary of the trends of publications, citation reports, total citing articles, total citing articles without self-citations. The growth trend of the number of publications and the citation reports are shown in Fig. 2.5 while the trends of the total citing articles and the total citing articles without self-citations are shown in Fig. 2.6. From the results, there was an increase in publications in preceding years except for a few fluctuations that could be found in 2000, 2002, 2007, 2013 and 2018 where the records for the previous years were higher. The reason of the fluctuation is not known. A similar fluctuation were found in other bibliometric review on natural resource accounting during a 1995-2014 period (Zhong et al., 2016)

Citation reports shows the extent at which the publications are used by other researchers. Table 2.3 presents the details of the top 10 papers with the highest citation reports in this study. From the analysis, the research on “slacks-based measure of efficiency in data envelopment analysis” by Tone (2001) has 1037 citations (Tone, 2001). This means that a lot of recent research has cited his results, methods or analysis. This also shows that DEA has been widely applied in eco-efficiency research. On the other hand, the study on “Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications” by Rebitzer et al. (2004) was ranked second in the citation reports The two papers that top the list described the two eco-efficiency techniques that were used in this study. The number of citations of these two articles shows that both techniques have been frequently used and cited in research in the last two decades.

Although, these techniques are usually applied singly, some recent research have applied both techniques jointly and this offers a more comprehensive assessment. Lozano et al. (2009) first used a joint application of LCA and DEA to provide a link between operational efficiency and environmental impacts. Afterwards, several other researchers have adopted this combination in their analysis. Also, the high number of citations in environmental sciences, business and economics, operations research and management science-based research indicates that a lot of studies have been done in these research areas within the last two decades.

Table 2.2: Trends of publications, citation reports, total citing articles, total citing articles without self-citations

| Year | Publications | Percentage | Citation Report | Total citing articles | Percentage | Total citing articles without self citations | Percentage |
|---|---|---|---|---|---|---|---|
| 2018 | 504 | 9.0 | 13,765 | 7,214 | 16.1 | 6826 | 16.4 |
| 2017 | 576 | 10.3 | 12,767 | 6,682 | 15.0 | 6289 | 15.1 |
| 2016 | 536 | 9.6 | 10,508 | 5,728 | 12.8 | 5357 | 12.9 |
| 2015 | 501 | 9.0 | 8,421 | 4,775 | 10.7 | 4443 | 10.7 |
| 2014 | 484 | 8.7 | 7,346 | 4,121 | 9.2 | 3813 | 9.2 |
| 2013 | 371 | 6.7 | 5,523 | 3,378 | 7.6 | 3165 | 7.6 |
| 2012 | 392 | 7.0 | 4,455 | 2,791 | 6.2 | 2592 | 6.2 |
| 2011 | 384 | 6.9 | 3,964 | 2,378 | 5.3 | 2159 | 5.2 |
| 2010 | 301 | 5.4 | 2,905 | 1,899 | 4.3 | 1743 | 4.2 |
| 2009 | 282 | 5.1 | 2,319 | 1,524 | 3.4 | 1383 | 3.3 |
| 2008 | 191 | 3.4 | 1,461 | 1,034 | 2.3 | 957 | 2.3 |
| 2007 | 173 | 3.1 | 1,139 | 834 | 1.9 | 759 | 1.8 |
| 2006 | 177 | 3.2 | 833 | 625 | 1.4 | 557 | 1.3 |
| 2005 | 164 | 2.9 | 560 | 446 | 1.0 | 386 | 0.9 |
| 2004 | 122 | 2.2 | 348 | 264 | 0.6 | 226 | 0.5 |
| 2003 | 76 | 1.4 | 260 | 209 | 0.5 | 188 | 0.5 |
| 2002 | 74 | 1.3 | 140 | 121 | 0.3 | 104 | 0.3 |
| 2001 | 83 | 1.5 | 116 | 94 | 0.2 | 78 | 0.2 |
| 2000 | 61 | 1.1 | 45 | 41 | 0.1 | 36 | 0.09 |
| 1999 | 70 | 1.3 | 54 | 49 | 0.1 | 42 | 0.1 |
| 1998 | 60 | 1.1 | 6 | 6 | 0.01 | 5 | 0.01 |

Table 2.3: The top 10 papers with the highest citation reports

| Rank | Title | Author/year | Journal | Research Area | Country/ Institute | Citations |
|---|---|---|---|---|---|---|
| 1 | A slacks-based measure of efficiency in data envelopment analysis | (Tone, 2001) | European Journal of Operational Research | Business & Economics; Operations Research & Management Science | Japan/ National Graduate Institute for Policy Studies | 1,037 |
| 2 | Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications | (Rebitzer et al., 2004) | Environment International | Environmental Sciences & Ecology | Switzerland/ Swiss Federal Institute of Technology | 693 |
| 3 | Analysis and quantification of the diversities of aerosol life cycles within AeroCom | (Textor et al., 2006) | Atmospheric Chemistry and Physics | Environmental Sciences & Ecology; Meteorology & Atmospheric Sciences | France/ Laboratory for Sciences of Climate and Environment | 615 |
| 4 | A comprehensive survey of the Plasmodium life cycle by genomic, transcriptomic, and proteomic analyses | (Hall et al., 2005) | Science | Science & Technology | USA/ Institute for Genomic research | 572 |
| 5 | Data envelopment analysis (DEA) - Thirty years on | (Cook and Seiford, 2009) | European Journal of Operational Research | Business & Economics; Operations Research & Management Science | Canada/ York University | 569 |
| 6 | A survey of data envelopment analysis in energy and environmental studies | (Zhou et al., 2008) | European Journal of Operational Research | Business & Economics; Operations Research & Management Science | Singapore/ National University of Singapore | 549 |
| 7 | Life cycle energy analysis of buildings: An overview | (Ramesh et al., 2010) | Energy and Buildings | Construction & Building Technology; Energy & Fuels; Engineering | India/ Motilal Nehru National Institute of Technology | 431 |

| Rank | Title | Author/year | Journal | Research Area | Country/ Institute | Citations |
|---|---|---|---|---|---|---|
| 8 | Efficiency decomposition in two-stage data envelopment analysis: An application to non-life insurance companies in Taiwan | (Kao and Hwang, 2008) | European Journal of Operational Research | Business & Economics; Operations Research & Management Science | Taiwan/ National Cheng Kung University | 410 |
| 9 | System boundaries and input data in consequential life cycle inventory analysis | (Ekvall and Weidema, 2004) | International Journal of Life Cycle Assessment | Engineering; Environmental Sciences & Ecology | Sweden/ Chalmers University of Technology | 372 |
| 10 | Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance | (Yang et al., 2011) | Bioresource Technology | Agriculture; Biotechnology & Applied Microbiology; Energy & Fuels | USA/ Georgia Institute of Technology | 368 |

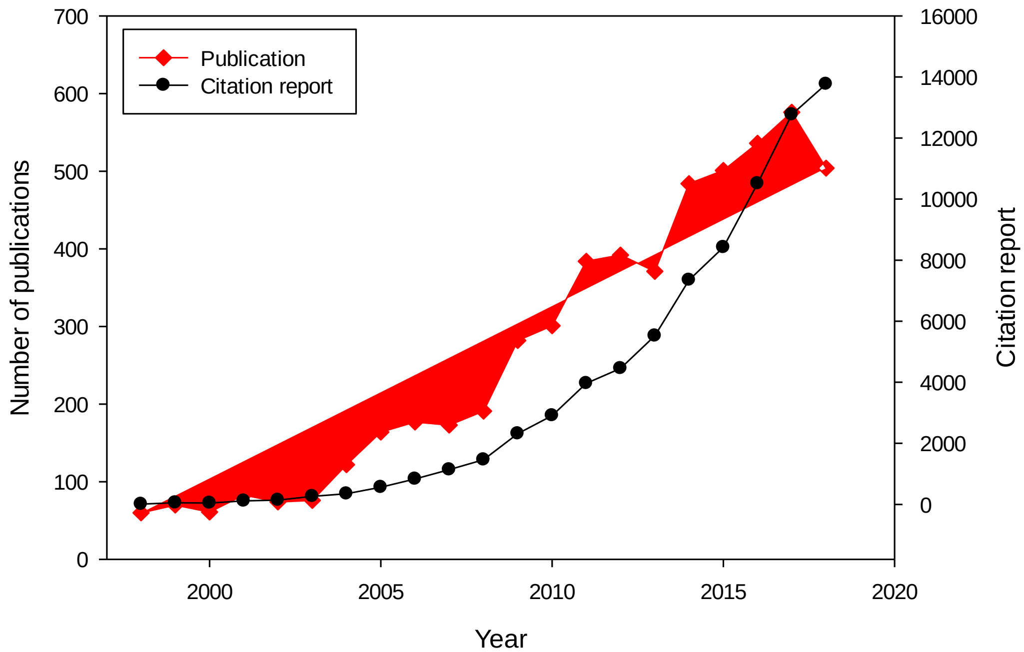


Fig. 2.5: Trends of the number of publications and the citation reports

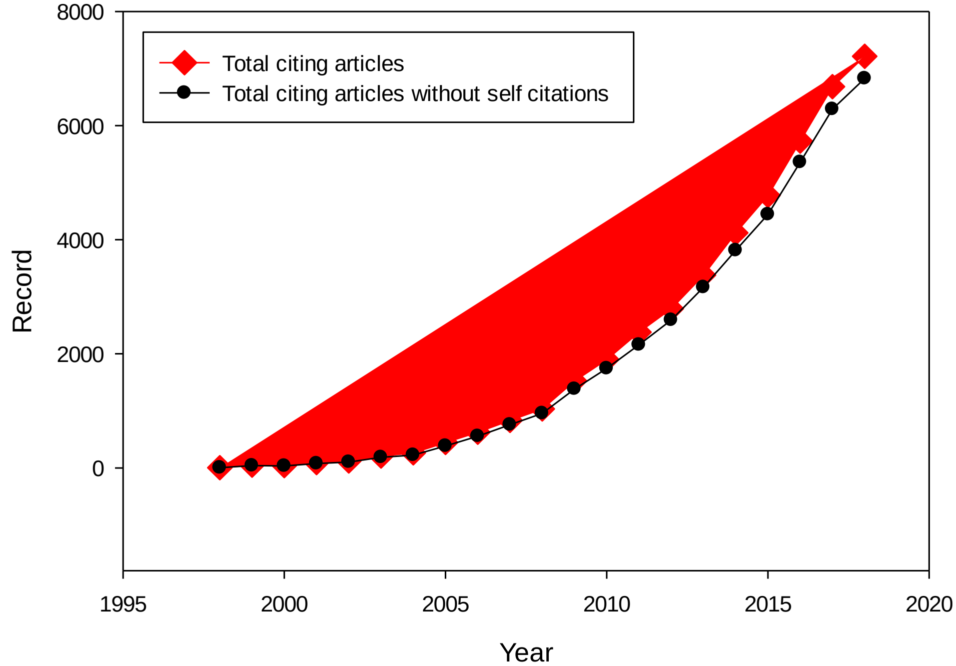


Fig. 2.6: Trends of the total citing articles and the total citing articles without self-citations

### *2.3.3 Keyword analysis*

The keyword analysis shows the most frequently used keywords by authors in eco-efficiency research. VOSviewer software develops a map of keywords based on the co-occurrence (multiple appearance) data (Van Eck and Waltman, 2010). Some authors have argued that bibliometric keyword analysis can be used to identify hot issues and research trends (Zhang et al., 2017). In this study, 14,349 kinds of keywords were identified by VOSviewer. In order to highlight the author keywords with the highest number of occurrences, the threshold was set at 10 (Li et al., 2018) . Threshold here means the minimum number of occurrences of a keyword. For author keywords, only 169 records met this threshold. Fig. 2.7 shows the top author keywords and the co-occurrence links with other keywords. The co-occurrence link shows the relationship between the two keywords connected. It could be seen from the figure that most keywords are connected to more than one other keywords. The circle represents a keyword while the curve/link shows the co-occurrence relationship. The size of the circle reflects the number of occurrences. The cluster in the map is divided mainly into three with each cluster having a unique colour. Author keywords with same colour are more likely to be used in same affiliation (e.g. operational research and management science, business economics, environment, science or engineering). These keywords help to highlight the key topics (Zhong et al., 2016).

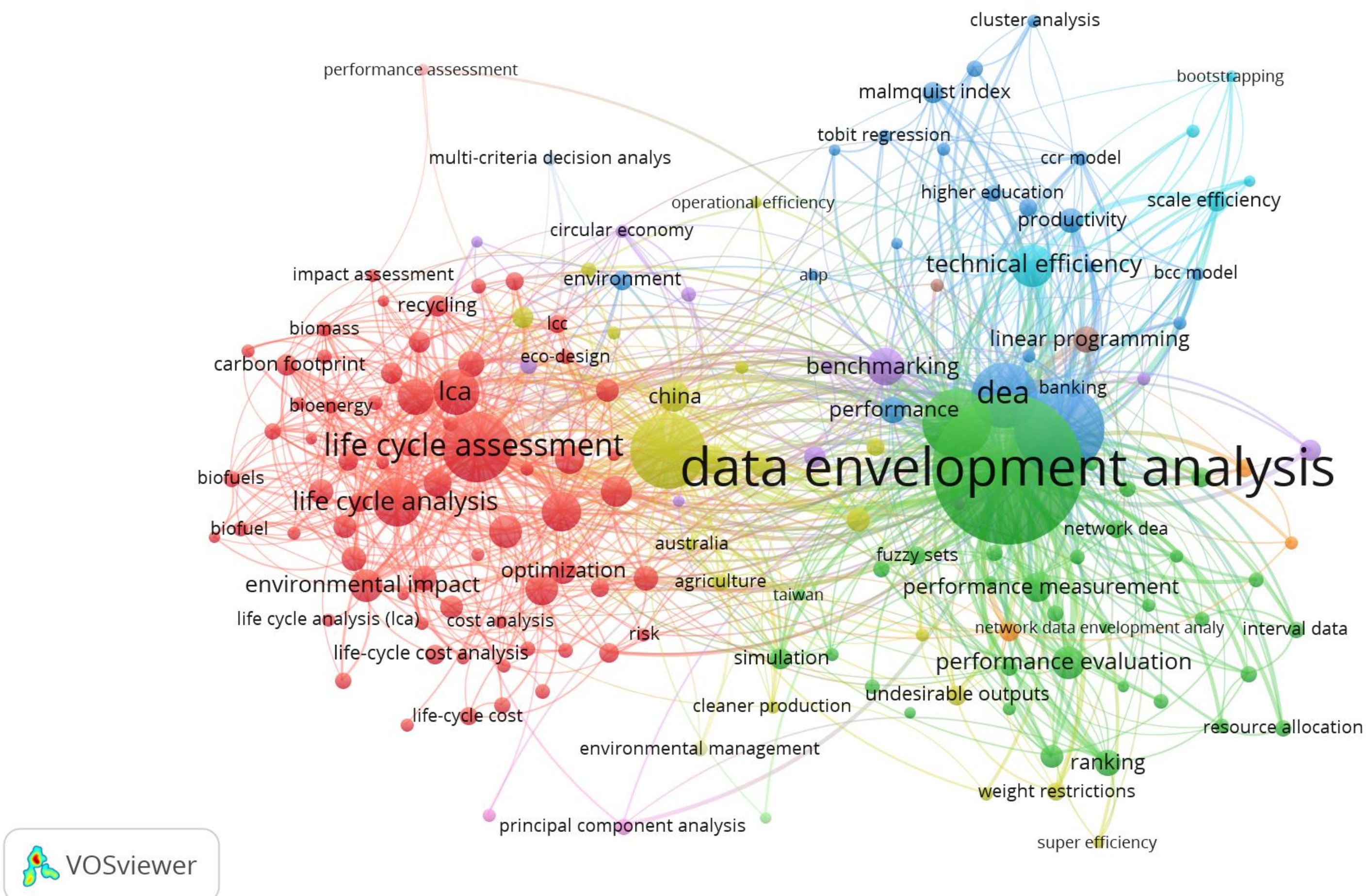


Fig. 2.7: Major author keyword analysis

*Cluster 1 (Blue Cluster):* This cluster includes words like: cluster analysis, CCR model, scale efficiency, technical efficiency, BCC model, Malmquist index, linear programming, benchmarking, performance, multi-criteria decision analysis, banking. The words in this cluster shows the different models used by DEA and the major focus of eco-efficiency analysis. The keywords are explained in the next section.

*Cluster 2 (Green Cluster):* This cluster includes words like: DEA, undesirable output, performance evaluation, decision making units, resource allocation, relative efficiency, fuzzy sets, analytic hierarchy process, simulation, ranking, super efficiency. These keywords are most likely used in operational research, management science and business economics research areas. For instance, the author keywords used by Hatami-Marbini et al. (2018) and Omrani et al. (2018) which belongs to the operational research and management science category are found in this cluster.

*Cluster 3 (Red Cluster):* This cluster includes words like: agriculture, environmental impact, impact assessment, carbon footprint, bioenergy, biofuels, life cycle analysis, life cycle cost analysis, environmental management, environment, cost analysis. The words in this cluster are related to environment. Hence, author keywords used in environmental science research areas are found in this cluster (Khanali et al., 2018; Vinyes et al., 2017; Zhu et al., 2018). Most of these research in environmental science are mainly focused on environmental impact assessment.

#### *2.3.3.1 Short explanation of the authors keywords*

Data envelopment analysis is an analytical tool used in measuring the efficiency and performance of unit processes referred to as decision making unit (DMU) (Cooper et al., 2004).

The appearance of "DMU" could be because it is always used to refer to the process studied in DEA. DMU is simply a unit process or production function. For example, a business process or food process. Hence each DMU consists of a set of inputs and outputs. DEA measures the performances of the selected DMU and give the efficiency of these processes. The best performing process (DMU) is called the frontier.

The keywords "CCR model" and "BCC model" are two types of DEA models. The model names come from the abbreviations of the founders. CCR means Charnes, Cooper and Rhodes while BCC means Banker, Charnes and Cooper. CCR model was proposed in 1978 (Charnes et al., 1978). The BCC model was proposed in 1984 (Banker et al., 1984). Both models are being used in calculating the "technical efficiency" of organizations using the input-output ratio. The technical efficiency is a measure of the input-output ratio. DEA produces a technical efficiency score of the

DMUs on a scale of 0-1. Hence, the best preforming DMU result in the analysis has a technical efficiency of either 1 or 100%. CCR model produces overall technical efficiency while BCC produces pure technical efficiency. The difference in the models is that CCR uses the constant returns to scale (an increase in input causes a corresponding increase in output) while BCC uses the variable return to scale (an increase in input does not result in a proportional increase in output) (Lee, 2009).

The keyword "scale efficiency" is simply overall technical efficiency divided by pure technical efficiency (Lee, 2009).

The keywords "performance evaluation" and "benchmarking" are common methods used in DEA. Performance evaluation in DEA means to assess the strengths and weaknesses of DMU. Benchmark serves as a reference point in multiple performance measures. Performance evaluation and benchmarking are used to identify better improvement options which is targeted at increase in productivity (Zhu, 2014).

The keyword "Malmquist Index" is a DEA method that evaluates the change in productivity of an organization or a unit process over a specific period of time (Sánchez, 2018). Malmquist Productivity Index have been used to measure the productivity changes in banks (Shah et al., 2019).

The appearance of words like fuzzy sets, cluster analysis, linear programming, simulation, raking, resource allocation, undesirable output reveals some terms used in eco-efficiency analysis. "Fuzzy set" is a theory proposed and applied in DEA model to compute vague data (Wen and Li, 2009). The "linear programming" as a keyword originates from the definition of DEA. It is described as a linear programming model (Halkos and Petrou, 2019). "Cluster analysis" here refers to the assessment of a group of data. "Ranking" simply shows the performance of the various units studied. The assessed units are ranked according to their performance. "Resource allocation" simply reveals the inputs and outputs associated with each unit process. This to a great extent determines the efficiency of the organization. "Undesirable outputs" affects the efficiency of the units. These undesirable outputs are accounted for in the DEA study and should be reduced to increase the efficiency of the process (Halkos and Petrou, 2019).

The keyword “analytical hierarchy process” reveals another eco-efficiency technique that is applied in analyzing complex data that requires several evaluation criteria (Lan et al., 2018).

The appearance of agriculture reveals an area of eco-efficiency research application. Some keywords in the red cluster are related to “environment” and “environmental management”. Environment simply refers to our natural world that are affected by human activities and “environmental management” refers to the activities targeted at controlling the influence of human activities in our surrounding.

The keyword “Life Cycle Analysis” reveals another eco-efficiency technique. It is an environmental assessment tool. It follows a four-step methodology. The first step in the LCA methodology is goal and scope definition, the life cycle inventory is the second step, the life cycle impact assessment is the third step while interpretation is the last step (ISO, 2006).

The keywords “impact assessment” and “environmental impact” reflected the third step in the LCA methodology. The impact assessment shows a reflection of the environmental impacts of a product. It shows the contribution to impact categories like global warming, acidification or eutrophication.

The keyword “carbon footprint” reveals another aspect of environmental assessment. Carbon footprint is the amount of greenhouse gas emission from the life cycle stages of a product (Pandey et al., 2011). The life cycle stages of a product starts from the production stage to the end of life stage.

The appearance of “bioenergy” and “biofuels” reveals two sources of energy. Bioenergy is derived from living organisms and their by-products. Some examples of biofuels include ethanol and biodiesel. Both are sources of renewable energy (Rasool and Hemalatha, 2016).

The keywords “life cycle cost” and “cost analysis” reflects the economic aspect of sustainability assessment. Life cycle cost methodology was proposed by (Hunkeler et al., 2008). It follows a similar methodology as life cycle analysis. But in this case, it is related to economic assessment. Cost analysis provides a full assessment of the cost of inputs and outputs.

### *2.3.4 Countries and Institutions analysis*

#### *2.3.4.1 Countries analysis*

This highlights the countries with high eco-efficiency research records. They will be referred to as productive countries in this study (as commonly referred to as in bibliometric analysis). The results of the 20 most productive countries are shown in Table 2.4. According to the Web of Science records, researchers from 112 different countries have published articles with one of the three search terms in the title during the period under review. The results indicate that USA has ranked first with a percentage record of 15.7% of the total publications and China ranked second. The first ten productive countries contribute 60.4% of the total records. These countries are major industrialized countries in the world. Even though China and USA are topping the list in the country's analysis, most prolific institutions are generally not in these two countries (see Table 2.4). The institutions list gives a clearer analysis of the institutions with the highest eco-efficiency research records. (Shiferaw et al., 2005)

The bibliographic coupling presented in Fig 2.8 shows the interactive relationship between countries. The size of the circle represents the strength or activeness of their collaboration. A country is represented by a circle with curves linking different countries together. This curve shows the collaborative relationship existing between them. The articles from countries with the same colour are more likely to have been jointly cited in the different publications. The thickness of the link signifies their collaboration strength.

Table 2.4. Top 20 countries and institutions publishing on “eco-efficiency” or "life cycle assessment" or "data envelopment analysis during the last two decades (1998-2018)

| **Countries/Regions** | | | **Institutions** | | |
|---|---|---|---|---|---|
| Rank | Countries/Regions | Records | Rank | Institutions | Records |
| 1 | USA | 1,070 | 1 | Islamic Azad university | 255 |
| 2 | China | 919 | 2 | University of Tehran | 69 |
| 3 | Iran | 444 | 3 | University of Science and Technology of China | 58 |
| 4 | England | 307 | 4 | Chinese Academy of Sciences | 52 |
| 5 | Taiwan | 265 | 5 | Aston University | 47 |
| 6 | Spain | 246 | 6 | National Cheng Kung University | 44 |
| 7 | Germany | 226 | 7 | Worcester Polytechnic Institute | 41 |
| 8 | Japan | 216 | 8 | Hong Kong Polytechnic University | 39 |
| 9 | Canada | 214 | 9 | Tsinghua University | 38 |
| 10 | Italy | 212 | 10 | University of Toronto | 38 |
| 11 | Australia | 175 | 11 | National Chiao Tung University | 34 |
| 12 | India | 175 | 12 | York University | 33 |
| 13 | Brazil | 170 | 13 | Indian Institute of Technology | 30 |
| 14 | South Korea | 141 | 14 | La Salle University | 30 |
| 15 | Netherlands | 135 | 15 | Argonne National Laboratory | 29 |
| 16 | Turkey | 135 | 16 | University of Michigan | 29 |
| 17 | Malaysia | 120 | 17 | North China Electric Power University | 28 |
| 18 | France | 117 | 18 | University of Massachusetts | 28 |
| 19 | Greece | 98 | 19 | Iran University of Science and Technology | 27 |
| 20 | Belgium | 95 | 20 | Federal University of Rio de Janeiro | 27 |

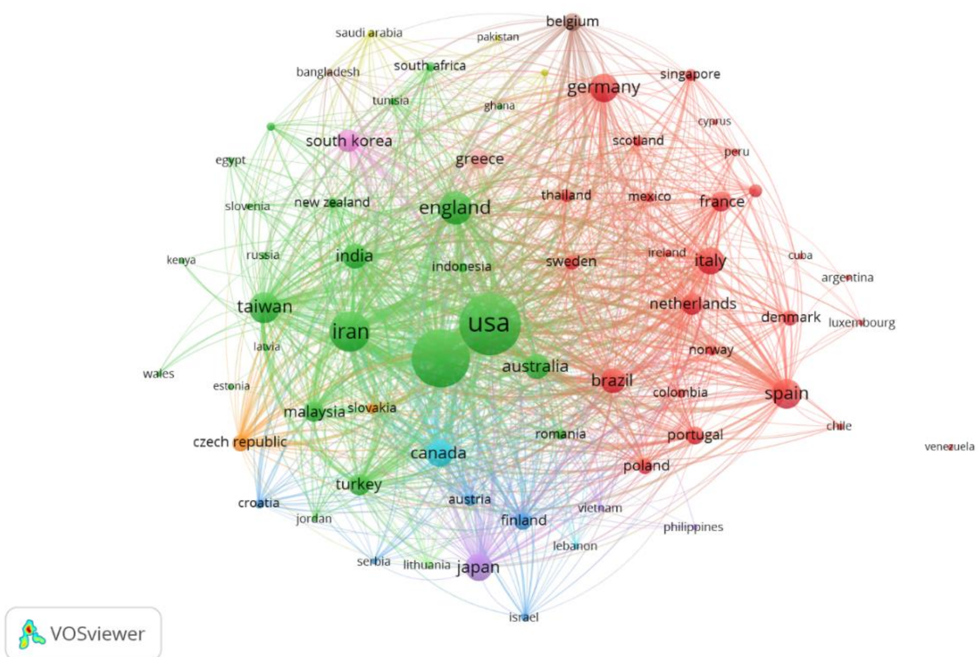


Fig. 2.8: Bibliographic coupling between countries.

### *2.3.4.2 Institutions analysis*

The institutions analysis gives a clearer picture of the institutions with eco-efficiency research records. According to the Web of Science records, authors from 3,738 institutions have published on eco-efficiency. Table 2.4 shows the top 20 most productive institutions conducting eco-efficiency research within the review period. Islamic Azad University, a semi-private university system in Iran is the leading institution with the highest publication records on eco-efficiency. The University of Tehran, which is the oldest modern university located in Tehran, Iran and one of the most prestigious universities in the Middle East is the second most productive institution. These two institutions from Iran have a significant record of 324. Also, apart from two institutions from Taiwan and four institutions from China, other research institutions (organizations) that topped the list came from developed countries (USA, United Kingdom, Hongkong, Canada, Brazil).

The bibliometric coupling shows the interactive relationship between the organizations. The bibliographic coupling between organisations is presented in Fig. 2.9. The research institutions (organisations) with the same colour are more likely to have been jointly involved in several publications. An organisation is represented by a circle with curves linking different institutions together. The thickness of the link signifies their collaboration strength while the size of the circle indicates the number of publications. In this case, Islamic Azad University has the largest circle because it had the most publications.

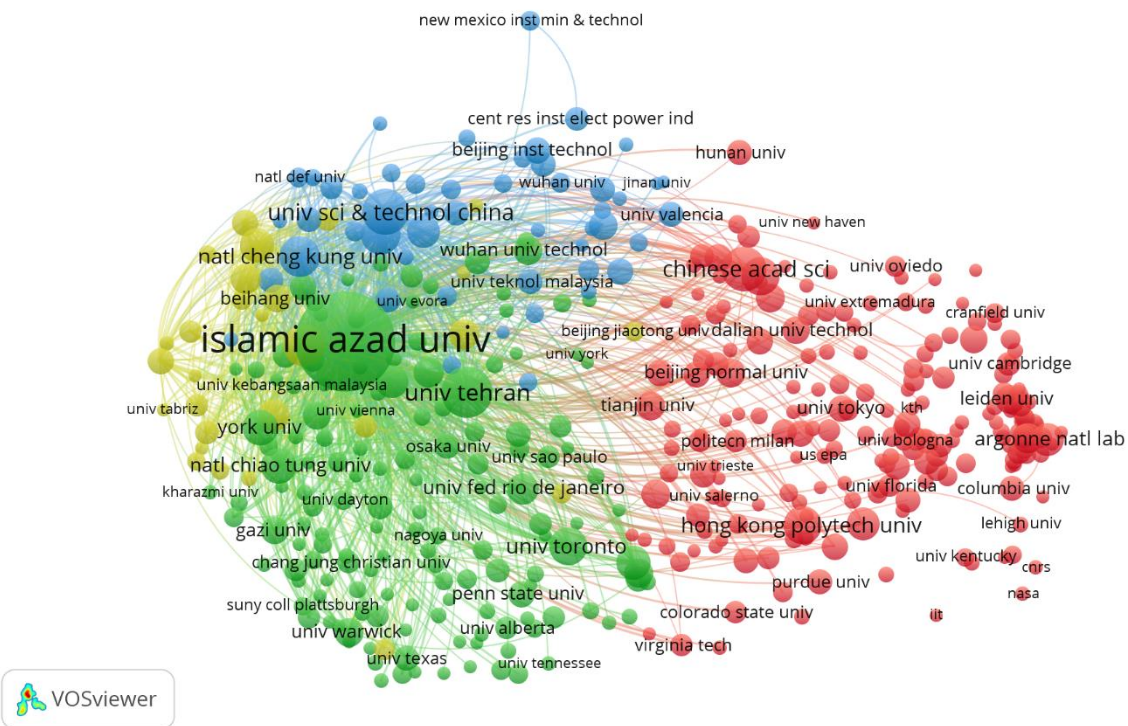


Fig. 2.9: Bibliographic coupling between organisations.

### *2.3.5 Author's analysis*

The author analysis shows the publication record of different authors in this study. Table 2.5 shows the top 30 productive authors. The number of publications by a researcher reflects their academic strength and prowess, which shows their relevance in the area of study (Wang et al., 2018). From the Web of Science records, there are 11,825 authors with 70 of them having publication records greater or equal to ten. The result shows that Saen R. F. and Zhu J. have the highest record of 48 publications. Most of their research are mainly on industrial management (Saen, 2010), environment (Shabani et al., 2015), business economics (Shabani et al., 2014), industrial technology and engineering (Rashidi and Saen, 2015), sustainability management (Lee and Saen, 2012), supply chain management (Mirhedayatian et al., 2014), business & economics, (Saen and Azadi, 2011), operations research & management science (Zhu, 2016), telecommunication company (Zhu, 2004), manufacturing industry (Gong et al., 2018). Zhu Joe's research on modelling undesirable factors in efficiency evaluation has the highest citation report with records of 533 among all the publications in his papers (Seiford and Zhu, 2002). Most of their studies were focused on the application of DEA technique for performance evaluation in the various sectors. This could reflect the multi-disciplinary application of eco-efficiency. It could also mean that the author is exploring the application of DEA in many research areas.

To further explore the collaboration citation between authors, the VOSviewer map analysis was used. Fig. 2.10 shows the collaboration citation between authors. Authors that have been jointly cited in a given research paper have the same colour on the map (Ertz and Leblanc-Proulx, 2018). An author is represented by a circle with curves linking different authors together. This curve shows the collaborative relationship existing between them. Collaboration among researchers gives rise to academic development (Wang et al., 2018).

Table 2.5: Top 30 Authors with published works on "eco-efficiency" or "life cycle assessment" or "data envelopment analysis" (1998-2018)

| Rank | Authors | Records | Rank | Authors | Records |
|---|---|---|---|---|---|
| 1 | Saen R. F. | 48 | 16 | Toloo M. | 17 |
| 2 | Zhu J. | 48 | 17 | Wu J. | 17 |
| 3 | Emrouznejad A. | 33 | 18 | Herrmann C. | 16 |
| 4 | Jahanshahloo G. R | 33 | 19 | Kara S. | 16 |
| 5 | Lotfi F. H | 32 | 20 | Nijkamp P. | 16 |
| 6 | Amirteimoori A | 31 | 21 | Suzuki S. | 16 |
| 7 | Chen Y. | 31 | 22 | Khodabakhshi M. | 15 |
| 8 | Kordrostami S. | 27 | 23 | Lozano S. | 15 |
| 9 | Tavana M. | 27 | 24 | Podinovski V. V | 15 |
| 10 | Liang I. | 24 | 25 | Guillen-gosalbez G. | 14 |
| 11 | Wang Y. M. | 23 | 26 | Iribarren D. | 14 |
| 12 | Hatami-marbini A. | 22 | 27 | Li Y. | 14 |
| 13 | Kao C. | 22 | 28 | Kuosmanen T. | 13 |
| 14 | Cook W. D. | 18 | 29 | Matin R. K. | 13 |
| 15 | Azadeh A. | 17 | 30 | Wen M. L. | 13 |

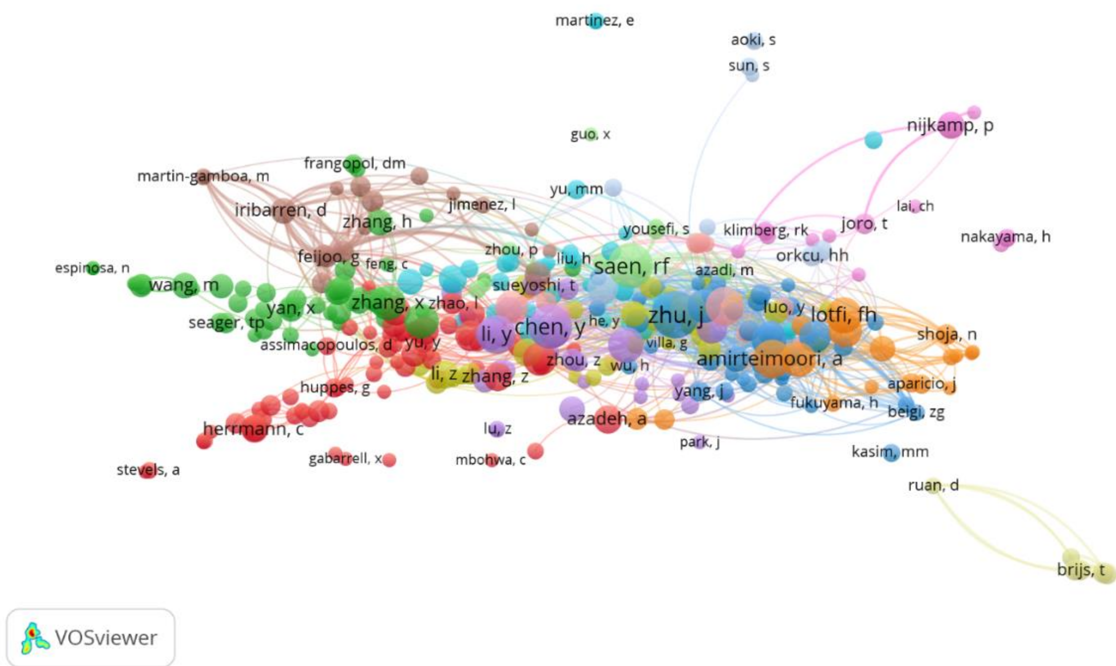


Fig. 2.10: Map analysis of citation between authors.

### *2.4 Discussion*

The result shows the different applications of eco-efficiency and the two eco-efficiency techniques (LCA and DEA) in different research areas, by different countries, institutions and authors with an additional analysis of the authors keywords. The cluster analysis shows the most frequent author keywords in the different fields. For instance, a study by Omrani et al. (2018) which falls in the Operations Research and Management Science category applied DEA to measure the efficiency of a hospital. The major author keywords are "fuzzy", "DEA" and "efficiency" which are found in the green cluster. A similar publication in the Operations Research and Management Science category by Hatami-Marbini et al. (2018) also has DEA, efficiency, fuzzy data and ranking as the author keywords. These keywords are also found in the green cluster. This shows the major focus of the study in this research area. On the other hand, research in environmental science related areas have words like agriculture, environmental impact, life cycle analysis, life cycle cost analysis, biofuels found in the red cluster as their major keywords. Considering the research focus of these two research areas, future eco-efficiency research could integrate the keywords in Operations Research and Management Science category in Environmental science research area. This could be a good potential of eco-efficiency future research. A good example of this combination is found in an environmental science research where Rybaczewska-Błażejowska and Masternak-Janus (2018) applied LCA and DEA in the eco-efficiency assessment of Polish region. Other authors also applied LCA and DEA in the eco-efficiency assessment of cotton-cropping systems in Pakistan (Ullah et al., 2016). This could offer a more comprehensive eco-efficiency assessment as it incorporates the strength of the two eco-efficiency techniques.

Most authors have worked in one research area while there are some authors who have worked in multiple research areas. The first and second most productive authors in this study have worked in multiple areas. For example, Sean has published articles about industrial management (Saen, 2010), environment (Shabani et al., 2015), business economics (Shabani et al., 2014), industrial technology and engineering (Rashidi and Saen, 2015), sustainability management (Lee and Saen, 2012), supply chain management (Mirhedayatian et al., 2014), business & economics, (Saen and Azadi, 2011), operations research & management science (Zhu, 2016), telecommunication company (Zhu, 2004), manufacturing industry (Gong et al., 2018). Since eco-efficiency can be applied across many disciplines, authors can strive to explore the application of this concept in different areas and not only in their specific field. This can be achieved by collaboration between authors from different institutions. The institutions that are home to people with interest in eco-efficiency research are shown in the institution analysis. An effective collaboration between them has the potential of producing more eco-efficiency research in different areas. Institutions from other countries that have low eco-efficiency research records could also collaborate with these institutions.

### *2.5 Author's views on eco-efficiency research*

The authors of this paper are of the view that beyond stringent regulations and eco-labelling practices, if business owners have evidence of reduced resource utilization or increased economic value while reducing environmental impact (eco-efficiency assessment), there might be a greater industrial desire for sustainability. For instance, if there were a recognized index/indicator that allowed enterprises to evaluate both environmental and economic components of process/products or options, it might lead to more sustainable decisions. Again, there is the need to include sector-specific elements to cater for important sector-oriented quality. For example, when eco-efficiency is applied to food production or processing, it would be necessary to include nutritional or product quality when assessing the value addition component of the eco-efficiency ratio/indicator. This will allow enterprises not only to evaluate their environmental performance but also their product quality or value-added. This will likely increase the efficiency of resource utilization (raw material, energy, and water), improving product and process quality, and evaluating the enviro-economic performance of food systems.

One of the essential benefits of eco-efficiency is the ability to integrate or combine tools like DEA and LCA for a more comprehensive sustainability assessment as well as evaluate various options. There could be advances in eco-efficiency research. One of the possible advances could be not only to measure the current efficiency of the system but to also provide alternative improvement options. The authors do suggest that future researchers could provide economic and environmental as well as technical efficiencies of proposed alternatives following the eco-efficiency assessment especially when decision-making tools are employed to rank proposed alternatives.

Although eco-efficiency research is dominated by the engineering (37.6%), business economic (22.8%), environmental science (19.3%) operational research (16%) field, there is a potential for its use in other areas. For example, applying the concept in tourism could allow the evaluation of economic and environment performance even in local guest houses or local restaurants. However, this will require simplified eco-efficiency models and techniques for easy application.

The data shows that most eco-efficiency research is from developed and fast-developing countries. It is therefore essential for developing countries to join in the eco-efficiency research space since global sustainability cuts across the countries of the world. Again, the developing countries are more exposed to hunger and starvation, have less technology or capacity to reduce waste, hence a need to ensure economic sustainability and good resource management among these countries. Global sustainability is certainly also dependent on rural sustainability since a significant number of rural dwellers are exposed to dangers associated with climate change and poverty.

### *2.6 Conclusions*

Over the twenty-year period reviewed, eco-efficiency research has grown cutting across several disciplines, with publication mostly in developed and fast developing countries. While several techniques may be used for eco-efficiency analysis, LCA and DEA have been the predominantly used approaches.

The categories analysis shows that the research areas are mainly in engineering, business economics, environmental and sciences. Also, the four most productive journals in eco-efficiency research are Journal of Cleaner Production, European Journal of Operational Research, International Journal of Life Cycle Assessment, Journal of the Operational Research Society. Countries like USA, China, Iran, England and Taiwan have a good eco-efficiency research record. Islamic Azad university and university of Tehran have the highest research record in the institution list. The major author keywords in this study were either related to eco-efficiency or to either of the two eco-efficiency techniques (LCA and DEA). The growth trend analysis shows that there has been an increase in eco-efficiency research in the years under review peaking in 2017. As sustainability concerns deepens, eco-efficiency could provide stakeholders the opportunity to improve overall sustainability performance.

**Connecting Text**

The bibliometric analysis of eco-efficiency research in the last two decades (1998-2018) has been presented in the preceding chapter. The next chapter gives a review of the concept of eco-efficiency, identifies the strength and weakness of the concept and its potential advances. The next chapter also reviews the concept and application of Life Cycle Assessment and Data Envelopment Analysis. It further highlights their major application in the food industry

# 3 REVIEW OF LITERATURE

***Abstract***
Eco-efficiency is an interdisciplinary sustainability technique with a broad application in different sectors and areas including the food and agricultural sector. Due to the quest for industrial development, the need for efficient resource use and appropriate assessment approaches make eco-efficiency an indispensable tool in the food sector. Eco-efficiency approaches can be applied across the entire food value chain. This section is a discussion of eco-efficiency as a sustainability tool with a focus on its application in the food industry. It is a review of the different applications of eco-efficiency and the primary assessment techniques employed including Life Cycle Analysis (LCA), Data Envelopment Analysis (DEA) and combined LCA and DEA techniques. Additionally, the strengths and benefits of its application, as well as the weakness in their uses as an assessment tool has been discussed.

**Keywords**: Eco-efficiency, sustainability, food processing, food value chain, data envelopment analysis, life cycle analysis.

### *3.1 Overview*

Recent impact of climate change on agriculture has intensified food system sustainability research (Béné et al., 2019). This food system sustainability can be linked to the broad sustainable development agenda. Sustainable development implies "a *development that meets the needs of the present without compromising the need of future generations*"(Brundland, 1987). It comprises of three components namely, economic, environmental and social. For a development to be considered as sustainable, it is imperative to integrate these three dimensions (Tonelli et al., 2013). In order to achieve these three components, organizations have adopted various approaches such as ISO 14001 for environmental assessments, sustainable supply chain (Seuring and Müller, 2008), Life Cycle Assessment (LCA) (EPA, 2006; Rebitzer et al., 2004), green engineering (Anastas and Zimmerman, 2003), sustainable energy management (Pohekar and Ramachandran, 2004), factor X (Robèrt et al., 2002), performance indicators (Singh et al., 2009), ecological footprinting (Wackernagel et al., 2002), cleaner production, the natural step framework and product stewardship (Arena et al., 2009; Remmen, 2007), theoretical models to study sustainability (Garriga and Melé, 2004), eco-efficiency (Lupan and Cozorici, 2015; Rybaczewska-Błażejowska and Masternak-Janus, 2018). While these approaches have different names, their intended outputs are all geared towards one or more of the dimensions of sustainability in the food industry and other organizations.

Eco-efficiency has been applied for sustainability assessment by several authors. In the food system, the two major eco-efficiency techniques such as LCA and Data Envelopment Analysis has been used for eco-efficiency assessments (Rybaczewska-Błażejowska and Masternak-Janus, 2018; Soteriades et al., 2016; Vázquez-Rowe et al., 2010). In this review, the focus is to understand the concept of eco-efficiency, defining the concept from a resource use perspective and sustainability (social, economic and environment) perspective. The application of the two eco-efficiency techniques (LCA and DEA) will be discussed. Similarly, the gap, potential advances, strength and weakness of eco-efficiency will also be reviewed in this chapter.

### *3.2 Eco-efficiency*

Eco-efficiency has been described as a trend pointer to sustainable development (Caiado et al., 2017). The concept is associated with creating more output with same or less input with a corresponding economic and environmental efficiency. Notably, the concept of eco-efficiency can be traced back to the 50s and since then, several authors have suggested myriad descriptions of the concept (Debreu, I951). For instance, Zhang et al. (2008) viewed eco-efficiency as an assessment tool for measuring sustainability. while, Zhou et al. (2018) considered eco-efficiency as a sustainability assessment that incorporates ecology and economics. Regardless of the definition, the application of the concept of eco-efficiency is essential for the sustainability of food systems. The implementation of its perceptions combined with other sustainability assessment approaches like green engineering can create a desired sustainable development in the food industry (Anastas and Zimmerman, 2003; Lupan and Cozorici, 2015; Zhang et al., 2008; Zhong et al., 2020).

The application of eco-efficiency in the food sector employs different techniques to assess the environment, economic and social efficiency. It targets the efficient use of resource while minimizing waste generation across the various life cycle stages of food systems. (Duflou et al., 2012; Müller et al., 2015). Eco-efficiency has been applied across different sizes of the industry (large, medium and small-scale), and for the developed, developing and underdeveloped regions (Alves and de Medeiros, 2015). The main aspects of eco-efficiency are environmental, economic and resource use efficiency (Lupan and Cozorici, 2015) .

### *3.2.1 Eco-efficiency from a resource use efficiency perspective*

The concept of eco-efficiency is built around efficiently using resources in a way that influences the various components of sustainability. The concept of resource use in the context of eco-efficiency entails input-output efficiency. Considering the fact that most activities in product-oriented industry are input-output focus, the practical implication of eco-efficiency would be to produce higher output with less input. A successful application use could lead to minimal emissions and pollutions, hence a better environmental performance. It could also influence the organization's profit as there is a reduction in the cost of inputs (Lupan and Cozorici, 2015). From a social perspective, a less polluted environment has less negative health implications, similarly, when local enterprises perform better economically there is indirect social implications on the communities they operate (jobs, community support, etc.). Achieving such eco-efficiency benefits requires implementations of methods like industrial ecology, reduce, reuse and recycle and green-supply chain management to achieve resource use efficiency (Davé et al., 2016). Details of the application of eco-efficiency to achieve the different components of sustainability is discussed below

### *3.2.2 Eco-efficiency from the environment efficiency perspective*

The ecology concept in eco-efficiency is built around assessing and improving the environmental efficiency of product or processes. Environmental accountability and stewardship are essential for any sustainability technique. Generally, humans and the environment are the main aspects of environmental sustainability. The inputs (materials, energy, water) and outputs (emissions, wastes, products and services) are the primary sub-dimensions of environmental sustainability (Arena et al., 2009). The effective management of these sub-dimension through human dynamics and industrial operations will have the potential of reducing the impact on the environment. These could mean some modifications of operations and activities that threatens the physical environment.

Several studies have applied eco-efficiency technique (LCA) to assess the environmental impact of food products and processes (Khanali et al., 2018; Soteriades et al., 2016; Zhu et al., 2018). In their research, they evaluated the environmental performance based on the emissions from the inputs and outputs. In the food industry, inputs and outputs contribute to environmental degradation (Allocca, 2000). For each unit process, eco-efficiency approaches focuses on increasing output and reduction of waste (Li et al., 2012). Organizational management policies and practices vary and this to a greater extent influences the environmental impact of the product and their adherence to environmental policies and regulations. For instance, the International Standard Organization provides the (ISO 14001) which is an environmental-related standard for organizations (Arena et al., 2009). The Life Cycle Assessment (LCA), an eco-efficiency technique is a reliable tool for evaluating the environmental performance of a product throughout its life cycle (Arena et al., 2009; EPA, 2006; Rebitzer et al., 2004). The Life Cycle Inventory (LCI) provides the inflow and outflow data of a product. This gives a reflection of the emissions associated with each unit processes and this subsequently gives direction to improvement (Lozano et al., 2009).

### *3.2.3 Eco-efficiency from the economic efficiency perspective*

The economic aspect of sustainability forms a major concern to the organizations, and this determines their competitive advantage in the marketplace. The overall price of the product in the market, the economic returns of the organization and the value placed on the goods by the consumers are a direct function of the operational and resource use efficiency. Therefore the main interest of organizations is to use processes, techniques and operations that produce more output with less input to be cost-effective (May and Kiritsis, 2017). For sustainability metrics of the food industry, the economic metrics comprises mainly the raw material, energy and the overall input-output ratio. By applying lean production techniques, eco-efficiency improves the organization's value and profit and its strategies suggest better alternatives that enhance better performance along the value chain (Carvalho et al., 2017). For organizations, economic, efficient use of resource and industrial development are closely linked (Gilli et al., 2017). Process improvement which gives rise to resource use optimization drives economic development (Winter et al., 2014). The fundamental preconditions in eco-efficiency assessment is concerned with value creation. It analyzes and quantifies how sustainable an organization is in terms of their products and processes (Saling et al., 2002). Industrial performance varies and this affects the society in terms of both economic and social values (Despeisse et al., 2016). The application of eco-efficiency techniques targets development and sustainability in business operations. Thus, helping businesses to maintain and develop profitable operations. Its indicators can be applied at the micro, macro and regional levels to achieve the organization's economic development target (Lupan and Cozorici, 2015)

Several studies have used Life Cycle Cost and DEA to evaluate the economic performance and operational efficiency of organizations, respectively (Laso et al., 2018; Picazo-Tadeo et al., 2011). The economic performance gives a clear picture of the major contributors to input cost, product cost and profit margin for the firm. The operational efficiency reviews the inefficiencies associated with the products or processes.  Each of these eco-efficiency assessments is based on the input-output ratio and resource utilization.

### *3.2.4 Eco-efficiency from the social efficiency perspective*

The worker, the consumer and society form the main dimension of social sustainability.  Working practices is one of the sub-dimensions of social sustainability. By promoting technological innovations, eco-efficiency improves working practices and conditions and product quality (Moll and Gee, 1999; Pop and Pop, 2007) For a business to be sustainable, its policies should not only consider the environment and economic aspects but should also have a social standard (Giovannoni and Fabietti, 2013). Social Accountability (SA 8000) is the standard for organizations related to the social aspect of sustainability (Arena et al., 2009). There are several social assessment tools that are being used. For instance, the Social Life Cycle Assessment have been used to study the social values of a product (Lenzo et al., 2017). Other eco-efficiency social assessment tools like SEEBALANCE assesses the social impact of an organization's process and products (Kolsch et al., 2008). In addition, socio-ecoefficiency ratio evaluates the corporate social responsibility (CSR) of an organization (Charmondusit et al., 2014). Similarly, AgBalance methodology considers the social impact of a food product (Laginess and Schoeneboom, 2016).

The concept of eco-efficiency has been applied in different disciplines. Its application in the food systems will be reviewed in the next section.

### *3.3 Application of eco-efficiency in the food industry*

Eco-efficiency in the food industry have been mainly applied to measure economic and environmental efficiency (Zhong et al., 2020). The need to preserve our resources has given rise to sustainability measures. Although, there are reports of eco-efficiency application for economic and social sustainability, the technique has primarily been applied to evaluate the environmental performance of various aspects of the food value chain. This may be attributed to the significant impact of climate change in the last two decades (Béné et al., 2019; Dury et al., 2019). The climate change impact, coupled with the dwindling natural resources makes the threat to industrial raw materials more evident, hence an efficient application of techniques such as eco-efficiency has become even more necessary to ensure not only resource use efficiency but also a sustainable food system (Dury et al., 2019; Keating et al., 2010). In the downstream sector of the food value chain, it largely emphasizes on improved industrial productivity, adding economic value and reduction in environmental impact. Achieving this sustainability feat entails that the best eco-efficient approaches are employed, and advances could also be made to ensure a more efficient production. Keating et al. (2013) see eco-efficiency as a concept whose techniques that have been largely adapted in the manufacturing industry. The commonly used eco-efficiency approaches used for food system sustainability including Life Cycle Assessment LCA, Data Envelopment Analysis DEA are discussed further.

### *3.4 Life Cycle Assessment*

The Life Cycle Assessment is an internationally recognized methodology for environmental assessment. It is the evaluation of the potential environmental impacts of inputs and outputs of a product throughout its life cycle (ISO, 2006). It could be traced back to as early as the late 1960s and since then, it has proven to be an effective environment assessment methodology. The assessment is based on the organization's inventory data. The results from the assessment provides environmental accountability and aids in decision making (Chang et al., 2014; Ji and Hong, 2016). There are other environmental assessment techniques such as carbon footprint, water footprint, energy footprint, nitrogen footprint, emission footprint (Čuček et al., 2012) Some LCA terminologies are defined in Table 3.1 with their examples. Table 3.2 presents some Life Cycle

Assessment research in the food industry; their functional unit, system boundary and the impact categories. LCA follows a four-step methodology as shown in Fig. 3.1 (Allocca, 2000; ISO, 2006).

In the first step, the goal and scope of the study are clearly defined which includes the reason of study, the targeted audience, the functional unit, system boundary, the software, the life cycle impact assessment (LCIA) methodology, LCA databases to be used, etc. The concepts have been defined in Table 3.1. Some examples of LCIA methodology are Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), ReCiPe and CML. The TRACI methodology is designed with United States data (Menoufi, 2011). ReCiPe presents the assessment results in different levels is mainly used in Europe (Goedkoop et al., 2009). Both methodologies are widely used in LCA studies.

The Life Cycle Inventory (LCI) is the second step of the LCA. This stage involves data collection, relating the data to the functional unit and data aggregation. The source of data can be from onsite operations or from existing database. The onsite data reflects the actual input and output of the processes. Some examples of LCA databases are Ecoinvent, National Renewable Energy Laboratory Life Cycle Inventory, IPCC Emissions Factor Database, Australia Department of Climate Change. This data forms the basis of assessment for the next step.

The Life Cycle Impact Assessment (LCIA) is the third step. This step involves classification of flows, characterization, normalization and weighting. Classification in LCA means assigning the inventory results to impact categories. Characterization means adding all the contributions of inputs and outputs to each impact category. In this step, normalization which is the calculation converting the category indicator results to a reference information is optional. Weighting is also optional in this step. Weighting is using numerical factors to aggregate the results of the impact categories. These assessments are done using an LCA software. The result of this assessment forms the basis for interpretation which is the last step in the methodology.

The last step in the LCA methodology is the interpretation phase, in this step, the key issues are identified, evaluation of completeness and consistency checks and sensitivity analysis are done (ISO, 2006). These terms have been defined in Table 3.1. The LCA research in the food system follows this four-step methodology in their environmental assessment. Table 3.2 presents some LCA studies. As seen from the table, most of the studies used a functional unit of 1kg of the product except in few cases like organic blueberry with a functional unit of 170g and sea cucumber with a functional unit of 1000 kg (Chapa et al., 2019; Hou et al., 2019). The system boundary for the different studies varies; some of which include cradle to cradle, cradle to grave, gate to grave, etc. as shown in Table 3.2. The system boundary determines the scope of the assessment. The impact categories for each study varies. Most of them have common impact categories like global warming potential, acidification and eutrophication, etc. The result of the impact assessment represents the environmental performance of the products.

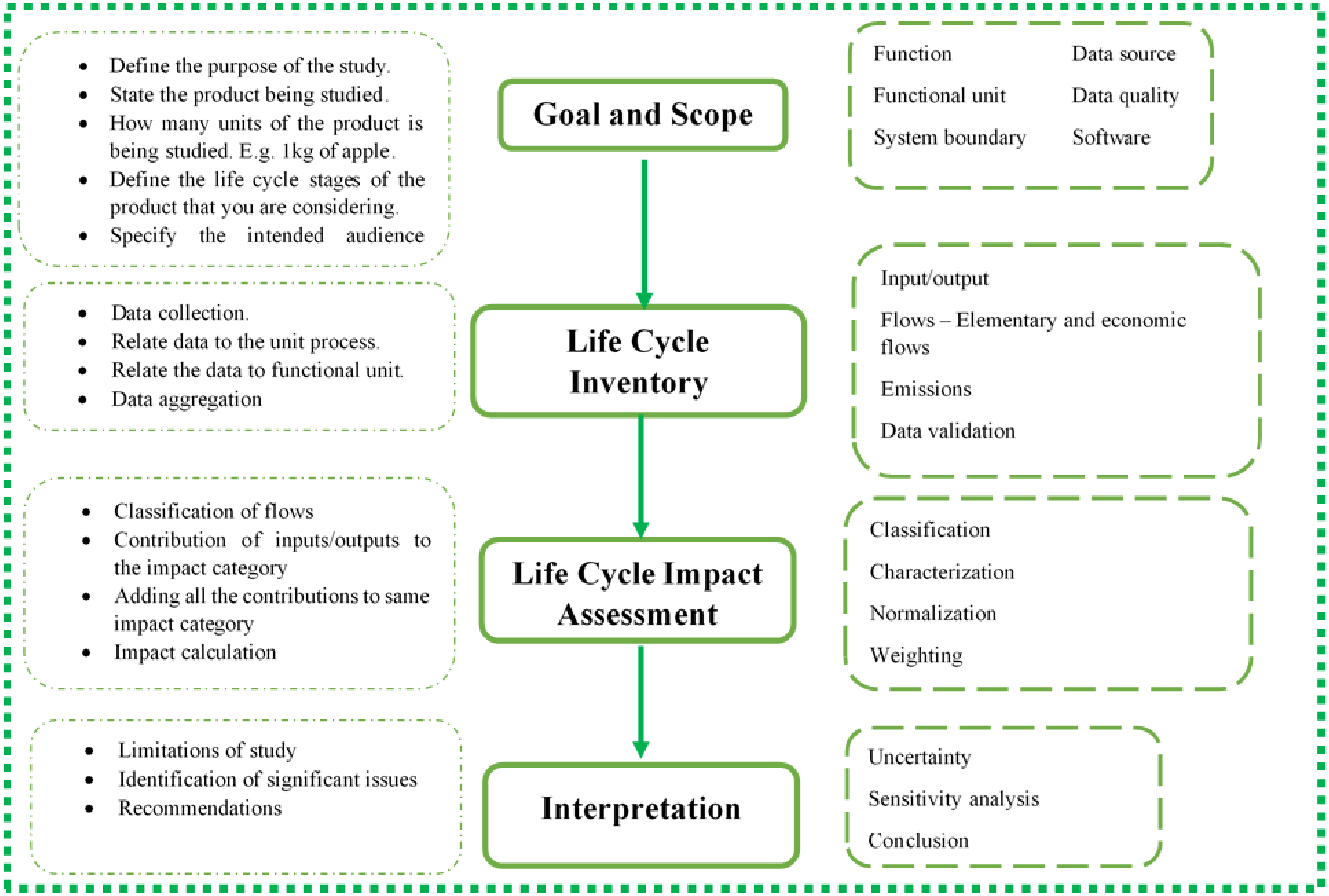


Fig 3.1. Life Cycle Assessment Framework

Table 3.1: Various terms used in Life Cycle Assessment, their definitions and some examples

| **Term** | **Definition** | **Example** |
|---|---|---|
| Function | The purpose of use | Food, meat for consumption |
| Functional unit | Refers to as the quantified function or calculation reference | 1kg of apple, 1kg of orange juice |
| System boundary | The unit processes included in the assessment | Cradle to cradle, cradle to gate, gate to gate, cradle to cradle |
| Unit process | Refers to a subdivision of the system | Production, processing, storage. |
| Data | Statistics gathered for calculation | Primary or secondary data |
| Data source | The origin of the data | On site or from database |
| Input | The resources that goes into the system | Raw material, electricity, water |
| Output | The emissions or products from the system | Products, $CO_2$, waste. |
| Emission | Discharge from the processes | Emission to water, air, lands. |
| Flow | Inputs/outputs moving in an out of the system | Economic and elementary flows |
| LCA software | A computer program used for the environmental assessment | GaBi, Open LCA, SimaPro |
| Impact category | A class representing an issue of environmental concern | Acidification, eutrophication |
| Classification | Assigning the inventory results to impact categories | $CO_2$ is linked to global warming |
| Characterization | Adding all the contributions of inputs and outputs to each impact category | Characterization results include acidification and eutrophication potential |
| Normalization | Calculation converting the category indicator results to a reference information | Area or person equivalents |
| Weighting | Using numerical factors to aggregate the results of the impact categories. | Could be expressed in monetary values |

| | | |
|---|---|---|
| Uncertainty | The things we do not know | Parameter or model uncertainty |
| Sensitivity analysis | An analysis to determine how a change in data or methodology affects the results | Data or methodology change |
| Variability | The extent to which the things we know may change | Object or geographical changes |

Table 3.2: Few Life Cycle Assessment research in the food industry, their functional unit, system boundary and the impact categories.

| **Product** | **Functional unit** | **System boundary** | **Impact category** | **Reference** |
|---|---|---|---|---|
| Organic apple | one tonne of apples | Cradle to the point-of-sale. | Global warming, acidification, aquatic eutrophication potentials, human toxicity, aquatic eco-toxicity, and soil eco-toxicity potentials | (Zhu et al., 2018) |
| Legume | 1kg of packaged product | Cradle to grave | Global warming potential, non-renewable energy demand, human toxicity, water scarcity index and fresh water aquatic eco-toxicity | (Del Borghi et al., 2018) |
| Food waste | 1 kg of food waste | gate-to-grave | Global warming potentials, acidification, ozone depletion, terrestrial land use, eutrophication, terrestrial ecotoxicity, marine water consumption | (Yeo et al., 2019) |
| Organic Blueberry | 170 g of blueberries | Cradle to customer | Global warming potential, abiotic resource depletion, acidification potential, ozone depletion potential, eutrophication potential, stratospheric human toxicity potentials, freshwater and marine aquatic ecotoxicity. | (Chapa et al., 2019) |
| Macauba fruit | One tonne of Macauba fruit | Cradle to farm gate | Human health, resources and ecosystem quality | (Fernández-Coppel et al., 2018) |
| Apple and peach | 1kg of fruit | whole production | Climate change, ozone depletion, photochemical oxidant formation, marine eutrophication, terrestrial acidification, | (Vinyes et al., 2017) |

| | | | | |
|---|---|---|---|---|
| | | cycle: Cradle to grave | freshwater eutrophication, agricultural land occupation, natural land transformation, urban land occupation, metal depletion, water depletion, ecotoxicity, fossil depletion, demand for non-renewable energy resources. | |
| Pork | 1 kg fresh Austrian pork | Production to consumption | Global warming potential, eutrophication and acidification potential | (Winkler et al., 2016) |
| Canola edible oil | one tonne of packaged canola edible oil | Cradle-to-factory gate | Global warming, Abiotic depletion eutrophication photochemical oxidation, ozone layer depletion, acidification, human toxicity, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity | (Khanali et al., 2018) |
| Sea cucumber | 1000 kg of salted sea cucumber | Cradle-to-grave | Global warming potential, eutrophication potential, ozone layer depletion potential, abiotic depletion potential, freshwater aquatic ecotoxicity potential, acidification potential, human toxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical ozone creation potential | (Hou et al., 2019) |
| Pig | 1 kg of live weight gain | Cradle to farm-gate | Global warming, abiotic depletion, eutrophication, acidification, and photochemical ozone formation | (Pirlo et al., 2016) |

### *3.5 Data Envelopment Analysis*

The Data Envelopment Analysis (DEA) can be described as an innovative "data-oriented" assessment tool that evaluates the performance of units known as Decision Making Units (DMU) (Cooper et al., 2004). In this chapter, DMU represents food processes. It evaluates the input and outputs associated with these units. It is also called frontier analysis and was proposed by Charnes, Cooper, and Rhodes in 1978. In their study, they defined DEA as a *'mathematical programming model applied to observational data that provides a new way of obtaining empirical estimates of relations such as the production functions and/or efficient production possibility surfaces'* (Charnes et al., 1978)**.** It offers a non-parametric approach to the assessment of DMU (Cooper et al., 2004; Zhu, 2014). A non-parametric approach in this context mean that it does not assume that data originates from any definite production function. From the data available, it produces the technical efficiency score of each DMU. The technical efficiency score is the percentage of the input-output ratio. The best-operating units are units that produce higher output with the same or lesser input (Lozano et al., 2009). The technical efficiency scores are presented on a scale of 0-1. The efficient DMU called the frontier is the best performing DMU with a relative technical efficiency of 1 (Zhu, 2014). Its application in the food industry is targeted at evaluating the performance of the unit processes.

The application of DEA in the food industry aids in modelling organizational processes and performance assessment in different areas (Cooper et al., 2011). Its major strength is in its ability to analyze complex data (Mohseni et al., 2018). It offers a lot of advantages and prospects ranging from its ability to help analysts and decision-makers in policymaking to addressing the choices of inputs and outputs. Also, it addresses the "what if" questions and could place the organization on a higher competitive advantage in the marketplace (Cooper et al., 2006). Zhu (2014) identified two main DEA models (BCC and CCR models) which uses the "Variable Return to Scale" and "Constant Return to Scale", respectively. Constant return to scale means that an increase in input causes a corresponding increase in output while variable return to scale means that an increase in input does not result in a proportional increase in output. CCR model produces overall technical efficiency while BCC produces pure technical efficiency. The overall technical efficiency divided by pure technical efficiency is called scale efficiency (Lee, 2009). Similarly, Vencheh et al. (2005) proposed a good DEA- based model that evaluates the efficiency of unwanted inputs and outputs concurrently. These models have been widely applied in different sectors, and organizations (Cooper et al., 2011).

There are numerous examples of DEA applications in the food industry which include agricultural water management (Geng et al., 2019), organic farming (Nastis et al., 2019), orange production (Nabavi-Pelesaraei et al., 2014), and wheat production (Khoshnevisan et al., 2013). The result from the analysis shows the inefficient units and the efficient process. For instance, Nastis et al. (2019) used DEA to measure the efficiency of 38 organic farms. Similarly, Picazo-Tadeo et al. (2011) used DEA in the eco-efficiency assessment of Spanish farmers. He found out that most famers are eco-inefficient. The reason is linked to their technical inefficiencies in input management. This shows the extent to which resource use affects the efficiency of organizations. In their study, they found out that some farmers are more eco-efficient and linked their efficiencies to their management strategies. Nabavi-Pelesaraei et al. (2014) in their assessment of the efficiency of orange orchardists in the Guilan province of Iran discovered that 73.3% of the units are efficient while 26.7% are inefficient. They applied the BCC and CCR model to calculate the technical efficiency, pure technical efficiency and the scale efficiency of the units. Geng et al. (2019) in their studies used the CCR and BCC DEA model to measure the water use efficiency for agricultural production in 31 provinces in China. The results of their analysis provided the pure technical efficiency and the overall technical efficiency of the blue water and green-blue water scenarios. Furthermore, Khoshnevisan et al. (2013) applied the BCC and CCR DEA model in evaluating the energy efficiency (technical efficiency, pure technical efficiency and scale efficiency) of the wheat farms. The result of the BCC model shows that 59% of the units were efficient.

### *3.6 The combined Life Cycle Assessment and Data Envelopment Analysis*

Accounting on the strengths of LCA and DEA, their combination could provide more benefits for sustainability evaluation and pursuit in the food system. This combination, although, not widely used in the food industry, has been found to give rise to a better eco-efficiency evaluation, result breakdown and decision making (Syrrakou et al., 2006). The combined LCA and DEA methodology could be applied in either a the three-step or a five-step LCA process. The first two steps (LCI and LCIA) are similar for both methods as described in the section 3.4 for each DMU. In the three-step approach, the third step is the environmental eco-efficiency analysis using the DEA. For the five-step method, the operational eco-efficiency of each DMU is computed using the LCI data. This is followed by assessing the LCI target values (new data) while the last step involves the assessment of the new LCI data. The last step of this method also includes the interpretation of results and target actions to advance the eco-efficiency performance in the organization (Iribarren et al., 2010; Lozano et al., 2009; Vázquez-Rowe et al., 2010). The "three-step LCA and DEA method" is an introductory approach while the five-step LCA and DEA method is seen as a good and more detailed approach for eco-efficiency analysis (Lozano et al., 2009). The five step LCA and DEA method is also described as an advanced eco-efficiency analysis approach (Iribarren et al., 2010).

The combined LCA and DEA approach have been used to evaluate the performance of arecanut production (Paramesh et al., 2018), grape production (Mohseni et al., 2018), tea production (Kouchaki-Penchah et al., 2017), and broiler production systems (Payandeh et al., 2017).

### *3.7 Strength of eco-efficiency analysis*

Eco-efficiency concept does not only offer technical solutions, its analysis offers solutions and approaches that aids in decision making at the different organizational level ranging from managers to the workers (Öztürk and Yılmaz, 2016). LCA which is an eco-efficiency approach is a basic part of Design for Environment has been recently been applied to provide practical methods that bring advancement in sustainability. In conducting eco-efficiency analysis, it focuses on both environmental and economic efficiency (Lupan and Cozorici, 2015). It helps in research and development by identifying gaps in the organization and suggesting better approaches that result in organizational performance (Saling et al., 2002). Eco-efficiency results provide a comprehensive assessment and this help companies to meet international standards (Penttinen and Pohjola, 2008). Baptista et al. (2014) proposed four key modules of the eco-efficiency framework that are employed by organizations for decision making. They are "the inventory, cost and value assessment, environmental performance evaluation, and the LCIA".

Eco-efficiency practices and approaches has the potential to increase sustainability in both small and medium enterprises (SMEs) and large firms (Fernández-Viñé et al., 2010). For SMEs in developing countries, eco-efficiency concepts through resource use efficiency provides basis for increase in productivity, and reduction of environmental impacts (Ciccozzi et al., 2003; Hilson, 2003; Lee et al., 2005; Suh et al., 2005). It is a sustainability approach that results in lower eco-costs (Pascual et al., 2003). Beyond the environmental and industrial regulatory compliance program, its approaches suggest better production practices (Cagno et al., 2012). Proctor and Gamble for instance, is a company practising an internal "closed-loop" processing cycle where the end of the pipe products are not released to the surrounding environment rather they are completely recycled or reused (Allocca, 2000). Organizations who adopt eco-efficiency practices are likely to be cost-effective since its approaches targets resource use efficiency (Öztürk and Yılmaz, 2016).

### *3.8 Gaps/ weaknesses of eco-efficiency*

Eco-efficiency as a sustainability approach has some drawbacks. Though the application of eco-efficiency concepts is vital to sustainability, but eco-efficiency is not the only factor needed to achieve sustainable development (Figge and Hahn, 2004; Jalas, 2002; Sharma and Ruud, 2003). Controlling the environmental impacts of industrial activities is a very complex task. While efficient resource use is an important step in reducing environmental impact and driving a sustainable food system, there are other problems facing the food system that eco-efficiency or resource use management cannot completely solve. For instance, the food system is facing the issues of diet quality and nutrition gap – "*inability to deliver a healthy diet*". Some authors have argued that while much concern has been given on producing enough food to feed the increasing global population, there should also be a corresponding discussion in food quality that meets the global nutritional needs. Other gaps like inequity and inequality in food access across the global population cannot be solved by eco-efficiency (Béné et al., 2019). In addition, research have not been able to prove that resource use management, recycling, and complete dependence on renewable energy sources are the most effective sustainability approach. Hence, eco-efficiency needs to be combined with other sustainability approaches to ensure a sustainable development (Scholz and Wiek, 2005). Another major gap is that eco-efficiency research has mainly focused in economic and environmental efficiency assessments, thereby neglecting the social component. For a comprehensive sustainability assessment, the social component should be integrated in food processes. On the other hand, eco-efficiency knowledge is available and accessible, but the main challenge is to apply it in organizations. Every organization desires growth and increase in productivity. In addition to applying the concept of ecoefficiency, it is also necessary to adopt an approach that enhances effective production (Stanciu, 2006). Also, the concept of eco-efficiency should be further excavated to illustrate the full resource use chain. This is necessary for areas that have a high product demand (Lupan and Cozorici, 2015).

### *3.9 Potential advances of eco-efficiency*

The advancement of eco-efficiency research should be more comprehensive integrating all the various stages in the organizational supply chain (Davé et al., 2016). Future studies should develop logical tools that integrate management decision and performance to sustainable development goals (Virtanen et al., 2013). Eco-efficiency should also be practised in all the sectors especially the industries characterized by high resource use, emissions, product demand and pollutions (Caiado et al., 2017). Organizational energy usage and carbon dioxide emission requires advanced research. Approaches that deals with energy efficiency and reduction of emissions are vital (Martínez and Silveira, 2013). Advance studies on regional resource availability conditions and sustainability criteria are needed (Hadian and Madani, 2015). Studies should also focus on merging different production phases with better technological drivers (Trianni et al., 2014). Furthermore, the future studies should explore how the application of eco-efficiency concepts influences technological progress, providing mathematical proofs and statistical methodologies (Huang et al., 2014; Park et al., 2015). Also, research should integrate the social aspects of sustainability (Müller et al., 2015). Thus, helping firms achieve their corporate social responsibility (Park and Behera, 2014). There is also a need to study on eco-efficiency development that incorporates relevance and functionality of optimization algorithms and simulation-based approach (Sproedt et al., 2015).

### *3.10 Conclusion*

This chapter provided a literature review on the concept of eco-efficiency, focusing on the two mainly used approaches (LCA, DEA and their combination) and identified key gaps and potential solution in the current eco-efficiency application. The concept of eco-efficiency from a resource use perspective, sustainability (social, environment and economic) were highlighted. It could be seen from literature that eco-efficiency has been applied in the food industry for sustainability assessments. Most of the applications are mainly to evaluate environmental, economic and operational efficiency. Results from the study shows that LCA which is an environmental assessment tool have been applied in the food industry. The studies show that food products have contributed to many impact categories like global warming potential, acidification, eutrophication, etc. The most used functional unit in the LCA of the food system is 1kg of the food product. The system boundary used in the studies varies and are in the upstream and/or downstream sector of the food value chain. The LCA follows a four-step methodology which are “goal and scope definition, life cycle inventory, life cycle assessment, and interpretation". The result of its assessment forms a basis for decision and improvement.

Another eco-efficiency technique discussed in this chapter is the DEA with a specific focus on its application in the food industry. The most used DEA model in the food industry is the CCR and BCC models which uses the "Variable Return to Scale" and "Constant Return to Scale", respectively. It is an input-output based assessment. It measures the efficiency of food processes referred to as DMU. A DMU consist of inputs and outputs which forms the basis for evaluation. From the data available, it produces a technical efficiency score on a scale of (0-1) or percentage for each DMU. The best performing DMU among the compared DMUs referred to as the frontier has a technical efficiency score of 1.

A combined application of LCA and DEA was also highlighted in this chapter. Even though it has few applications in the food industry, but it could be noted that the combination of both techniques offers a more comprehensive assessment as it employs the strength of both techniques. The combined application follows a three step or five step approach which has been discussed. This review serves as a guideline to apply eco-efficiency concepts, LCA and DEA methodologies in the food industry.

## Connecting text

Having reviewed eco-efficiency within the sustainable development dimensions (environmental, economic and social), and the primary eco-efficiency modules used in the food industry and identified gaps and the potential of advances to enhance it application, the thesis makes two key steps. First is to do an eco-efficiency assessment (environmental and economic) of a fruit processing plant in Honduras.

# 4 Enviro-economic assessment of a fruit processing enterprise using Life Cycle Assessment and Life Cycle Cost

**Abstract**

A combined environmental and economic evaluation provides a broader sustainability assessment that identifies hotspots in the value chain. This study presents a gate to gate life cycle assessment (LCA) and life cycle costing (LCC) of a fruit juice processing enterprise. A functional unit of one tonne of fruit juice was used to evaluate the impact of processing passion fruits, tamarind and lime. Seven impact categories were evaluated using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) assessment tool in the GaBi software. Electricity usage, wastewater and fruit waste were found to be the major contributors to the environmental changes. The data for the analysis was gotten from APRAL fruit processing plant in Honduras. The characterized LCA results shows a contribution to global warming, acidification and eutrophication potential, human toxicity (cancer and non-cancer category), ecotoxicity and resources. The normalized result shows that lime processing has the worst environmental performance while tamarind processing has the best environmental performance among the three fruits. Generally, the normalized result of lime is 3.9 higher than tamarind and 1.07 higher than passion fruit. Overall, it was evident that this small-scale fruit processing plant poses a relatively lower environmental risk per kg-product compared to fruit production or other food value chains. A life cycle costing shows that for a small-scale fruit juice enterprise in Honduras, the raw material cost may be the most significant cost component accounting for more than two-thirds of the total cost.

**Keywords**

Life Cycle Assessment, Life Cycle Cost, Environment, Waste, Sustainability

### *4.1 Introduction*

Fruits production and processing form a significant part of the food industry and are listed among the manufacturing sectors in many countries (Sinha et al., 2012). Fruits are processed and consumed due to their nutritional significance in the human diet (Kader, 2001). Fruits, like many perishable commodities, are usually processed into various forms, such as juice, concentrate, purees etc. to increase shelf life and ensure their availability all year round. This process in addition to delivering the product of interest is characterized by large amounts of by-products, waste and various emission to the air, land and water. Bhat (2017) argued that an increase in food production and processing have resulted in an increase in unsustainable production pattern.

Attaining sustainability in the production and processing phases of a product requires integrating processes and practices that are both economical and environment effective (Falcone et al., 2015). One of the goal of sustainability proposed earlier by World Commission on Environment and Development was meeting present needs without compromising the needs of the next generation (Brundland, 1987). The literature has described this goal of sustainability in a three-dimensional pillars known as social, economic and environment dimensions of sustainability (Arena et al., 2009). Improving sustainability in fruit processing will require a good environment, and economic efficiency practices. To this end, the application of enviro-economic techniques such as Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) that simultaneously evaluates the environmental and economic aspects is paramount.

Life Cycle Assessment evaluates the inputs and outputs of a product. It further classifies their flows and calculates their environmental impact at the various life cycle of the product (ISO, 2006; Ullah et al., 2016). It shows the stages in the value chain that have the highest environmental impacts and this aids in management decision making to improve efficiency and achieve manufacturing excellence. This is essential for achieving food industry sustainability since operational efficiency and processes associated with the manufacturing of the product directly influence the environmental impact of that product (Lozano et al., 2009).

Even though price and market value is a vital aspect of every organizational development, the LCC of food products is rarely assessed (Konstantas et al., 2019). LCC allows enterprises to determine the cost of a product in its life cycle stages (Reich, 2005). It analyzes their economic performance from a sustainability perspective, thus, providing the opportunity for a cost-environment trade-off evaluation (Falcone et al., 2015; Huppes et al., 2004).

A combined LCA and LCC study establishes a relationship between the environmental influence of a product and cost evaluation at different life cycle stages (Norris, 2001). Most studies have focused on only one component of sustainability (either environmental, economic or social only). Few studies have applied both methodologies in the food industry. For example, De Luca et al. (2014) combined both methods in analyzing different citrus growing systems; other LCC research include wine-growing management systems (Falcone et al., 2015), wine grape production (Strano et al., 2013). However, these studies mainly focused on food production (the farming aspect of the food system), it is necessary to take a step beyond food production to food processing. The goal of this component of the thesis is to apply combined LCA and LCC to assess eco-efficiency in a small-to-medium scale food processing enterprise. Specifically, the analysis is to evaluate the environmental and economic impact of fruit processing using a juice processing plant in Honduras as a case study.

## *4.2 Materials and methods*

The environmental assessment of tamarind, lime and passion fruits was performed using the LCA methodology – ISO Standard 14040:2006 (ISO, 2006). The system studied is presented in Fig. 4.1 while the details and steps of the methodology is presented in Fig. 4.2.

The economic assessment was performed using the LCC methodology proposed by (Hunkeler et al., 2008) and adopted by (Laso et al., 2018).

### *4.2.1 Life Cycle Assessment*

The four-step LCA methodology used in this study is discussed below (ISO, 2006).

#### *4.2.1.1 Goal and scope of the LCA study*

Definition of the goal and scope is the first stage in the LCA methodology. In this evaluation, the goal is to assess the environmental impact of the production of three different fruits juices (passion fruit, tamarind, lime) at a small-scale fruit enterprise using a processing plant in Honduras as a case study. Accordingly, a small cooperative processing plant called APRAL located at Pespire (13.590328 $^{o}$ N, 87.359219 $^{o}$ W) in the dry corridor of Honduras was selected as the case study. The assessment only includes the fruit processing stages which carried out by the APRAL processing plant. The scope of this study is limited to these processing stages because the aim of the study is to complete an environmental assessment of the activities within the plant. The functional unit, system boundary, LCA software are defined in this first step.

#### *4.2.1.2 Functional unit*

The functional unit is important in an LCA study because it defines the quantity of the product being studied and this serves as a reference unit. In this study, the same functional unit was selected for the three fruits to ease assessment and comparison. The functional unit is one tonne of fruit juice.

N/B: The functional unit is one tonne of the processed fruit juice (output) and not the freshly harvested fruit (input). The processed fruit juice is selected since the individual fresh fruit consumption and output of the three fruits are different. In order to compare their performances, it is preferable to choose the fruit juice (output) as the functional unit.

#### *4.2.1.3 System boundary*

The system boundary is the unit processes included in the assessment. In this study, the system boundary, as shown in Fig. 4.1, is from gate to gate and includes raw material storage, fruit processing, fruit juice packaging, and fruit juice storage. The upstream activities including the production of the raw material, transportation of both raw materials and some downstream activities like transportation of the finished products, marketing, and the end of use stages, are not considered in the study. Other interactions of the functional unit with other products and services are not considered too.

#### *4.2.1.4 Life Cycle Assessment software*

The Ganzheitlichen Bilanzierung (Gabi) 8.1 version Sphera Solutions GmbH (formerly thinkstep AG), Leinfelden-Echterdingen, Germany software was used in this study (see Appendix; Fig. A.1). The Ecoinvent commercial licence v3.6 database in GaBi was used. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1 was used as the Life Cycle Impact Assessment (LCIA) method. TRACI methodology which is designed based on US environmental data was chosen because it could offer a more reliable assessment considering that Honduras is a Central American country (Menoufi, 2011). Other available assessment methodology such as ReCiPe and CML are based on European environmental data.

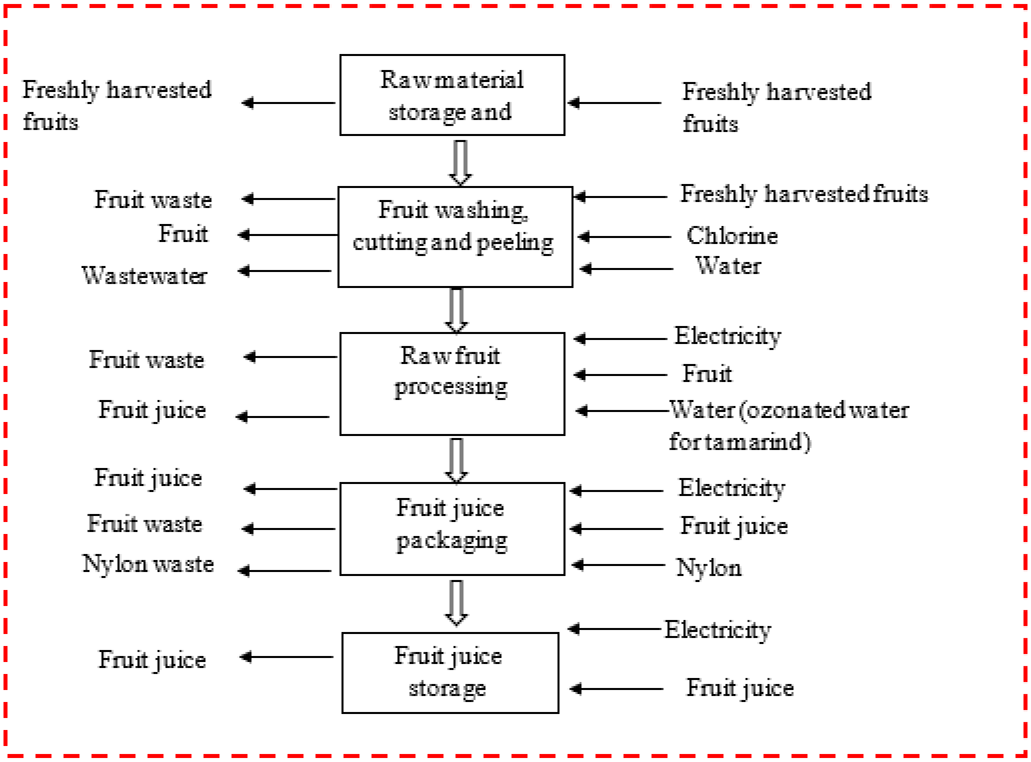


Fig. 4.1: System boundary and flow diagram processes used for the study

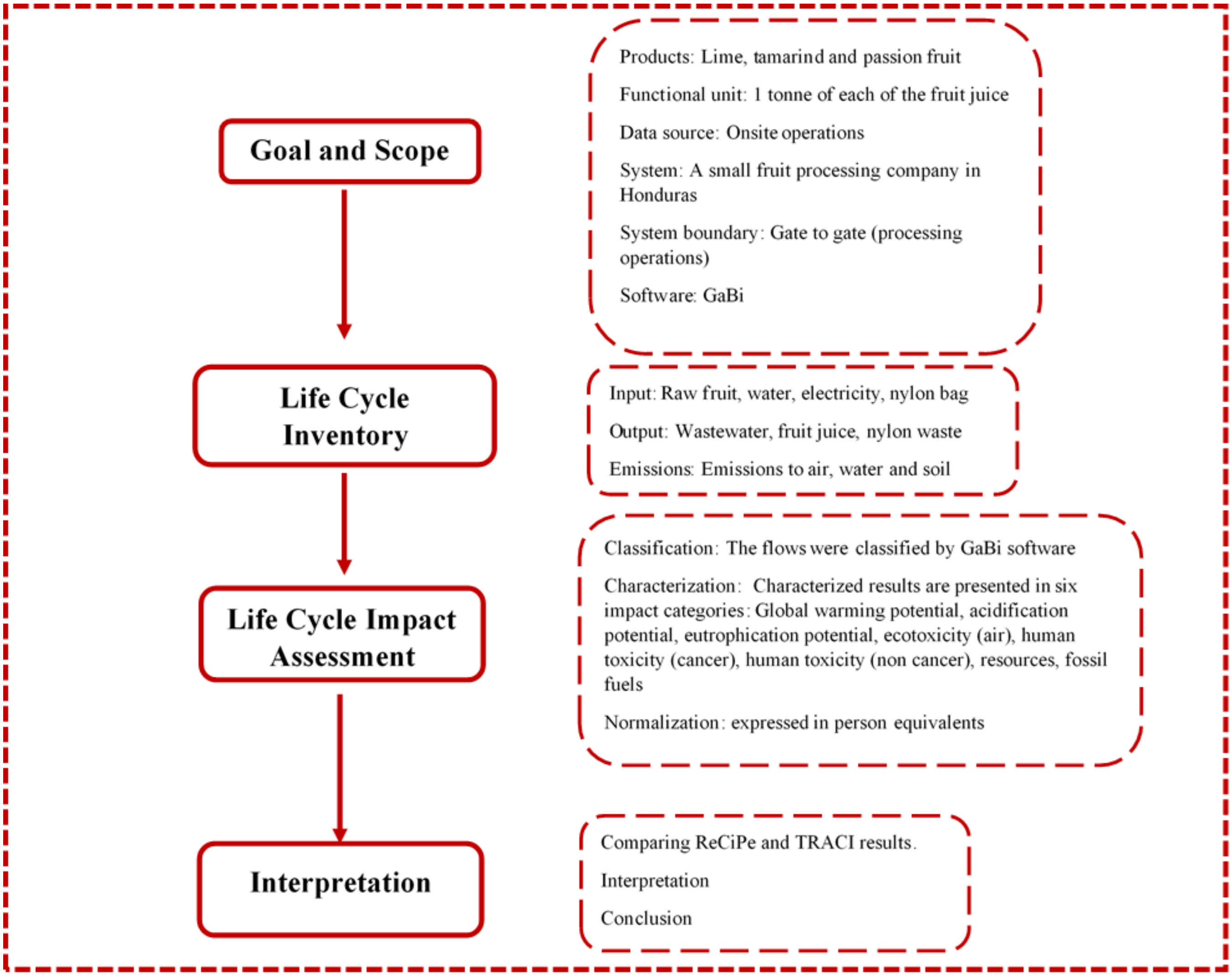


Fig 4.2: Methodology for the Life Cycle Assessment of one tonne of fruit juice.

### *4.2.2 Life Cycle Inventory*

The second stage in the LCA methodology requires collecting input and output data of processes from which the environmental performance is evaluated. The output of data collection activity is an inventory of primary data from site and secondary data from environmental databases. The primary data was obtained from the processing plant through actual measurements, interviewing the factory workers (onsite operation), and reviewing recorded mass balance datasheet. The data collected are then related to the unit processes and the functional unit. A unit process is a subdivision of the system. For example, the storage unit, etc. (see Appendix; Fig. A.2 and A.3). The last step was data aggregation. The input and output data collected are presented in Table 4.1. All the data presented in table 4.1 correspond to the functional unit of the product (one tonne of lime, tamarind or passion fruit).

Table 4.1: Life cycle inventory data of one tonne of passion fruit, tamarind, lime juice

| **Input/output** | **Processing Stage** | **Units** | **Passion fruits** | **Tamarind** | **Lime** |
|---|---|---|---:|---:|---:|
| *Inputs* | | | | | |
| Fresh harvested fruit | Raw material storage | Kg | 2,651.93 | 687.29 | 2,147.77 |
| Water | Fruit washing | Litres | 7,308.14 | 1,894.01 | 7,891.69 |
| Water | Fruit processing | Litres | 42.36 | 756.01 | 64.44 |
| Water (total) | | Litres | 7,350.50 | 2,650.02 | 7,956.13 |
| Electricity | Fruit processing | Kwh | 32.27 | 63.87 | 261.37 |
| Electricity | Fruit packaging | Kwh | 19.49 | 37.88 | 157.84 |
| Electricity | Fruit storage | Kwh | 431.69 | 431.69 | 431.69 |
| Electricity (total) | | Kwh | 483.45 | 533.44 | 850.90 |
| Chlorine | Fruit washing | Kg | 0.02 | 0.05 | 0.20 |
| Nylon bag | Fruit packaging | Kg | 3.95 | 3.95 | 3.95 |
| *Outputs* | | | | | |
| Wastewater | Fruit washing | Litres | 7,161.98 | 1,856.13 | 7,733.86 |
| Fruit waste | Fruit cutting | Kg | 1,662.76 | 412.37 | 1,181.27 |
| Fruit waste | Fruit processing | Kg | 20.63 | 20.62 | 19.33 |
| Fruit waste | Fruit packaging | Kg | 10.10 | 10.10 | 10.10 |
| Fruit waste (total) | | Kg | 1,693.49 | 443.09 | 1,210.70 |
| Nylon bag (waste) | Fruit packaging | Kg | 0.59 | 0.59 | 0.59 |

#### 4.2.2.1 Data collection overview

Primary and secondary data were collected for this assessment. Primary data included raw material, energy, and water use for the various processes obtained from the processing plant (onsite operations). Secondary data including emissions were computed using the Ecoinvent database from the GaBi software. The elementary flows are flows that link the unit processes with the environment. They are the overall emissions based on the inputs and outputs. These flows are generated by the software.

The fruit processing of the three fruits were similar, but the input and output quantities varied. The fruit juices were produced in batches with an average input of 408.23, 54.43 and 40.82 kg of freshly harvested passion fruit, tamarind and lime, respectively. The output per batch were 153.94, 79.20 and 19.01 kg of passion fruit, tamarind and lime, respectively.

#### 4.2.2.2 Data quality/variability

The processing conditions of the APRAL fruit juice was carefully studied and it was confirmed that the data represents the real-life processing operations. These numbers were estimated based on the measurement of the quantity used per batch. The inputs and output mass streams were measured using a weighing balance. An average of one-month data was collected and confirmed with the processing plant's existing records. In Honduras, the gross electricity generation is mixed; 53% are petrol power plants, 42% hydro power plants, 1% coal power plants, 1% gas and 3% co-generation. The breakdown of the inventory in the different unit processes is discussed below.

#### 4.2.2.3 Raw material Storage

The freshly harvested fruits were carefully received, sorted, packed, and stored in the storage room (31 $m^3$) under room temperature. The storage room can store about 4,500 kg of fruits. Although the fruits may have a shelf life of about ten days, they are typically processed within three days of storage. For this study, it is assumed that variation in the raw material quality is negligible during the 3-day waiting period.

#### 4.2.2.4 Fruit washing, cutting and peeling

During this stage, the fruits undergo a three-step thorough manual washing. For the selected functional unit, a total of 7,308, 1,894 and 7,891 liters of water are used for passion fruits, tamarind, and lime, respectively. The first washing removes all the debris and organic matters. During the second washing, 0.02, 0.05 and 0.2 kg of chlorine was added to the freshwater for passion fruit, tamarind and lime, respectively. This is essential to destroy the fungi and bacteria that infected the fruits during the production, harvesting and post-harvest handling stages. Chlorine has been described as an effective disinfectant for removing contaminants in fresh fruits and vegetables (Suslow, 2000). The final washing potentially removes all the chlorine from the fruits, which is necessary to avoid chlorine contamination of the fruits. Wastewater from all washing stages is disposed of directly to the environment (nearby dried stream) without treatment. After washing, the undesirable parts of the fruits such as the outer surface and inner seeds are removed before cutting into small sizes for milling. This is done manually by the labourers. About 37.3% of the washed passion fruits goes into the next processing stage while 62.7% are discarded as fruit waste; 60% of tamarind fruits and 55% of lime are also discarded as fruit waste.

#### *4.2.2.5 Fruit Processing*

The cleaned cut fruits are milled to produce the fruit juice. For each processing cycle, the milling machine runs for about 4.5 hours with a power consumption of 1104 W. For tamarind, ozonated water is added during the processing stage. A 150 W ozone machine runs for 1.5 hours produces 150 litres of ozonated water in each operation to process about 136 kg of tamarind. Milling efficiency and product uniformity is improved by adding 6.5, 60 and 1.2 litres of water per batch to the passion fruits, tamarind, and lime, respectively, per batch. The electricity consumption and water used at this stage for processing one tonne of these fruit juice are shown in Table 4.1

#### *4.2.2.6 Fruit packaging and storage*

At this stage, the processed juice is packaged into a nylon bag and sealed using a 1 kW sealing machine. The individual energy consumption of the sealing machine for processing the fruits during the packaging stage are 19.5 kwh for passion fruit, 37.9 kwh for tamarind, and 157.8 kwh for lime. The packaged juice, weighing 0.45 kg each, is stored in the deep freezer for up to five days before distribution. The energy consumption in the storage phase is estimated as 431.7 kwh as presented in Table 4.1

### *4.2.3 Life Cycle Impact Assessment*

The impact assessment provides the environmental performance of the fruits. The Life Cycle Impact Assessment (LCIA) is an essential step in the environmental assessment. It is the third step in the LCA methodology. The assessment is done using the inventory data by the GaBi 8.1 software. First, the quantified flows from the inputs and outputs are classified and characterized into their respective environmental impact categories. Classification means assigning the inventory results to impact categories. For example, $SO_2$ linked to acidification. Characterization simply means adding all the contributions of inputs and outputs to each impact category. Impact categories are classes representing an issue of environmental concern (e.g. acidification) (ISO, 2006). Characterization and normalization (see Equations 4.1, 4.2 and 4.3) were done at this stage using the TRACI methodology. The TRACI 2.1, USA 2008 database was used for normalization.

#### *4.2.3.1 Characterization*

In the impact assessment, characterization converts the life cycle inventory value for each impact category to a common unit and adds them up to generate a value that represents the total contribution of the flows to the impact category as seen in Equation 4.1. This is achieved by relating the flow to the characterization factor (CF) (ISO, 2006). The resultant impact will be a product of the emission and the characterization factor as seen in Equation 4.2 (Bare et al., 2012). The characterization factor is a product of fate, exposure and effect factors. These results give a clear indication of the process contribution to environmental degradation.

$$S_j = \sum_i CF_{ji} . M_i \qquad 4.1$$

Where; $S_j$ = The impact score for each category (j) measured in different units; $CJ_{ji}$ = The characterization factor of the elementary flow (i) for each impact category j; Mi = Elementary flow related to the functional unit of the study;

For example, for each impact category like global warming potential,

$$GWP = \sum e_i * GWP_i \qquad 4.2$$

Where; $e_i$ = emissions; GWP = Global warming potential

The environmental effects of processing the fruits were evaluated using seven impact categories as presented in Table 4.2. The ecotoxicity is measured in Comparative Toxic Units ecotoxicity (CTUe), human toxicity results are presented in Comparative Toxicity Unit for humans (CTUh) while resources are measured in Mega Joule (MJ) surplus. The units of other impact categories are shown in Table 4.2.

Table 4.2: Environmental impact categories and their measurement units

| Impact Categories | Unit | Impact Categories | Unit |
|---|---|---|---|
| Global warming potential | kg $CO_2$-eq. | Human Toxicity (cancer) | CTUh |
| Acidification potential | kg $SO_2$-eq. | Human Toxicity (non cancer) | CTUh |
| Eutrophication potential | kg N-eq. | Resources, Fossil fuels | MJ surplus |
| Ecotoxicity (air) | CTUe | | |

Comparative Toxic Units ecotoxicity (CTUe; Comparative Toxicity Unit for humans (CTUh); Mega Joule (MJ) surplus

#### *4.2.3.2 Normalization*

Normalization compares the characterized results to a certain reference information. It presents the results of the environmental impact results across the impact categories in same unit (in this case, person equivalents) (ISO, 2006). The calculations of normalized results is shown in Equation 4.3 (Aymard and Botta-Genoulaz, 2017). The comparison of the results is within the product system and hence cannot be compared with other products outside the system being studied. By presenting the results of these impact categories in same unit , it therefore, shows the relative significance of these impact categories (Aymard and Botta-Genoulaz, 2017; Prado et al., 2017).

Mathematically,

$$N_i = S_i / R_i \tag{4.3}$$

i = the impact category (e.g. acidification)

$S_i$ = the characterized result of the impact category (e.g. 12.6 kg$CO_2$ eq.)

$N_i$ = the normalized result of the product being studied (expressed in person equivalents in this study)

$R_i$ = the characterized impact of i (impact category) of the reference system. Example of a reference system could be the total input/output or population of a given geographical area over a given reference period.

#### 4.2.4 Interpretation step

The interpretation stage provides a discussion and result analysis of the fruits. This is the last stage of the LCA. At the stage, the general assessment results are interpreted with reference to LCIA. For countries that do not have environmental database and LCIA, the chosen LCIA could influence the assessment. Some authors reported that if we use different LCA evaluation methods like TRACI or ReCiPe, there might be up to 20% significant differences in the results (Kwofie and Ngadi, 2017; Speck et al., 2016). For this study, the TRACI results were compared with the ReCiPe results to ascertain if there are differences in the result. Also, the contribution of the inputs to the impact categories and a general interpretation of the result was done based on the impact assessment results.

#### 4.2.5 Life cycle cost

The Life Cycle Cost was used to measure the economic performance of the product throughout its life cycle stages. The LCC methodology proposed by Hunkeler et al. (2008) was used in this study. The functional unit and system boundary are the same as those used for the LCA. In this LCC methodology, the first step is goal and scope definition followed by information gathering, then interpretation, which involves the identification of hotspots and the last step is sensitivity analysis and discussion. All the costs of the raw materials and inputs were provided by the processing plant. The capital investment was not taken into consideration and the cost of transporting the raw materials and finished products were not considered because they were covered by the suppliers or the distributors. The input cost associated with processing each of the fruits is presented in Table 4.3. The cost of the inputs and outputs for the LCC are the actual prices obtained from the enterprise. The conversion rate used in this study is 1 Canadian dollar (CAD) equivalent to 18.55 lempira (Honduran currency).

##### 4.2.5.1 Calculation of life cycle cost

A methodology proposed by (Hunkeler et al., 2008; Rivera and Azapagic, 2016) and adopted by (Laso et al., 2018) was used in estimating the LCC. The total cost is the sum of all the inputs at each processing stage.

##### 4.2.5.2 Value Added

The value added represents the economic performance of each product in this study. The economic definition of Value Added (VA) according to Coltrain et al. (2000), is the difference in the price of the product in its raw form and its processed form. For this study, the value-added was estimated as the difference in the price of the product (processed juice) and the raw material adding all the cost associated in the conversion of the freshly harvested fruit to fruit juice. The VA for tamarind, passion fruits and lime are as shown in Table 4.3.

Table 4.3: Life cycle cost inventory for producing one tonne of passion fruit, tamarind, lime juice

| **Input/output** | **Passion fruits** | | | **Tamarind** | | | **Lime** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Qty | Cost (CAD) | Contribution to input cost (%) | Qty | Cost (CAD) | Contribution to input cost(%) | Qty | Cost (CAD) | Contribution to input cost (%) |
| Raw fruit (kg) | 2,652 | 857.77 | 74.22 | 687 | 407.56 | 60.96 | 2,147 | 810.48 | 65.37 |
| Water (litre) | 7,351 | 0.17 | 0.01 | 2,650 | 0.06 | 0.01 | 7,956 | 0.18 | 0.01 |
| Electricity (kwh) | 483 | 143.34 | 12.40 | 533 | 158.16 | 23.66 | 851 | 252.29 | 20.35 |
| Nylon (kg) | 3.95 | 0.02 | 0.0020 | 3.95 | 0.02 | 0.0034 | 3.95 | 0.02 | 0.0019 |
| Chlorine (kg) | 0.02 | 0.48 | 0.04 | 0.05 | 0.94 | 0.14 | 0.20 | 3.91 | 0.32 |
| Labour rate (CAD) | 2.96 | 153.93 | 13.32 | 2.96 | 101.83 | 15.23 | 2.96 | 172.87 | 13.94 |
| Total cost of input | | 1,155.70 | | | 668.57 | | | 1,239.75 | |
| Juice (kg) | 1,000 | 1,780 | | 1,000 | 1,941 | | 1,000 | 1,672 | |
| Value Added (VA) | | 625 | | | 1,272 | | | 432 | |
| % profit | | | 35 | | | 66 | | | 26 |

Qty – quantity

## 4.3 Results and discussion

### 4.3.1 Environmental performance

The overall environmental impact results are presented in Table 4.4. The characterized results are the contributions of inputs and outputs to each impact category. The results for the seven (7) impact categories are discussed in this section.

Table 4.4: Environmental impact results of fruit processing using TRACI 2.1

| Impact Categories | Unit | Passion fruit | Tamarind | Lime |
|---|---|---|---|---|
| Global warming potential | kg$CO_2$-eq | 1,460 | 942 | 1,330 |
| Acidification potential | kg$SO_2$-eq | 2.29 | 1.82 | 2.29 |
| Eutrophication potential | kgN-eq | 3.67 | 1.03 | 3.65 |
| Ecotoxicity (air) | CTUe | 5,990 | 1,560 | 6,470 |
| Human Toxicity (cancer) | CTUh | 1.28E-04 | 3.31E-05 | 1.38E-04 |
| Human Toxicity (non cancer) | CTUh | 1.09E-03 | 2.87E-04 | 1.16E-03 |
| Resources, Fossil fuels | MJ surplus | 453 | 581 | 562 |

#### 4.3.1.1 Global Warming Potential (GWP)

The Global Warming Potential (GWP) expressed in $CO_2$-equivalent of a product measures the impact of the product on climate change (Trottier, 2015). It gives the $CO_2$ equivalent of all the greenhouse gases. For example, an emission of 1 kg of methane ($CH_4$) is about equivalent to the emission of 25 kg of $CO_2$; an emission of 1 kg of nitrous oxide ($N_2O$) is about equivalent to the emission of 298 kg of $CO_2$ (EPA, 2014). It is a method for comparing and measuring how greenhouse gasses (GHG) emissions affect climate change (Shine, 2009). The GWP results for the three fruits are shown in Table 4.4. The results show that tamarind has the lowest GWP result of 942 kg $CO_2$-eq. while passion fruit has the highest GWP result of 1460 kg $CO_2$-eq. The GWP result of lime is 1.4 higher than tamarind. Similarly, the contribution of passion fruit to this impact category is 1.6 higher than tamarind and 1.1 higher than lime. The high GWP result of passion fruit could be attributed to the large amount of passion fruit waste. Lime waste is also higher than tamarind waste which could be a major reason while its GWP result is higher. Since fruit waste is involved, the GWP may likely come from degradation of the organic waste from the fruits. On the other hand, electricity consumption for lime processing is the highest among the three fruits (see Table 4.1) and this could have added up in its GWP results. In this study, electricity generation, which is a significant contributor to GWP, is minimal as most of the processes are done manually and hence their electricity usage is low. This may be the reason why the results are significantly lower than the processing of one tonne of canola edible oil reported to be 3086 kg CO2-eq. (Khanali et al., 2018).

#### *4.3.1.2 Acidification Potential*

The acidification potential results are presented in Table 4.4. The acidification result of tamarind is 1.82 kg $SO_2$-eq. This is the lowest compared to lime and passion fruit with both fruit showing a result of 2.29 kg $SO_2$-eq. This is 1.3 times higher than the acidification result of tamarind. On the average, the processing of the three fruits shows an acidification potential of 2.13 ± 0.27 kg $SO_2$-eq. to the environment. The low acidification result of tamarind may be attributed to the relative lower quantity of fruit waste. As seen from the inventory result in Table 4.1, tamarind fruit waste is 2.73 lower than lime waste and 3.8 lower than passion fruit waste. Another reason for the general low acidification results may likely be due to the manual processes involved. Other LCA on fruits shows a record of their contributions to this impact category. Most of these results are difficult to compare because of the difference in the scope of study and functional units. However, studies show that similar fruits like orange and lemon juice contributes to acidification (Parajuli et al., 2019). Acidifying substances can reduce the pH of the soil or water, lead to changes in species diversity, and decreases productivity (Singh et al., 2018).

#### *4.3.1.3 Eutrophication potential*

Eutrophication measures the contributions of macronutrients to the ecosystem (Singh et al., 2018). The eutrophication results are presented in Table 4.4. The results show that tamarind has the lowest contribution to this impact category while passion fruit has the highest contribution of 3.67 kg N-eq. This eutrophication result of passion fruit is slightly (1.01 times) higher than lime but 3.56 times higher than tamarind. The average contribution of the three fruits to this impact category are 2.78 ± 1.52 kg N-eq. Although the results are similar to those from the production of natural citrus juice (1.4-2.3 kg PO4-eq.), we cannot clearly compare the results as both results are presented in different units. Literature shows that the production of concentrated citrus has been reported to be 6.4-12.2 kg PO4-eq. (Parajuli et al., 2019). (Note: eutrophication may be measured either in kg N-eq. or kg PO4-eq.). The results show emissions of wastewater are the primary source to eutrophication. Thus, the higher amount of water used for passion fruit and lime processing would imply a relatively higher eutrophication potential. Therefore, a good wastewater management will be required to reduce the contribution to this impact category.

#### *4.3.1.4 Ecotoxicity (air)*

Table 4.4 shows the characterized ecotoxicity results measured in Comparative Toxic Units ecotoxicity (CTUe). The results show that processing passion fruit, tamarind and lime contributes 5990, 1560 and 6470 CTUe, respectively. Comparing the three different fruits, the ratio of their contributions to this impact category is 1: 3.84: 4.15 for tamarind, passion and lime, respectively. This is largely dependent on the wastewater output from the three processes. In this study, wastewater disposal, therefore, is causing a lot of damage from an ecotoxicity perspective contributing more than 99% of the overall ecotoxicity impact. Other LCA in fruit production shows that fruits have a contribution to ecotoxicity (Hou et al., 2019; Vinyes et al., 2017);

#### *4.3.1.5 Human toxicity*

Human toxicity represents the direct implication on human health and represent emissions from substances with various concentrations and amounts that affect human health (Carpenter et al., 2002). The results for human toxicity (cancer and non-cancer) expressed in Comparative Toxicity Unit for humans (CTUh) are shown in Table 4.4. It shows that passion fruit contributes 1.28E-04 and 1.09E-03 CTUh to human toxicity (cancer and non-cancer), respectively. The processing of one tonne of tamarind juice contributes 3.31E-05 and 2.87E-04 CTUh to human toxicity (cancer and non-cancer), respectively. The human toxicity result of processing of one tonne of lime is 1.38E-04 and 1.16E-03CTUh for (cancer and non-cancer) categories, respectively. From the results in this study, wastewater disposal is the dominant contributor to human toxicity (cancer and non-cancer) impact category. Therefore, a good wastewater management strategy is needed for this firm to reduce the environmental impact caused by wastewater. The World Health Organization reported that over 4.3 million untimely deaths are caused by pollutions from solid waste, agricultural products, landfill gas and biogas, and alcohol fuels (WHO, 2014).

### *4.3.2 Normalized results*

The normalized results present the results (environmental impacts) of the different impact categories in same unit. In this study, the normalized results are presented in person equivalents. Fig. 4.3 shows the normalized result of the tamarind, lime and passion fruit. From the results, acidification has the lowest normalized results when compared to other impact categories with passion fruit, tamarind and lime showing 0.025, 0.02 and 0.025 person equivalents, respectively. Summing all the results of the three fruits, lime has the highest normalized results while tamarind has the lowest normalized results. The normalized result of lime is 3.9 times higher than tamarind and 1.07 times higher than passion fruit. Similarly, the normalized result of passion fruit is 3.6 times higher than tamarind. The comparison of normalized results of products is within the reference system being studied (Prado et al., 2017). It therefore helps to compare the magnitude of the environmental impact of these three fruits across the impact categories. Since the different impact categories results are presented in different units, it is difficult to compare the results of these impact categories (Bare et al., 2012). Hence, to provide a better comparison assessment of the impact categories, the normalized results of these fruits are presented. Attention should mainly focus on the contributors to the impact categories that have the highest normalization results. This is because reducing their impacts will significantly reduce overall environmental impacts of the products.

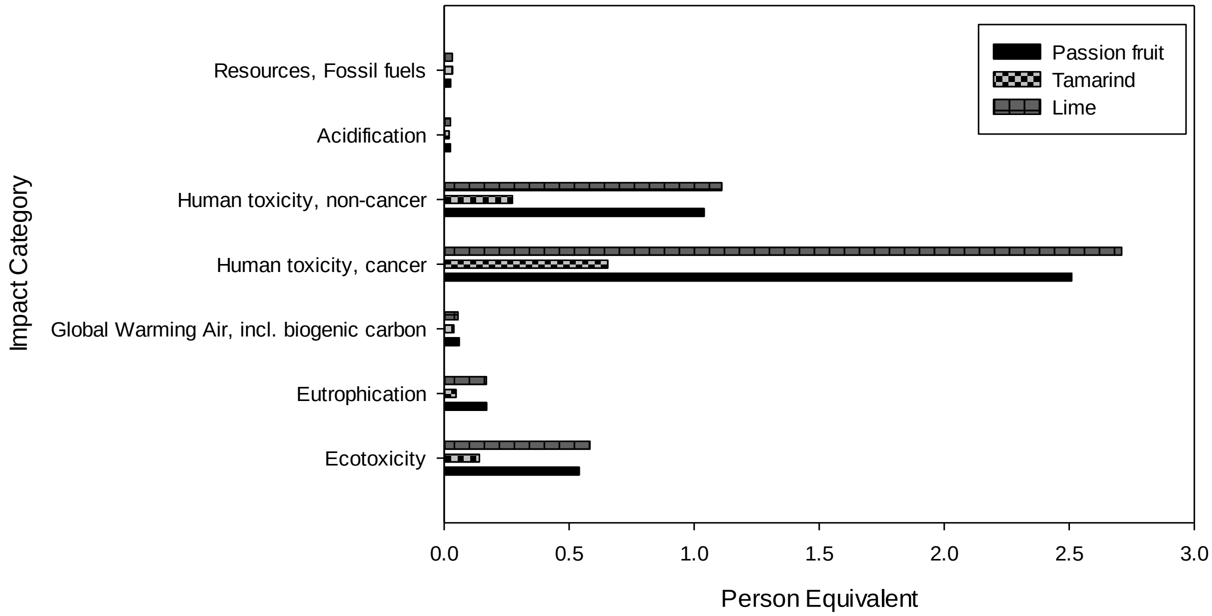


Fig 4.3. Normalized result for the seven impact categories

### *4.3.3 Major contributors to environmental impacts*

The results of the assessment show that electricity use, wastewater disposal and fruit waste disposal are the major contributors to the environmental impact (see Appendix; Table. A.1 and A.2). Table 4.5 shows the activities related to important environmental impacts in processing tamarind, lime and passion fruits. In this section, the detailed contributions of fruit waste and wastewater are discussed along with potential remedies. Electricity is not a major problem in this fruit processing plant as most of the activities are done manually. Also, they may not be able to afford another alternative energy source.

Table 4.5: Major contributors at different stages in fruit processing

| **Impact categories** | **Washing** | **Processing** | **Packaging** | **Product Storage** | **Total** |
|---|---|---|---|---|---|
| Global warming potential | | Electricity, fruit waste | Electricity | Electricity | Electricity, fruit waste |
| Acidification potential | | Electricity, fruit waste | Electricity | Electricity | Electricity, fruit waste |
| Eutrophication potential | wastewater | fruit waste | | | Wastewater, fruit waste |
| Ecotoxicity (air) | wastewater | | | | wastewater |
| Human Toxicity (cancer) | wastewater | | | | wastewater |
| Human Toxicity (non cancer) | wastewater | | | | wastewater |
| Resources, Fossil fuels | | Electricity, fruit waste | Electricity | Electricity | Electricity, fruit waste |

#### *4.3.3.1 Wastewater*

Wastewater is a major contributor to the human toxicity, ecotoxicity and eutrophication impact categories. Fig. 4.4 shows the percentage contribution of wastewater to the impact categories. Wastewater has the most contribution to human toxicity (cancer and non-cancer), eutrophication and ecotoxicity. In this study, wastewater is generated from the fruit washing stage. About 98 % of the water used during the washing stage are disposed of as wastewater. Inventory results from Table 4.1 shows that the average quantity of wastewater generated in the processes is 5,583.99 litres. Generally, the average percentage contribution of wastewater to eutrophication is 73.84 %; The contribution of wastewater to eutrophication potential was expected as Cashman et al. (2014) in his study reported that wastewater contributes to eutrophication. Wastewater also contributes an average of 99.68% to ecotoxicity. This agrees with similar research where Raghuvanshi et al. (2017) in his study on wastewater treatment plant, reported that wastewater has an impact in ecotoxicity. Similarly, wastewater contribution to human toxicity (cancer and non-cancer) are about 99.3 and 96.06%, respectively. On the other hand, wastewater does not have any significant impact on global warming in this study. This is in line with similar studies where Kweku et al. (2017) reported that wastewater does not contribute largely to GHG emissions The other impact categories in this study are not significantly influenced by wastewater. This could be because the main pollutant in this study is chlorine.

There is a potential environmental impact reduction when there is a good wastewater management practice. Untreated wastewater, when released to water bodies causes numerous environmental and health damages to aquatic organisms. It makes the water unfit for both drinking and recreational purposes. Specifically, chlorine compounds in wastewater are harmful to fishes, algae and aquatic invertebrates. Also, the wastewater releases small quantities of certain volatile compounds (in this case chlorine) to the air (Canada, 2014).

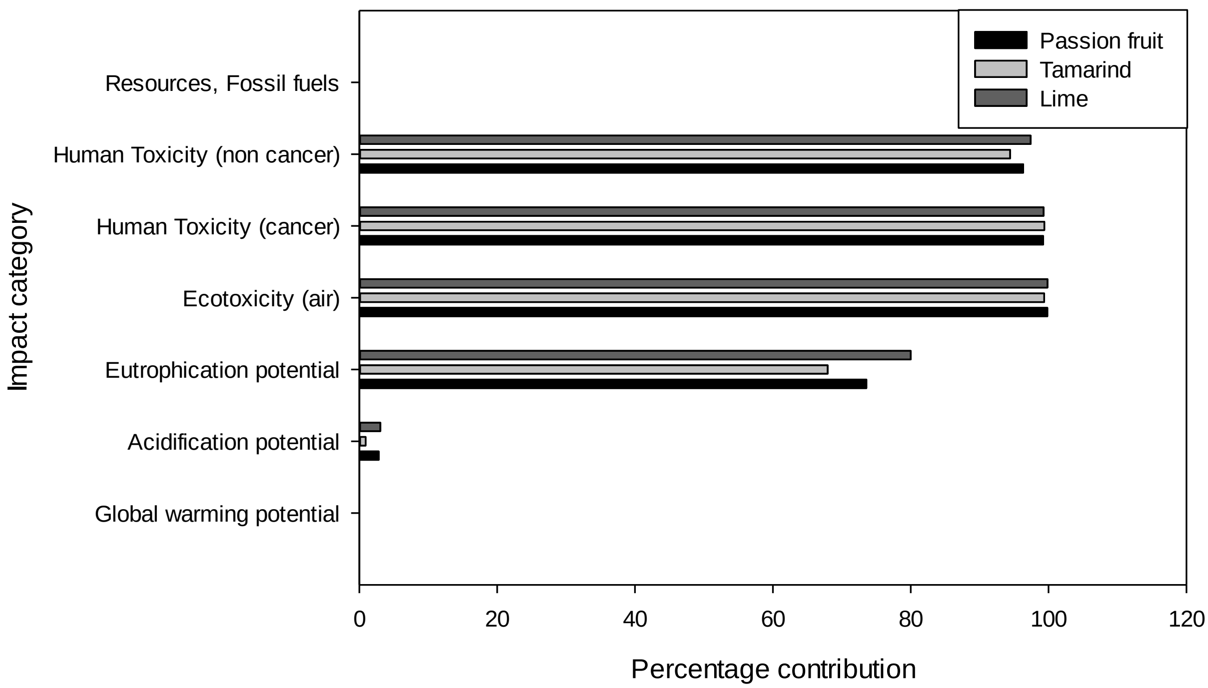


Fig. 4.4: Percentage contribution of wastewater to the impact categories

#### *4.3.3.2 Fruit waste*

Fruit waste which is one of the outputs shows a significant contribution to some impact categories. Results from the inventory table shows that for every 2,651.93kg of freshly harvested tamarind fruit needed to produce one tonne of tamarind juice (the functional unit), it generates a fruit waste of 1,693.49kg. For tamarind, 687.29kg freshly harvested fruit generates 443.09kg waste while 2147.77kg of lime fruit generates 1,210.7kg lime fruit waste. The percentage contribution of these fruit wastes to the impact categories is presented in Fig. 4.5. These fruit wastes have a significant contribution of (passion fruit – 80.82%; tamarind – 32.91%, and lime 63.61 %) to the total GWP result. For the acidification category, passion fruit waste contributes 70.74%, tamarind waste contributes 23.3% while lime waste contributes 50.66% to the acidification results. In the resource category, passion fruit, tamarind and lime contribute 49.23, 10.03, and 28.29%, respectively. In a similar study, Fernández-Coppel et al. (2018) reported that macauba palm cultivation affects the human health, resources, ecosystem quality and GWP impact categories. In another study, Zhu et al. (2018) reported that organic apple production has a contribution to, GWP, human toxicity, acidification potential and eutrophication potential. Studies show that food loss and waste contributes about 8 percent of the global anthropogenic green house gas emissions (Wieben, 2017). These wastes occurs in all the stages in the supply chain and could be largely avoided (Martin et al., 2019).

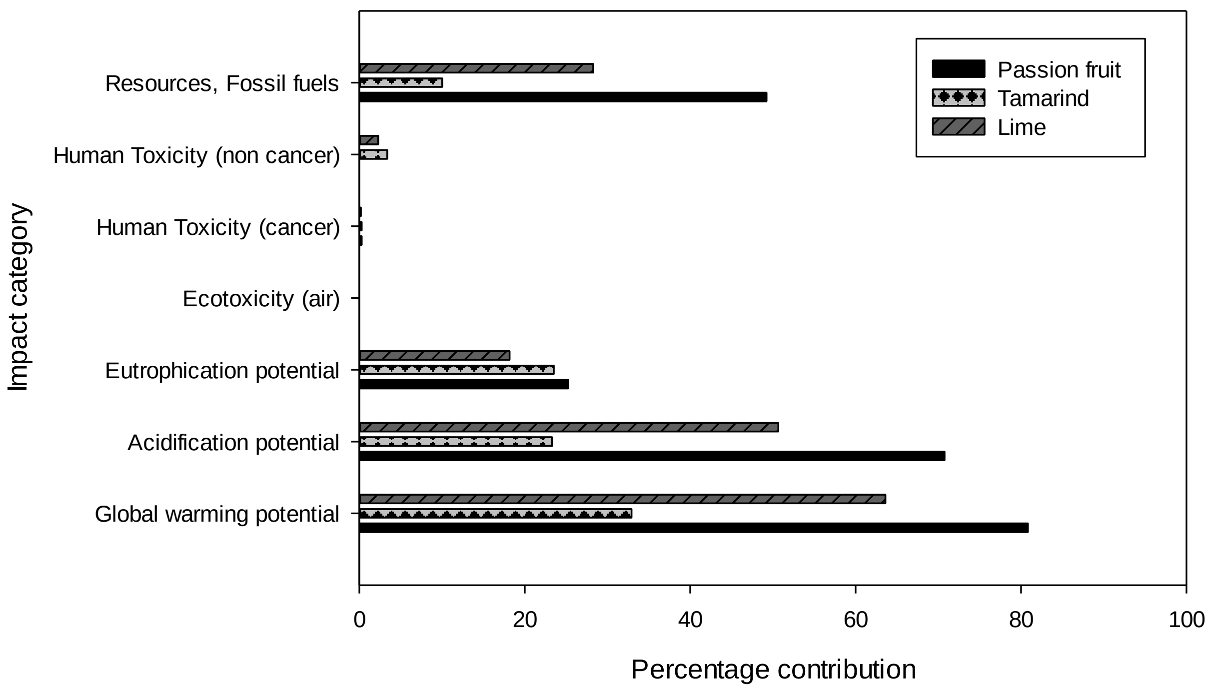


Fig. 4.5: Percentage contribution of fruit waste to the impact categories

### *4.3.4 Economic performance*

The life cycle inventory for producing one tonne of tamarind, lime and passion fruit is presented in Table 4.3. With each input contributing to the processing cost, the result shows that the value added for passion fruit, tamarind and lime is 624.68, 1272.53 and 431.75 CAD, respectively. This implies that processing tamarind generates the highest profit in the firm compared to passion fruit and lime. The value added for processing tamarind is 2.95 higher than lime and 2.04 higher than passion fruit. The percentage of contributions of the inputs to processing cost is shown in Fig. 4.6. The freshly harvested fruit has the highest contribution to input cost. From the assessment, freshly harvested passion fruit, tamarind and lime contributes 74.22 60.96 and 65.37%, respectively. Electricity cost is another major contributor to processing cost. The electricity cost of processing passion fruit, tamarind and lime contributes 12.40, 23.66, 20.35%, respectively to the processing cost. The labour cost of processing passion fruit, tamarind and lime contributes 13.32, 15.23 and 13.94%, respectively to the processing cost. Results from this study show that material resources (raw fruit), energy resources (electricity) and human resources (labour) contribute to >99% of the processing cost. Hence, to achieve economic sustainability in this fruit juice processing plant in Perspire, more attention should focus on these three areas given that these input costs generally affects the cost of the product.

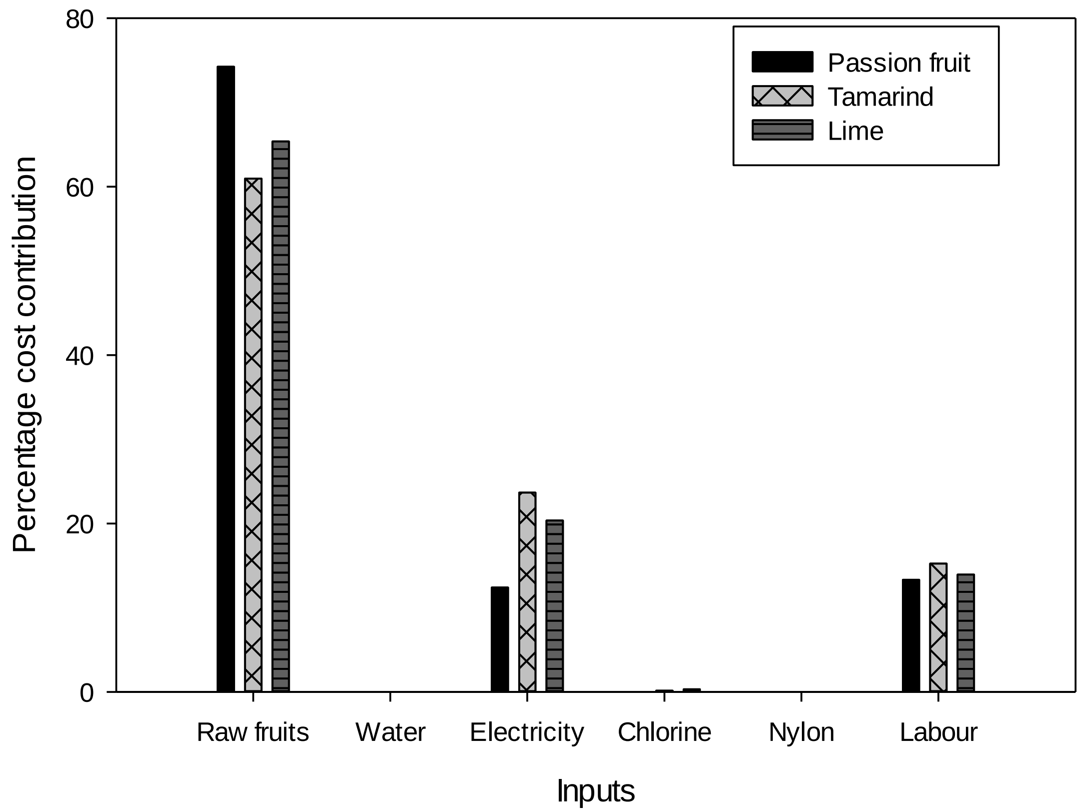


Fig. 4.6. Percentage contribution of inputs to processing cost for passion fruit, tamarind and lime

#### *4.3.5 Comparison of TRACI and ReCiPe results*

Some uncertainties could result from a change in a parameter, model or scenario. The results of TRACI which was the chosen methodology for this study were compared with ReCiPe. Table 4.6 presents a comparative result of TRACI and ReCiPe results. In LCA, the results are sensitive to the assessment methodology used. Therefore, a comparison analysis was conducted to determine the influence of the assessment methodology on the environmental impact results. The choice of assessment methodology should take into consideration the regions under study because the data for each methodology is developed using the specified region. Hence, this will represent a source of uncertainty as TRACI is mainly used for research in US regions (Menoufi, 2011) while ReCiPe is mainly used in Europe (Goedkoop et al., 2009). For the comparative analysis, the inputs and outputs were not varied and all the emissions from the processes are fixed. The analysis for the characterized results is done by comparing the results from the preferred assessment methodology (TRACI 2.1) and ReCiPe 1.08 midpoint (H). The results are presented in Table 4.6.

From the results, the impact of greenhouse gases measured as GWP in TRACI and climate change (CC) in ReCiPe had the same results. Both shows a result of 1460, 942 and 1330 kg CO2-eq., for passion fruit, tamarind and lime, respectively. Notably, GWP and climate change (CC) is the only impact category in both assessment methodology that has the same result. The acidification potential result of TRACI showed a contribution of 2.13 ± 0.27 kg SO2-eq. Comparing with the terrestrial acidification in ReCiPe which shows a result of 1.16 ± 0.197 kg SO2-eq, it was noticed that TRACI result in this category was 1.83 times higher than the ReCiPe results. The difference in the results could be attributed to the variation in the methodological approaches for the impact estimation. For instance, TRACI uses $H^{+}$. while ReCiPe, on the other hand includes the base saturation of the soil in its calculation. Also, ReCiPe produced a different characterization factor for NO/NOx (Bare, 2002; Goedkoop et al., 2009; Norris, 2002). ReCiPe presents eutrophication results in two categories which are freshwater eutrophication measured in kg P-eq and marine eutrophication presented in kg N-eq while TRACI measured eutrophication in kg N-eq. For both assessments, passion fruit has the highest result in this category while lime and tamarind ranked second and third, respectively. The ecotoxicity results in ReCiPe are presented in three different categories which are freshwater, marine, terrestrial ecotoxicity measured in kg 1, 4-DB eq with total contributions of 23.17 ± 13.04, 8.68 ± 4.89, 21.13 ± 11.92 kg 1, 4-DB eq., respectively. The results in TRACI is measured in Comparative Toxic Unit ecotoxicity (CTUe) as shown in Table 4.6. Human toxicity results in TRACI are grouped under two categories (cancer and non-cancer) measured in CTUh while ReCiPe result in this category is measured in kg 1, 4-DB eq. Other impact categories that were covered by ReCiPe include fossil fuel depletion, ionising radiation, metal depletion, natural land transformation, particulate matter formation, photochemical oxidant formation and water depletion.

Table 4.6: Comparison of TRACI and ReCiPe results

| Impact categories | Unit | Passion fruit | | Tamarind | | Lime | |
|---|---|---|---|---|---|---|---|
| | | TRACI | ReCiPe | TRACI | ReCiPe | TRACI | ReCiPe |
| GWP/Climate change | kg$CO_2$-eq | 1,460 | 1,460 | 942 | 942 | 1,330 | 1,330 |
| Acidification | kg$SO_2$-eq | 2.29 | 0.943 | 1.82 | 1.32 | 2.29 | 1.23 |
| Freshwater eutrophication | kgP-eq | - | 0.474 | - | 0.124 | - | 0.402 |
| Marine eutrophication | kg N-eq | 3.67 | 1.95 | 1.03 | 0.544 | 3.65 | 1.94 |
| Ecotoxicity | kg 1, 4-DB eq | - | 74.2 | - | 19.53 | - | 65.2 |
| Ecotoxicity | CTUe | 5,990 | - | 1,560 | - | 6470 | - |
| Human toxicity | CTUh | 1.22E-03 | - | 3.2E-04 | - | 1.3E-03 | - |
| Human toxicity | kg 1, 4-DB eq | - | 4,900 | - | 1,300 | - | 4,310 |

### *4.4 Conclusion*

A comprehensive life cycle assessment and life cycle cost for processing tamarind, lime and passion fruits was presented. The results are based on a one tonne functional unit of three fruit juice produced by APRAL a small-scale fruit processing plant in Honduras. The inventory data were obtained from onsite operations and analyzed using the TRACI methodology in the GaBi software. The environmental assessment results of the fruits are presented in seven categories which are global warming potential, acidification potential, eutrophication potential, ecotoxicity, human toxicity (cancer and non-cancer), and resources. Comparing the normalized results of the three fruits, tamarind has the lowest normalized results signifying a good environmental performance when compared to lime and passion fruit. The normalized result of lime is 3.9 higher than tamarind and 1.07 higher than passion fruit. Similarly, the normalized result of passion fruit is 3.6 higher than lime. Results from this study shows that environmental damage is mainly caused by electricity, fruit waste and wastewater. Hence, a good waste management policy can lead to a better environmental efficiency for this firm.

From the economic assessment results, the material resources (freshly harvested fruits) constitute > 60% of the total production cost. This highlights the importance of resource use efficiency in producing fruit juice in rural Honduras. Comparing the economic performance of the three fruits, tamarind processing shows the best percentage profit of 65.56%. The valued added result of tamarind processing is 2.95 times higher than the value added for lime processing and 2.04 times higher than passion fruit. In this category, lime also have the worst economic performance.

The results serve as a guide for decision making and process improvement at this facility. Overall, these joint assessments provide a useful insight for improvement options. Future research could help to increase the environmental and economic efficiency of this firm as well as other small-scale food industry.

## Connecting text

The combined LCA and LCC study of the APRAL fruit processing plant provides an insight of resource use, environmental and economic efficiency in this firm. To further provide a complete sustainability assessment, it is necessary to include the operational efficiency of the processes. In the next part of this study, LCA, LCC and DEA will be applied in a model that assesses a food processing system. The DEA component measures the operational efficiency which shows the resource use efficiency of the processing units. The results from the model could provide the necessary information for process improvement and performances of the various potential improvement options for decision making.

# 5 Development of a food system eco-efficiency model based on eco-environmental and operational performances


## Abstract

Eco-efficiency has been identified as an important sustainability tool to enhance food systems performance. However, in its current form, it is usually applied for environmental sustainability assessments. In this study, a new eco-efficiency sustainability model which combines analysis of environmental, economic and operational performance was developed. The new model quantifies the various performances into a single eco-efficiency score (EES). The primary benefit of the model is its ability to provide economic, environmental, and operational efficiency data on current and proposed improvement for informed enterprise decisions. The model was applied to evaluate the sustainability performance of a small-scale fruit processing enterprise. In this case study, six decision-making units (DMUs) were evaluated including the current process. An index was generated from an economic-environmental assessment to estimate the EES. This model applies to both product and process-based food assessments. It offers a wider and all-inclusive assessment, analysis and results that could be used to improve production processes in all the stages of the value chain which subsequently reduces the environmental impacts of food industry. Additionally, it provides data for informed management decisions and policy for competitive advantage in the marketplace while helping enterprises achieve their corporate social responsibility.



**Keywords/Acronyms:**

Life Cycle Assessment, Data Envelopment Analysis, Life Cycle Costing, sustainability, eco-efficiency, decision-making unit

### *5.1 Introduction*

Food security has been a crucial challenge that is facing the world partly because of current unsustainable food systems (Bhat, 2017). One out of eight of the world population suffers chronic hunger which is directly caused food system inefficiencies (FAO, 2014). There are significant inefficient practices and systems associated with the 7 billion tonnes of food produced annually with serious implications for global food security (Cristóbal et al., 2016). As food production increases, a reasonable fraction is either lost or wasted (Cristóbal et al., 2016). The Food and Agriculture Organization of the United Nations reported that about 1.3 billion tonnes of food are wasted annually (Timmermans et al., 2014). Considering that the food industry is resource-based, sustainable development through resource use management and efficiency is paramount.

Food systems sustainability has largely been focused on environmental assessment and in some cases include economics. Although, small-scale firms play a vital role in food security especially in ensuring rural sustainability (McDonagh, 2013), food systems sustainability has primarily been focused on large scale food companies. For most enterprises, the development of a concept/model that integrates the firm's environmental and economic performance to ensure evidence-based decision making is essential (Krajnc and Glavič, 2005). This will allow the use of available natural resources to meet the growing global food demand, reduce associated environmental impacts and provide high-quality food products at a reduced price (Krajnc and Glavič, 2005; Tang and Zhou, 2012; H. Zhou et al., 2018).

Eco-efficiency techniques present such opportunities for broader sustainability evaluation. It involves the combination of environmental assessment techniques such as Life Cycle Assessment, (LCA) and decision-making tools such as Data Envelopment Analysis (DEA). Several researchers have applied such combined tools to evaluate food systems including cotton production (Ullah et al., 2016), grape (Mohseni et al., 2018; Vázquez-Rowe et al., 2012), soybean (Mohammadi et al., 2013), rice (Mohammadi et al., 2015), wheat (Masuda, 2016), arecanut (Paramesh et al., 2018), tea (Kouchaki-Penchah et al., 2017), as well as reduction of food waste (Cristóbal et al., 2016). Although these reports provided data on environmental performance and technical (operational) efficiency, they did not provide a suggestion for improvement neither did they incorporate resource use efficiency. Achieving sustainability will require more than environmental performance. It is essential that alternatives that are touted as more sustainable are presented with evidence of optimized resource use potential, and environmental, economic or operational improvement.

Models with such capacity provide more incentives even for small scale enterprises to seriously consider and pursue sustainability.

The primary objective of this study was to develop an eco-efficiency-based sustainability model for food systems that will give room for process optimization and improvement, evaluation of the operational efficiency, and environmental and economic assessment of the various processes. The secondary objective is to test the model using a small-scale fruit processing enterprise in Honduras as a case study.

## *5.2 Material and method*

An eco-efficiency-based sustainability model for a small-scale food processing plant was designed and tested in this study. The model was tested using the data obtained from APRAL processing food plant. The data represents a real-life processing conditions obtained from the onsite operations and from the processing plant's existing records.

### *5.2.1 Eco-efficiency model development*

#### *5.2.1.1 Eco-efficiency concept*

Eco-efficiency is a concept that incorporates environment and economic efficiency (Lupan and Cozorici, 2015). It is a measure of value-added and environmental impact (Zhang et al., 2008). It is a resource-based sustainability concept. In this study, eco-efficiency will be viewed from a resource-based, environment and economic efficiency perspective.

#### *5.2.1.2 Overview of the eco-efficiency model*

The proposed model is developed not only to assess the current food process but also to access potential improved options for sustainability. These virtual options are first tested by the model before implementation. The proposed eco-efficiency model and the model workflow are presented in Fig. 5.1 and Fig. 5.2, respectively. Sustainability in this study refers to social, economic and environmental efficiency. This model incorporates the following assessments.

1. Environmental assessment – Using the Life Cycle Assessment (LCA) methodology

2. Economic assessment - Using the Life Cycle Cost (LCC) methodology

3. Operational efficiency - Using the Data Envelopment Analysis (DEA)

These three assessments are referred to as independent assessments in this study.

A further assessment incorporated in the model is referred to as dependent assessment which are

4. Economic-environmental assessment – which is a combination of assessment (1) and (2) above.
5. Eco-efficiency assessment - a combination of assessment (3) and (4).

The details of the assessments are discussed below

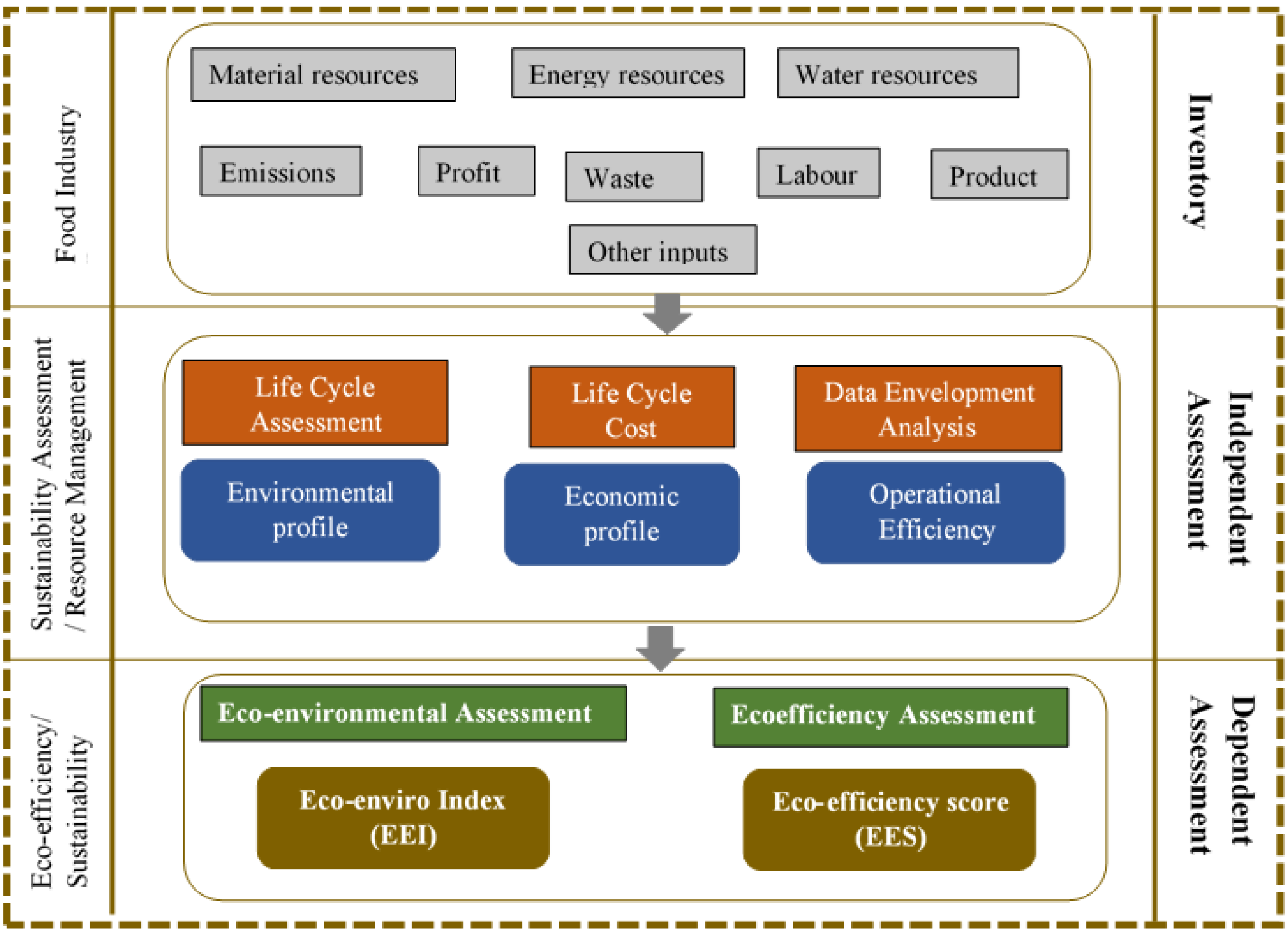


Fig. 5.1: Proposed eco-efficiency model

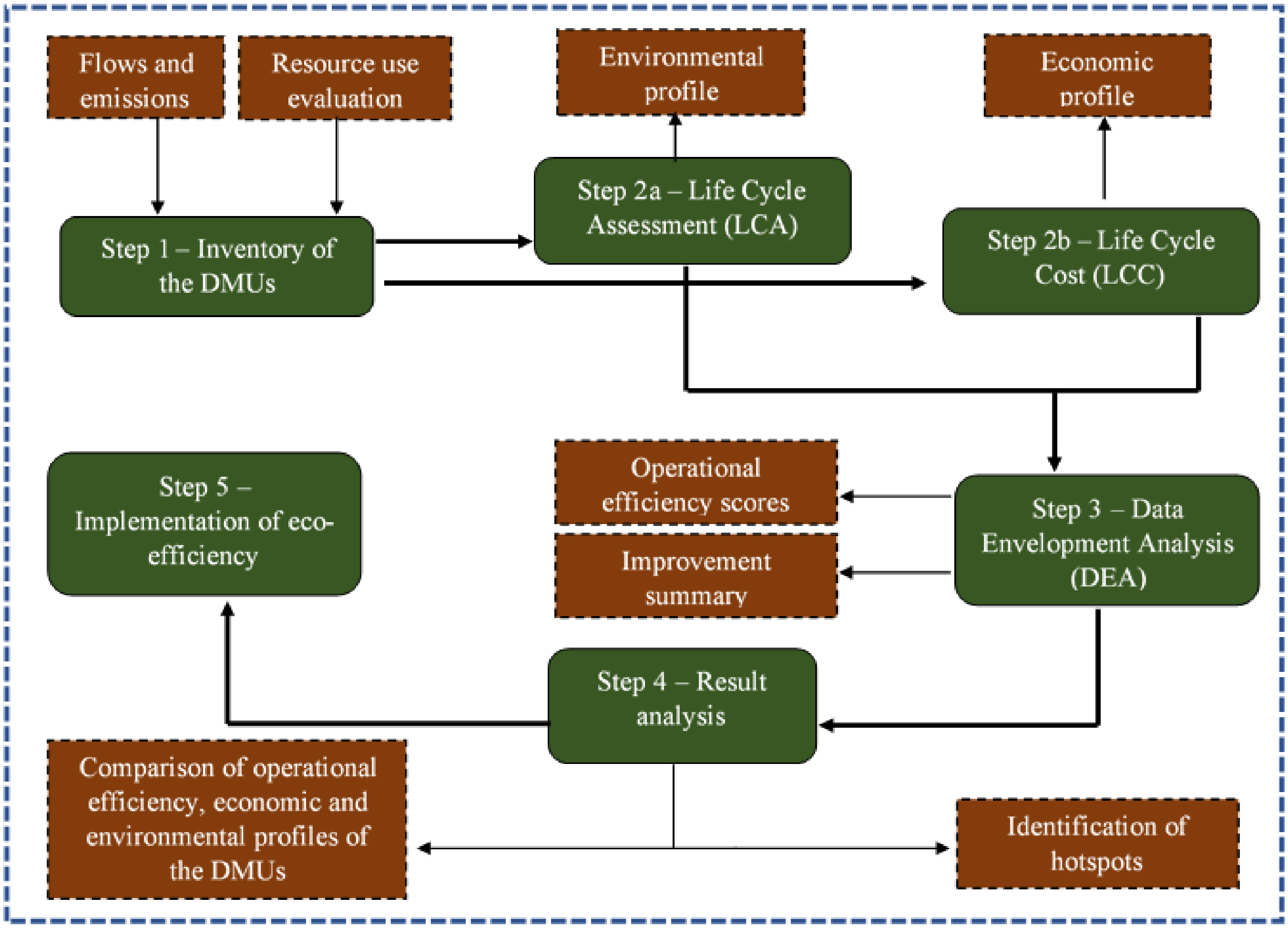


*Fig. 5.2: The model workflow*

*5.2.1.2.1 The environmental assessment*

The LCA is an internationally recommended and accepted tool for environmental assessment of a product within its life cycle (Kwofie and Ngadi, 2017; Lozano et al., 2009). The LCA component of the model uses the already established four step framework for LCA (ISO, 2006). This includes the goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and result interpretation.

In the goal and scope step, we define the functional unit which is quantified function or calculation reference. The main aim or objective of the study and the system boundary are clearly defined. The system boundary which are the unit processes included in the assessment is defined too. The impact assessment tool or methodology is also defined in this step. The data quality and the source of data (on-site operation or from database) are also specified in this step. The software is also specified in this step.

For the case study in this chapter, the functional unit is 1 tonne of lime, tamarind and passion fruit. The system boundary is shown in Fig. 5.3. The impact assessment tool is the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) and the data is from onsite operations. The software used is Ganzheitlichen Bilanzierung (Gabi) 8.1 version Sphera Solutions GmbH (formerly thinkstep AG), Leinfelden-Echterdingen, Germany.

The second stage is the LCI where input and output data are collected. The LCI data may consist of actual input and output measured from each unit of the processes being studied or estimates from an existing database. The data generated are related to the functional unit and further aggregated. The data obtained at this stage is further used for the next step. For the case study, the data is gotten from onsite operations. The inputs and outputs are presented in Table 5.1.

The third step in the LCA is the assessment stage. In the LCIA stage, the flows are classified, characterized, normalized and weighted by the LCA software. These terms are herein defined: Classification means assigning the inputs and outputs to impact categories. Impact categories are classes representing an issue of environmental concern (e.g. is acidification). Characterization is defined as adding all the contributions of inputs and outputs to each impact category. Characterization results are a product of the inventory value with a characterization factor of each substance. The product becomes the quantified environmental impact of that substance (Menoufi, 2011). Normalization is a calculation converting the category indicator results to a reference information. Weighting means using numerical factors to aggregate the results of the impact categories. Normalization and weighting are optional steps in LCIA according to the ISO standards (ISO, 2006; Menoufi, 2011). But it could be done in the model to compare the characterized results to a certain reference or equivalent value (time, person equivalent or area) and then aggregating the results into a single score. There are several LCIA tools available for environmental assessments. Some well-established tools are like The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), (Bare et al., 2012), ReCiPe (Goedkoop et al., 2009), or many other impact assessment tools could be used at this step.

*5.2.1.2.1.1 Characterization*

Characterization converts the life cycle inventory value for each impact category to a common unit and adds them up to generate a value that represents the total contribution of the flows to the impact category as seen in equation 5.1. This is achieved by relating the flow to the characterization factor (CF) (ISO, 2006). The resultant impact will be a product of the emission and the characterization factor as seen in equation 5.2 (Bare et al., 2012).

$$S_j = \sum_i CF_{ji}.M_i \qquad 5.1$$

Where; $S_j$ = The impact score for each category (j) measured in different units; $CJ_{ji}$ = The characterization factor of the elementary flow (i) for each impact category j; Mi = Elementary flow related to the functional unit of the study;

For example, for each impact category like global warming potential,

$$GWP = \sum e_i * GWP_i \qquad 5.2$$

Where; $e_i$ = emissions; GWP = Global warming potential

*5.2.1.2.1.2 Normalization*

Normalization compares the characterized results to a certain reference information. It presents the results of the environmental impact results across the impact categories in same unit (in this case, person equivalents) (ISO, 2006). The calculations of normalized results is shown in equation 5.3 (Aymard and Botta-Genoulaz, 2017). By presenting the results of these impact categories in same unit , it therefore, shows the relative significance of these impact categories (Aymard and Botta-Genoulaz, 2017; Prado et al., 2017).

Mathematically,

$$N_i = S_i / R_i \qquad 5.3$$

i = the impact category (e.g. eutrophication)

$S_i$ = the characterized result of the impact category (e.g. 7.6 $kgCO_2$ eq.)

$N_i$ = the normalized result of the product being studied (expressed in person equivalents in this study)

$R_i$ = the characterized impact of i (impact category) of the reference system. Example of a reference system could be the total input/output or population of a given geographical area over a given reference period.

*5.2.1.2.1.3 Weighting*

The objective of weighting is to provide an overall environmental performance score. It could be expressed in dimensionless weighting factors (as in this case study). The results are provided by the software and are based on the impact assessment methodology used (Huppes and van Oers, 2011). In our case study, TRACI was chosen as the impact assessment methodology and the environmental performance score is the weighted score.

The last step in LCA is the interpretation stage which is basically the result analysis and conclusion.

*5.2.1.2.1.4 Case study – Life Cycle Assessment of a fruit processing enterprise*

The model was applied in a small-scale fruit processing enterprise, APRAL, situated at Pespire (13°36'N 87°22'W) in the dry corridors of Honduras. The processing cycle of three fruits (passion fruit, lime and tamarind) were considered for the evaluation. The system boundary is a gate to gate involving the conversion of fruits into juice. The system boundary and process flow are shown in Fig. 5.3. The freshly harvested fruits are supplied by farmers who form part of the cooperative that owns the enterprise. The goal of the case study is to optimize the process and present the best operational management strategies that could improve the economic, environmental performance, operational efficiency of the enterprise. Primary and secondary inventory data are collected from the enterprise and LCA database. The inputs include raw material (harvested fruits), electricity, labour, chlorine (for disinfection), water, and ozone (for tamarind), nylon. Outputs include wastewater, fruit waste, nylon waste and juice as presented in Table 5.1. GaBi software was used for the analysis. The TRACI impact assessment tool was used to determine the environmental performance. Five impact categories including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ecotoxicity and human toxicity (cancer and non-cancer) were used to evaluate the environmental performance. The software generates the characterized, normalized and weighted results. The normalized results are expressed in person equivalents. The weighted results were also presented. In this study, our main interest is in the weighted result as weighting gives us a single score for the environmental performance for each DMU.

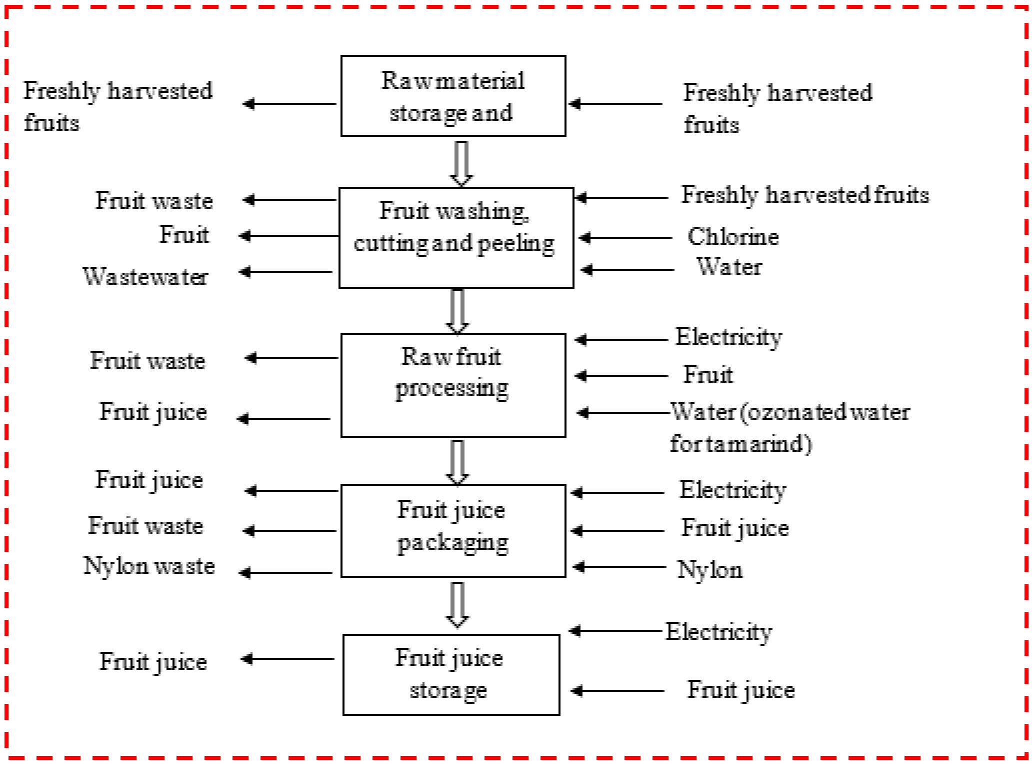


Fig. 5.3. System boundary and flow diagram of fruit juice production

Table 5.1: Life Cycle Inventory for processing one tonne of tamarind, lime and passion fruit

| Input/Output | Units | Passion fruit | Tamarind | Lime |
|---|---|---|---|---|
| **Inputs** | | | | |
| Fresh harvested fruit | Kg | 2,651.93 | 687.29 | 2,147.77 |
| Water | Litres | 7,350.50 | 2,650.02 | 7,956.13 |
| Electricity | Kwh | 483.45 | 533.44 | 850.90 |
| Chlorine | Kg | 0.02 | 0.05 | 0.20 |
| Nylon bag | Kg | 3.95 | 3.95 | 3.95 |
| **Outputs** | | | | |
| Wastewater | Litres | 7,161.98 | 1,856.13 | 7,733.86 |
| Fruit waste | Kg | 1,693.49 | 443.09 | 1,210.70 |
| Nylon bag waste | Kg | 0.59 | 0.59 | 0.59 |

*5.2.1.2.2 Economic assessment*

The economic assessment of the system was done using the Life Cycle Cost (LCC) methodology proposed by (Hunkeler et al., 2008). The LCC is an assessment of the cost of a product in its life cycle stages (Reich, 2005). It is an approach for analyzing the organization's economic performance (Falcone et al., 2015; Huppes et al., 2004). Hunkeler et al. (2008) noted that there are three categories of LCC which are Conventional LCC, Environmental LCC and Societal LCC. This study/model used the environmental LCC since its methodology allows the use of same functional unit, system boundaries and product system model as LCA. The methodology for LCC has been described by Hunkeler et al. (2008). LCC and LCA have some differences in their methodology simply because they focus on different aspects of sustainability. LCC targets cost-effectiveness while LCA targets environmental performance.

In the case study, the economic assessment for the system is evaluated based on the value-added to the product (Laso et al., 2018). It is an evaluation of the difference between the cost of the inputs and the corresponding output cost. The inputs and outputs are same with the LCI as shown in Table 5.2. The LCC methodology used was proposed by (Hunkeler et al., 2008). Like LCA, a functional unit of one metric tonne of each of the fruit juice was used for the current process. Input and output cost were used for the estimation. The conversion rate used in this study is 1 Canadian dollar (CAD) equivalent to 18.55 lempira (Honduran currency).

Table 5.2: Inventory results for the three different fruits produced by APRAL processing plant

| DMU | Input/output | unit | Passion fruit | Tamarind | Lime |
|---|---|---|---|---|---|
| 1 | Freshly harvested fruits | CAD | 857.77 | 407.56 | 810.48 |
| | Electricity | CAD | 143.34 | 158.16 | 252.29 |
| | Labour | CAD | 153.93 | 101.83 | 172.87 |
| | Time | hrs | 52 | 34.4 | 58.4 |
| | Product | CAD | 1,780.38 | 1,941.1 | 1,671.5 |
| | Profit | CAD | 624.68 | 1272.53 | 431.75 |
| 2 | Freshly harvested fruits | CAD | 857.77 | 543.41 | 1,080.64 |
| | Electricity | CAD | 143.34 | 168.22 | 293.72 |
| | Labour | CAD | 175.92 | 155.08 | 230.41 |
| | Time | hrs | 59.43 | 52.39 | 77.84 |
| | Product | CAD | 1,780.38 | 2,588.13 | 2,228.67 |
| | Profit | CAD | 602.68 | 1,720.07 | 618.42 |
| 3 | Freshly harvested fruits | CAD | 857.77 | 407.56 | 1080.64 |
| | Electricity | CAD | 143.34 | 158.16 | 293.72 |
| | Labour | CAD | 192.41 | 116.38 | 288.02 |
| | Time | hrs | 65 | 39.31 | 97.3 |
| | Product | CAD | 1,780.38 | 1,941.1 | 2,228.67 |
| | Profit | CAD | 586.19 | 1,257.99 | 560.18 |
| 4 | Freshly harvested fruits | CAD | 857.77 | 407.56 | 810.48 |
| | Electricity | CAD | 143.34 | 158.16 | 252.29 |
| | Labour | CAD | 115.44 | 76.37 | 129.65 |
| | Time | hrs | 39 | 25.8 | 43.8 |
| | Product | CAD | 1,780.38 | 1,941.1 | 1,671.5 |
| | Profit | CAD | 663.16 | 1,297.99 | 474.97 |
| 5 | Freshly harvested fruits | CAD | 1,572.58 | 624.92 | 1,485.88 |
| | Electricity | CAD | 156.13 | 174.25 | 355.87 |
| | Labour | CAD | 307.68 | 234.09 | 345.66 |
| | Time | hrs | 103.94 | 79.08 | 116.77 |
| | Product | CAD | 3,264.03 | 2,976.35 | 3,064.42 |
| | Profit | CAD | 1226.41 | 1941.54 | 869.49 |

| | | | | | |
|---|---|---|---|---|---|
| 6 | Freshly harvested fruits | CAD | 1,715.54 | 815.11 | 1,620.96 |
| | Electricity | CAD | 158.69 | 188.33 | 376.58 |
| | Labour | CAD | 205.08 | 135.77 | 230.49 |
| | Time | Hrs | 69.28 | 45.87 | 77.87 |
| | Product | CAD | 3,560.76 | 2,740.95 | 3,343.01 |
| | Profit | CAD | 1,480.11 | 3,882.2 | 1,106.75 |

##### *5.2.1.2.3 Operational efficiency*

The operational efficiency of the system/model is calculated using the Data Envelopment Analysis (DEA). The operational efficiency score is calculated based on the input to output ratio. In this study, it is expressed in percentage. The DEA offers a non-parametric approach in determining the operational efficiency of the processes which are referred to as the decision making units (DMU) (Cooper et al., 2004; Lozano et al., 2010). A non-parametric approach in this case means that it does not assume that data originates from any definite production function. In this study, a DMU represents a unit food process. There are real and virtual DMUs. The real DMU is the current process while the virtual DMU (hypothetical scenarios) are potential improvement options of the current process. DEA applications mainly use two models which are Variable Return to Scale (VRS) and Constant Return to Scale (CRS). According to Tone (2001), DEA measures the efficiency of a DMU. It identifies the slacks in the production process which are the excess inputs and output losses which is vital in analysis the total efficiency of the system.

###### *5.2.1.2.3.1 DEA for the food industry*

Performance evaluation and process optimization are the key elements to sustainable development and both elements are represented in the model. In this study, the model incorporates the current practice evaluation. The optimized processes account for potential improvement and the resulting scores are used to calculate the performance indexes. The first step to optimization is to establish a functional relationship between the inputs and outputs which are the performance variables (Zhu, 2014). In the model, the food process is regarded as a DMU. For example, the processing of one tonne of tamarind is considered as a DMU. The DEA mathematical model used in this study was proposed by Zhu (2014) which is an input-oriented model where the inputs are reduced to give a higher output or same output. It identifies the efficient process called the efficient frontier that acts as the benchmark for other DMUs. Among all the compared DMUs, at least one DMU will have an operational efficiency score of 100 (also means technical efficiency of 1). This is called the frontier. Other DMUs will have their scores less than the frontier. This frontier is referred to as the best performing DMU (process). These DMUs are sets of sub-unit processes and consists of inputs and outputs which determines the operational efficiency.

*5.2.1.2.3.2 Relative operational efficiency*

Using a variable return to scale (VRS) and an input-oriented approach, the model measures the operational efficiency of $DMU_j$. The mathematical equations for calculating the operational efficiency for inputs, outputs are presented in Equation 5.4, and 5.5, respectively.

$\theta^*$ = Relative operational efficiency scores

$\theta^* = \min \theta$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij} \qquad (5.4)$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rj} \qquad (5.5)$$

Any DMU that has its $\theta^* = 1$ is the efficient frontier. Say for a study $DMU_j$ where $j(1, 2, \ldots \ldots, n)$, $DMU_2$ is efficient if its $\theta^* = 1$ and it means that no other DMU under consideration performs better than $DMU_2$. The efficiency of the DMUs increases as you move along the scale from 0 to 1. For any DMU whose $\theta^* < 1$ is either weakly efficient or inefficient.

For DEA of a food system with a set of DMUs, say $DMU_j$ where $j(1, 2, \ldots \ldots, n)$

DMU = decision making units; n = number of $DMU_s$; m = number of inputs in $DMU_j$; s = number of outputs in $DMU_j$

The inputs for j are given as $x_{ij}(i = 1, 2, \ldots \ldots, m)$

The outputs for j are given as $y_{rj}(r = 1, 2, \ldots \ldots, s)$

In this case study, the Frontier Analyst (Banxia, Kendal, Cumbria, United Kingdom) software was used in calculating the operational efficiency of the DMUs using an input-oriented approach as illustrated above (see Appendix B). There are six DMUs; DMU 1 reflects the current process (processing of one tonne of tamarind, lime and passion fruit). The other five DMUs are potential improvement options (hypothetical scenarios). DMU 2 is an improvement in the raw material storage, DMU 3 is an improvement in the product storage, DMU 4 is an improvement in the peeling process, DMU 5 is an improvement of both storage conditions, DMU 6 is an improvement of all the storage conditions and the peeling process. For the DEA, only the major input and outputs which affects the operational efficiency were measured. The major inputs – labour, electricity, raw materials and time are selected while profit and product form the output for the analysis. The efficiency is a measure of the input-output ratio. Details of the input and output parameters are of proposed sustainable options are presented as DMU 2-6 on Table 5.2. Any DMU with an operational efficiency score less than the current process (DMU 1) is not a good improvement option. The major inputs – labour, electricity, raw materials and time are selected while profit and product form the output for the analysis. For the frontier analyst assessment, labour, time and electricity are the controlled inputs while the raw material (freshly harvested fruits) is an uncontrolled input. The efficiency is a measure of the input-output ratio.

*5.2.1.2.4 Economic-environmental assessment*

This dependent assessment of the model is simply a combination of the environmental and economic performance. The scores are represented on an XY cartesian plan which is referred in this study as the eco-enviro graph. The score from both assessments is also referred to an eco-enviro index. Both scores can be plotted using the Microsoft Excel. The eco-enviro graph which is a two-dimensional (X, Y) cartesian system is shown in Fig. 5.4. The X-axis is the environmental performance while the Y-axis is the economic performance. The graph is a quadrant (plane geometry) with the joint economic and environmental performance of the DMUs plotted on the graph. The current DMU is located on the (0,0) of the graph while the other DMUs are measured by the improvement in their economic and environmental performance. Quadrant 1 (A, B) has a positive improvement in both economic and environmental performance. Quadrant 2 (B, D) has a negative economic improvement and a positive environmental improvement when compared to the current DMU. Quadrant 3 (C, D) represents a region with a negative improvement in both economic and environmental performance. Quadrant 4 (A, C) represents a region with a positive economic improvement and a negative environmental improvement when compared to the current DMU. Negative environmental performance of the DMU signifies an improvement in the impact of the food process or product to the ecosystem while a positive economic performance indicates that there is an increase in the profit margin of the process when compared to the reference or current process (DMU 1). A positive score in the environmental performance signifies that the process has more environmental impacts than the current process while a negative score in the economic improvement signifies that the cost-benefit for the DMU is lower than the current process. Hence, a combined positive economic and negative environmental performance gives the best eco-enviro score. But this is not the general eco-efficiency score. As shown in Fig. 5.4, $DMU_e$ and $DMU_j$ are the best performing DMUs in the graph because they have a positive improvement in economic performance and a reduced (negative) impact in environmental performances when compared to the current DMU. $DMU_d$ and $DMU_h$ are the worst performing DMUs because they have a negative economic improvement and a positive environmental improvement. Similarly, $DMU_c$ and $DMU_g$ have a negative improvement in both economic and environmental performance while $DMU_e$ and $DMU_j$ have has a good economic performance and a bad environmental performance when compared to the current process – DMU 1 (0,0). For eco-efficiency evaluation discussed in the next section, the four axes have different degrees of performance co-efficient. Degree of performance is measured by the environmental and economic performances. Axis AC with the best performance (good economic and environmental performance) has a degree of performance co-efficient of 1. Axis AB, CD and BD have a degree of performance of 0.75, 0.50 and 0.25, respectively. So, the location of the DMU on the axis determines their degree of performance co-efficient.

Note: For the eco-enviro scores, the LCA generates a single environmental score that reflects the environmental profile of the DMU. It could be a weighted average or a normalized value. The economic score generated by LCC reflects the valued added (VA) of each DMU.

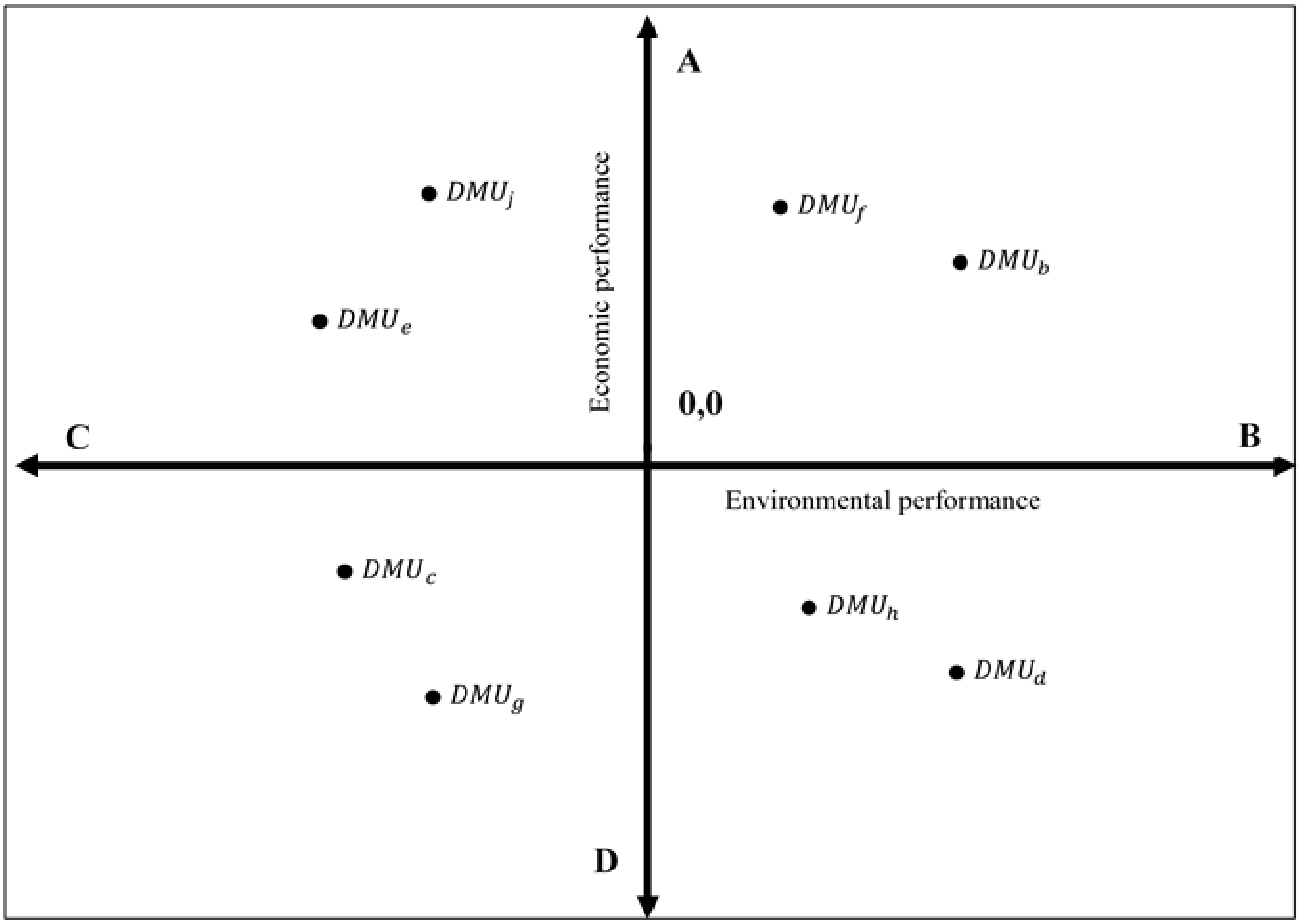


*Fig. 5.4. The eco-enviro graph for a food industry*

#### *5.2.1.3 Eco-efficiency assessment*

To generate an eco-efficiency score (EES), both the operational efficiency performance and the eco-enviro scores are computed. This is the final stage in the model and evaluation. The EES reflects the eco-efficiency performance of each DMU in this study. A high eco-efficiency score reflects a good performance in economic, environmental assessment and operational efficiency. There is no scale of measurement for EES. Rather, the most efficient unit is selected in comparison with other compared DMU. As stated earlier, the four segments of the eco-enviro graph (AC, AB, CD and BD) have a degree of performance co-efficient of (1, 0.75, 0.50 and 0.25), respectively. A simple equation to generate the eco-efficiency score for food industry is given in equation 5.6.

$$EES = mx + c \qquad (5.6)$$

x = economic-environmental nexus. This is simply the connection between the environmental and economic score. The score is derived from the difference between the relative economic score and the relative environmental score of the DMU.

m = degree of performance co-efficient is simply a constant attached to the four segments of the eco-enviro graph based on their economic and environmental performances. (AC, AB, CD and BD) have a degree of performance co-efficient of (1, 0.75, 0.50 and 0.25), respectively.

c = operational efficiency (obtained in the independent assessment)

#### *5.2.1.4 Model workflow*

The model follows the 5-step eco-efficiency approach (Iribarren et al., 2010). It was modified to include an economic component evaluated using LCC. The proposed model is presented in Fig. 5.1. The model workflow is shown in Fig. 5.2. The five steps in the model are discussed below

***Step 1***

The model workflow begins with an inventory of the current process (DMU1) and the virtual DMUs. These virtual DMUs are options for potential improvements which are first tested by the model before implementation. With the LCI data, the environmental and economic performance were assessed.

***Step 2***

The step two consist of the two independent assessments which are LCA and LCC. The LCA is used for the environmental assessment and generated a weighted score which represents the environmental performance of each DMU. The LCA methodology has been discussed earlier in this chapter. The LCC measures the contribution of each input to the production cost and hence shows the economic profile of the DMUs.

***Step 3***

A data envelopment analysis was performed on all identified DMUs to estimate their performances. This provides the operational efficiency score for all the DMUs from the inventory data based on an input-oriented approach.

***Step 4***

This step is basically the dependent assessments and the general result interpretation. The results from the LCA, LCC and DEA are used for result analysis in step 4. The details of the dependent assessments have been discussed earlier in this chapter. This stage could be referred to as eco-efficiency evaluation.

***Step 5***

The last stage of the methodology is the implementation of the eco-efficiency studies which could be a change in policy by the firm based on the assessments of the DMUs.

It could be noted that the decision is based on (1) the eco-environmental performance from the eco-enviro graph (graph of economic vs environmental performance), (2) operational efficiency and (3) the eco-efficiency performance which is a function of the eco-environmental performance and the operational efficiency. For the eco-enviro graph, any plot that is above (0,0) is either weakly efficient or strongly efficient (the frontier). The operational efficiency in this study are expressed in percentage with the best performing DMU having a relative operational efficiency of 100.

## ***5.3 Results and discussion***

### *5.3.1 Life cycle assessment results*

The environmental assessment results reflect the environmental performance of the products. Even though, our focus in this study was the weighted result as it presents the environmental performance in a single score which makes it easier for comparing the performance of all the DMUs. It is also important to show the environmental performance of the current process and identify the need for improvement. Therefore, Table 5.3 shows the characterized and normalized results for producing a tonne of tamarind, lime or passion fruit juice. This result reflected the environmental performance of the current process (DMU 1). From the result, the relative contribution of the processes to GWP was 1244 ± 269.5 kg CO2-eq. (including biogenic carbon). Biogenic carbon emissions are the emissions from the combustion of biologically based materials (Harris et al., 2018). Excluding the biogenic carbon, the contribution becomes relatively smaller – 970.67 ± 149.5 kg CO2-eq. The normalized GWP results was relatively low when compared with the other studied impact categories. On the other hand, fruit processing also showed a significant contribution to acidification and eutrophication. Acidification potential results showed a relative contribution of 2.13 ± 0.27 kg SO2-eq. Eutrophication result showed a relative contribution of 2.78 ± 1.52 kg N-eq. These results are similar to other LCA results for food production (Parajuli et al., 2019). Comparing the normalized results of the three fruits, tamarind had the lowest normalized result while lime had the highest normalized result. This implies that processing one tonne of lime had the worst environmental performance while tamarind had the best environmental performance in this study.

The weighted score helps us to compare the different DMUs. It generates a single score representing the environmental performance for all the DMUs. The weighted scores are presented in Table 5.5.

For the passion fruit, DMU 1-4 had the same weighted score. It means that they showed same environmental performance. Alternatively, DMU 5 and 6 showed a lower environmental performance. Hence it means DMU 5 and 6 were more environmentally friendly than DMU 1-4.
For tamarind, DMU 2, 5 and 6 offered a better environmental performance than the current process (DMU 1). But DMU 3 and 4 had same environmental performance as DMU 1. Hence DMU 2, 5 and 6 were good improvement options in this category.
For lime, DMU 2 and 3 (33.23) had a higher environmental performance than DMU 1 (33.2). This was certainly not a good improvement option since its environmental score was higher than DMU 1 which is the current process. Alternatively, DMU 5 and 6 (33.17 and 33) showed a lower environmental performance which means that it was a good improvement option in this category. Also, DMU 4 showed same environmental performance of 33.2 as the current process. Generally, the DMUs with a lower environmental performance than DMU 1 were good improvement options in this category while DMUs with a higher environmental performance are not good improvement options from the environmental standpoint.

Table 5.3: Normalized and characterized results of one tonne of tamarind, lime and passion fruit

| **Impact category** | **Unit** | **Characterized results** | | | **Normalized results (person equivalents)** | | |
|---|---|---|---|---|---|---|---|
| | | Passion fruit | Tamarind | Lime | Passion fruit | Tamarind | Lime |
| Global warming potential | kgCO2-eq | 1,460 | 942 | 1,330 | 0.0605 | 0.0389 | 0.0552 |
| Acidification potential | Kg SO2-eq | 2.29 | 1.82 | 2.29 | 0.0253 | 0.0201 | 0.0253 |
| Eutrophication potential | kgN-eq | 3.67 | 1.03 | 3.65 | 0.17 | 0.0475 | 0.169 |
| Ecotoxicity | CTUe | 5,990 | 1,560 | 6,470 | 0.54 | 0.141 | 0.583 |
| Human toxicity (cancer and non cancer) | CTUh | 1.22E-03 | 3.2E-04 | 1.3E-03 | 3.55 | 0.927 | 3.82 |

Comparative toxic units ecotoxicity (CTUe); Comparative Toxicity Unit for humans (CTUh).

### 5.3.2 *Life cycle costing results*

The life cycle result revealed the economic profile. Fig. 5.5 shows the percentage contribution of the inputs to the processing cost for the current process. From the Fig.5.5, water, chlorine and nylon have a significantly low contribution to the input cost. From Fig. 5.5, it could be seen that raw material contributed 66.85%, electricity contributed 18.8% while labour contributed 14.16% to input cost. This means that other inputs (water, chlorine and nylon) contributed less than 1% to the input cost. Hence, the major contributors were raw material, electricity and labour with raw material having the highest contribution. In Table 5.2, a detailed inventory cost for the 6 DMUs is presented. In this case, the value-added represents the economic performance (Huppes et al., 2008; Laso et al., 2018). The results are presented in Table 5.5. Generally, DMU 6 reflects a perfect processing condition when compared to other DMUs for the three fruits.

For passion fruit, the current process showed a VA of 624.68 CAD. This was higher than DMU 2 and 3 showing VA results of (602.68 and 586.19 CAD), respectively. This implies that DMU 2 and 3 did not offer a better economic advantage than the current process. Alternatively, DMU 4, 5 and 6 showed a better economic performance than DMU 1 in this category. Hence, they were good improvement options.

For tamarind processing, DMU 3 and 5 had a lower economic performance when compared to DMU 1. Therefore, they were not good improvement options in this category. Other DMUs (DMU 2, 4 and 6) were good improvement options in this category.

For lime processing, only DMU 3 had a lower economic performance than the current process. Other DMUs in this category had a better economic performance than DMU 1. Generally, any DMU will a lower economic performance than DMU 1 is not a good improvement option while a DMU with a higher economic performance than DMU 1 is a good improvement option from the economic assessment standpoint.

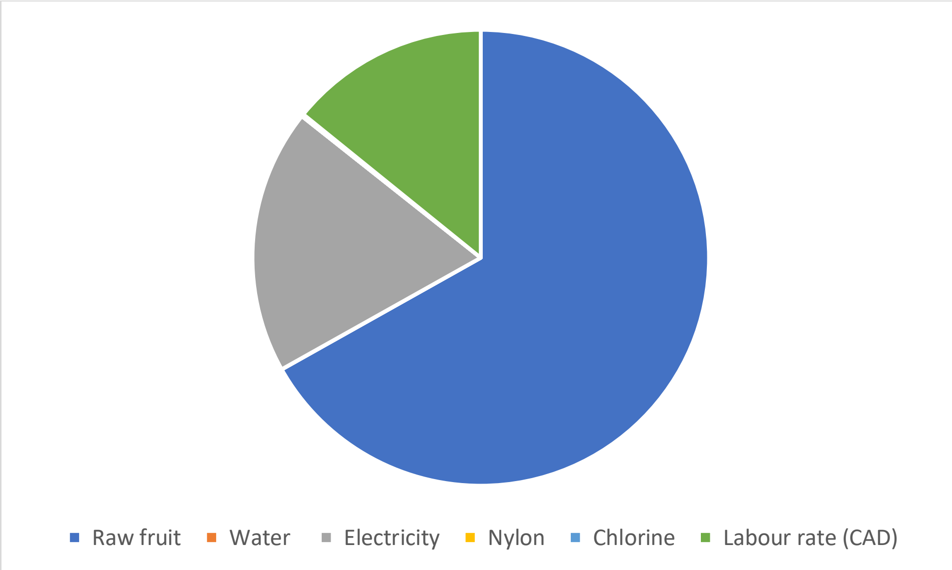


Fig. 5.5: Percentage contribution of inputs to processing cost

### *5.3.3 Data envelopment analysis results*

The DEA is used to calculate the operational efficiency of the three fruits. The results of the operational efficiency are presented in Table 5.4 based on the input-oriented approach. From the results, the efficient frontier is DMU 6. These efficient frontiers are characterized by best practices and high operational efficiency (Cook and Seiford, 2009; H. Zhou et al., 2018).

For passion fruit, DMU 3 had the worst operational efficiency score of 55.4% which was less than the current process (66.6%). DMU 2 also had a bad operational efficiency score of (58.3%). On the other hand, DMU 4 and DMU 5 had good operational efficiency scores of (88.8 and 92.9%), respectively which was generally higher than the current process. This implies that DMU 4 and DMU 5 performed better than the current process and hence "good improvement options". For this category, DMU 2 and DMU 3 were not "good improvement options". Hence it was better to continue with the current process than to adapt DMU 2 or DMU 3 options.

For tamarind, DMU 3 had the worst operational efficiency score of 59.5% among the six DMUs. DMU 2, 4 and 5 had good operational efficiency scores of (74.6, 88.9 and 82.9%), respectively which was better than the current process (66.7%). Hence these three DMUs were good improvement options for tamarind processing.

For lime processing, all the virtual DMUs performed better than DMU 1 which means that DMU 2-6 were good improvement options in this category. This result serves as a basis for decision making in this assessment stage. The inefficiencies in DMUs are the reason for the low operational efficiency scores. Improving these inefficient factors increases the resource efficiency which produces more output from the same input or less input. Identifying the best performing process (DMU) is one of the usefulness of DEA (Iribarren et al., 2010).

Table 5.4: Operational efficiency scores for the 6 DMUs

| DMU | Passion | Tamarind | Lime |
|---|---|---|---|
| 1 | 66.6% | 66.7% | 74.6% |
| 2 | 58.3% | 74.6% | 85.5% |
| 3 | 55.4% | 59.5% | 85.5% |
| 4 | 88.8% | 88.9% | 88.9% |
| 5 | 92.9% | 82.9% | 97% |
| 6 | 100% | 100% | 100% |

### *5.3.4 Evaluation of the economic-environmental performance*

The economic-enviro assessment establishes an index for both sustainability components. It is called a dependent assessment since it depends on the results of the two independent assessments (LCA and LCC). The economic scores represent the value-added for each DMU while the environmental score is the weighted average. Table 5.5 shows the economic and environmental performance of each DMU. Even though weighting is an optional step in LCA (ISO, 2006), in this study, it was done to aggregate the environmental performance to a single score which is plotted on the eco-enviro graph. Since our focus in this case study was a better improvement option for the current process (DMU 1). We tried to measure the improvement in environmental and economic performances of the other DMUs with respect to DMU 1. For environmental performance, a negative score indicates a better performance than the current DMU while a positive score indicates a worse performance. Hence, it proposes that it was better to continue in the current process than to change to a process that had a positive environmental performance score. Also, for economic performance, a positive economic score indicates a better performance while a negative score denotes a worse performance. The eco-environmental performances of the three fruits are presented in Fig. 5.6, 5.7 and 5.8. The graphs for each of the fruits are further discussed below.

The results of the eco-enviro performance for passion fruit is presented in Fig. 5.6. From the results, DMU 5 and 6 had the best performance as there was an increase in economic performance and a decrease in the environmental impact of the processes. DMU 1 is in the (0,0) region in the graph since the improvements of other DMUs are measured with respect to it. DMU 2 and 3 had the same environmental performance as the current process (DMU 1) and hence is in the 0 region of the X-axis but had a decrease in economic performance. Hence it falls in the BD axis of the graph.

The eco-enviro performance for tamarind is shown in Fig. 5.7. DMU 6 had the best eco-environmental performance with a good score of (97.95, -0.54) which showed an increase in economic performance and a decrease in environmental weighted score when compared with the current DMU. It is hence located in axis AC that has the best performance DMUs. DMU 2 was also a good performing unit, it had a decrease in environmental performance and an increase in economic performance, hence located in axis AC. It performed better than the other DMUs apart from DMU 6 with an overall eco-enviro score of (20.76, -0.42). DMU 3 was the worst performing DMU with the same environmental scores with the current DMU and a decrease in economic performance and hence is in the BD axis. DMU 4 is found in the AB axis because of an increase in its economic performance and a zero increase in its environmental scores. DMU 5 is in the CD region with a reduction in both environmental and economic performance.

The eco-enviro performance for lime is presented in Fig. 5.8. Notably, none of the DMUs lies in axis CD which implies that none of the DMUs had a negative (decrease) environmental and economic performance when compared with the current process (DMU 1). DMU 3 had the worst performance for this fruit with a decrease in economic performance and zero decrease in environmental scores, hence it is in the BD axis. DMU 2 and 4 are found in the AB axis. DMU 2 had an increase in both economic and environmental performance; DMU 4 had a zero increase in environmental score and a higher increase in economic score with both DMUs having an overall score of (0.03, 3.323); (0, 4.322), respectively. DMU 5 and 6 are in the AC region which is the best axis of the cartesian graph. Comparing DMU 5 and 6, DMU 6 had better economic performance when compared to DMU 5 even though they are in the same axis. On the other hand, DMU 5 performed better than DMU 6 environmentally. Both DMUs were the best performing DMUs. In this case, if economic performance is more important to the firm, they will choose DMU

6 to DMU 5. On the other hand, if environmental sustainability is more important to the firm, they will prefer DMU 5 to DMU 6. Several studies in the food industry have combined LCC and LCA to provide joint economic and environmental assessments. Recently, Laso et al. (2018) used both methodologies to find an economic and environmental balance in the fish canning industry.

Table 5.5: Environmental (weighted) and economic (value-added - CAD) performance

| **DMU** | **Passion fruit** | | **Tamarind** | | **Lime** | |
|---|---|---|---|---|---|---|
| | Environmental performance | Economic performance | Environmental performance | Economic performance | Environmental performance | Economic performance |
| 1 | 31 | 624.68 | 8.69 | 1,272.53 | 33.2 | 431.75 |
| 2 | 31 | 602.68 | 8.27 | 1,293.29 | 33.23 | 464.98 |
| 3 | 31 | 586.19 | 8.69 | 1,257.99 | 33.23 | 421.19 |
| 4 | 31 | 663.16 | 8.69 | 1,297.99 | 33.2 | 474.97 |
| 5 | 30.86 | 668.71 | 8.22 | 1,268.98 | 33.17 | 475.13 |
| 6 | 30.85 | 740.06 | 8.15 | 1,370.48 | 33 | 553.38 |

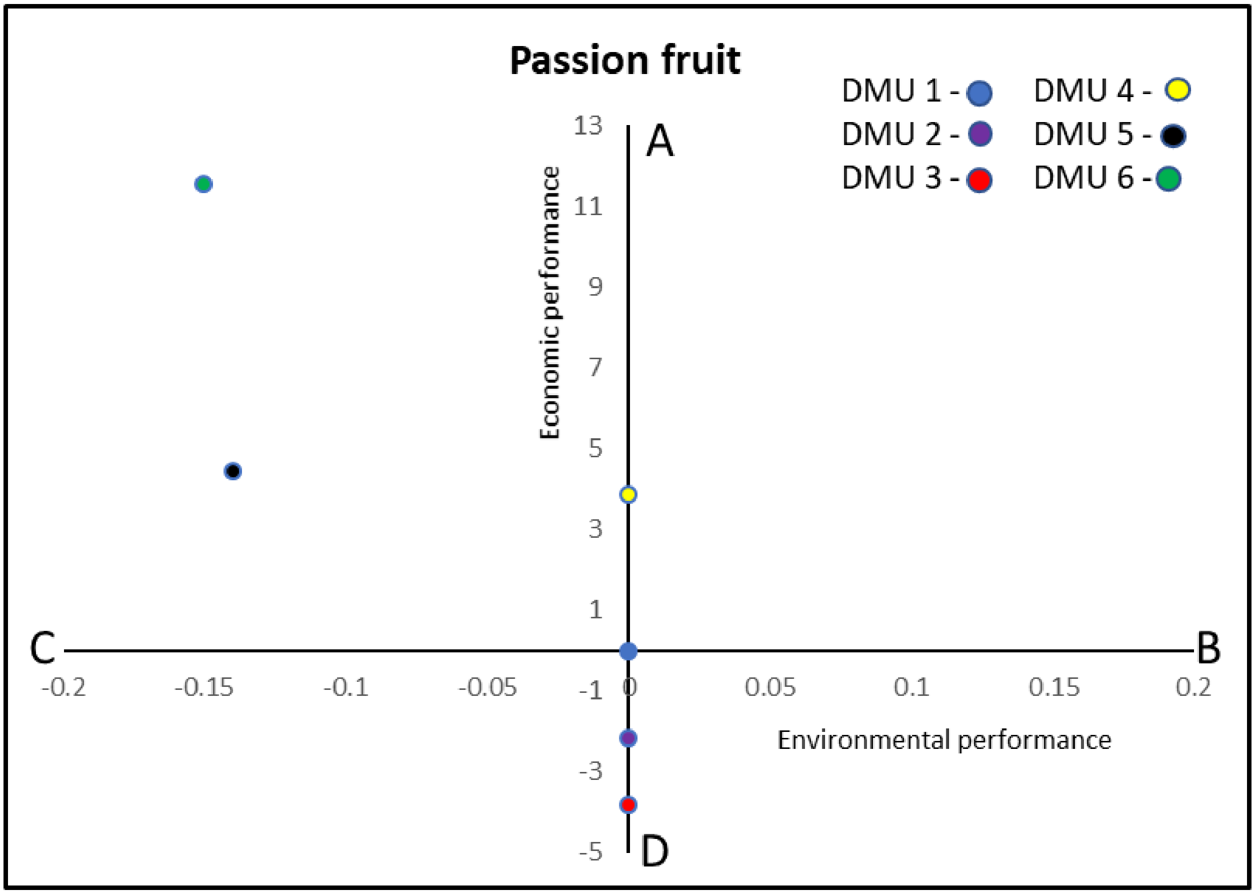


*Fig. 5.6: The eco-enviro graph for passion fruit*

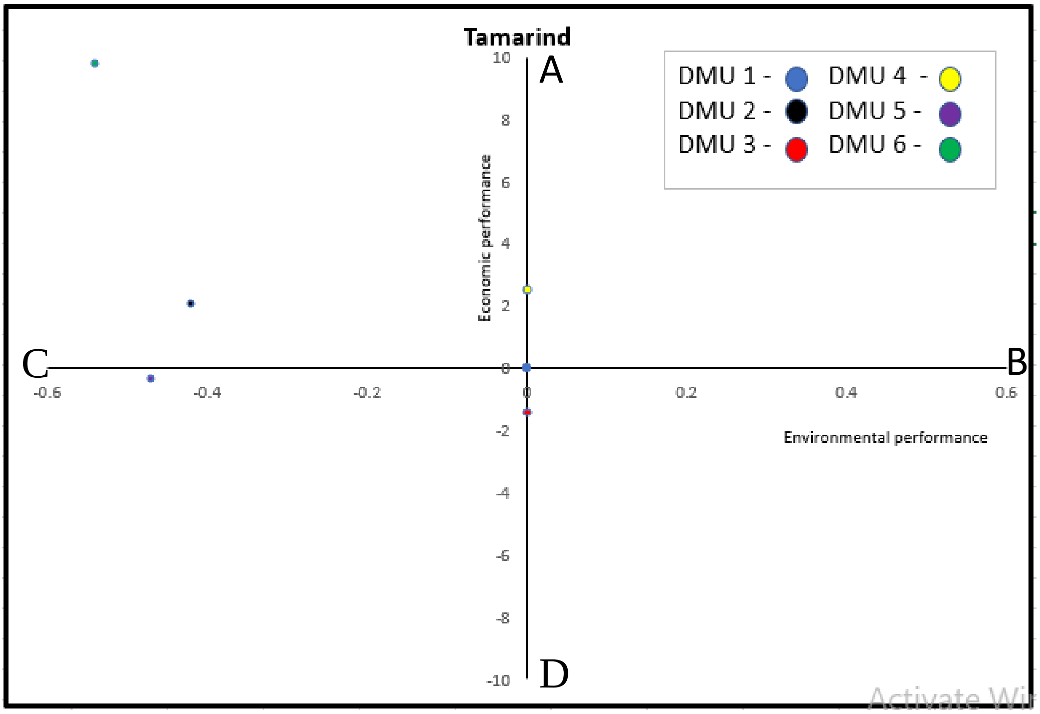


*Fig. 5.7: The eco-enviro graph for tamarind*

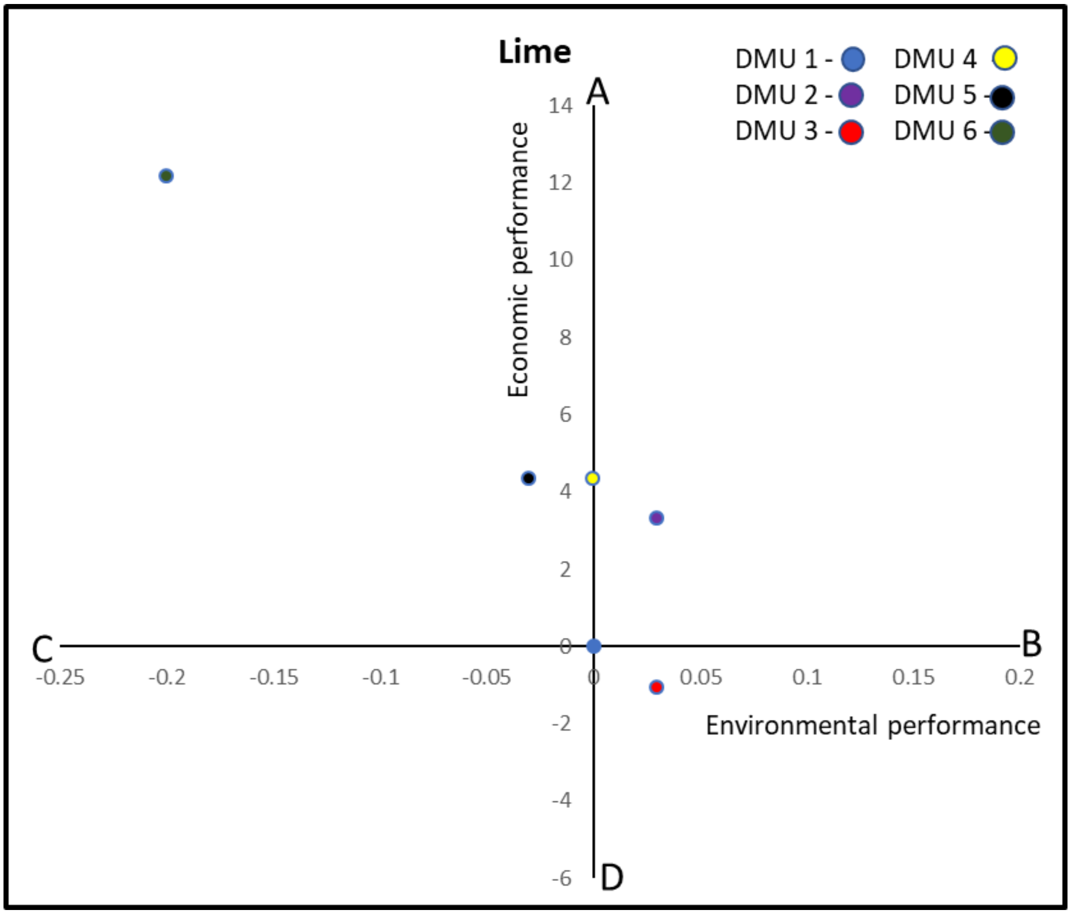


*Fig. 5.8: The eco-enviro graph for lime*

### *5.3.5 Overall eco-efficiency score*

The eco-efficiency scores (EES) for the DMUs are presented in Table 5.6. It is a combination of the eco-enviro performance and the operational efficiency scores as shown in equation 5.6. From the results, DMU 6 gave the best score. This is because it has the best eco-enviro score and operational efficiency. A positive EES means a potential improvement compared to the current DMU which has a default score of zero. A negative EES signifies a worse efficiency when compared to the current DMU. Unlike the operational efficiency that has a scale between 0 and 1 (0-100%), EES does not have any scale. Also, there is no single score for the most efficient frontier but the best DMU is chosen by comparing all the evaluated units. From the results in this case study, in the passion fruit category, DMU 6 had the best EES and hence will be the best improvement option. On the other hand, DMU 3 showed a negative EES which means that it is not a “good improvement option”. Generally, DMU 5 had a higher score when compared to (DMU 2-4) which makes it a better option than DMU 2-4. A higher EES indicates a better improvement option from the eco-efficiency standpoint. For the tamarind category, DMU 6 had the highest EES followed by DMU 2. It therefore indicates that they are the first and second choice improvement options, respectively. Generally, all DMUs in this category have a positive EES. Comparing the EES for lime, DMU 6 and 5 had the highest EES and hence the best improvement options. DMU 2 and 4 also showed good EES with DMU 3 having the least EES.

At this stage, it is very easy for a firm to decide as it offers an all-inclusive basis for decision making. In this model, the eco-efficiency analysis is the final stage and it incorporates resource efficiency, environmental and economic sustainability. Eco-efficiency offers a viable sustainable assessment for small and medium enterprises (Alves and de Medeiros, 2015). The application of the concept offers a pathway to sustainable development through resource utilization (Caiado et al., 2017).

Table 5.6: Eco-efficiency scores (EES) for the three different fruits

| DMU | Passion | Tamarind | Lime |
|---|---|---|---|
| 1 | - | - | - |
| 2 | 0.033 | 3.242 | 3.32475 |
| 3 | -0.408 | 0.2315 | 0.5835 |
| 4 | 3.774 | 2.7985 | 4.1305 |
| 5 | 5.472 | 0.886 | 5.338 |
| 6 | 12.688 | 11.335 | 13.363 |

### *5.4 Implications of the model for food system sustainability*

This study provided a model and framework that assesses sustainability in small-scale food industry. Several studies have provided a sustainability assessment for the food industry. For instance, Ribeiro et al. (2018) in their study developed a triple-layer business model to fight food waste. Lozano et al. (2009) also noted that there is a link between environmental impact and operational efficiency. However, it is essential to assess the sustainability performances of current practices and that of potential alternatives. Also, most of these assessments have been based on large scale firms. Therefore, in this study, an eco-efficient sustainability model for small-scale food industry was proposed, tested and validated using a typical food processing condition. The assessments provide a comprehensive insight of the performances.

Analyzing the different assessments in the model, the LCA gave a weighted average which showed the environmental performance of the different DMUs. The LCC results clearly showed the economic profile of the DMUs in a single score. Both scores were plotted in the eco-enviro graph with the economic scores forming the Y-axis and the environmental scores plotted on the X-axis. The different segment in the eco-enviro graph shows different performances of the DMUs on the environmental and economic basis. There could be variations in whether DMUs in segment AB performs better than DMUs in segment CD. This is because both segments show an improvement in one of the two sustainability components. Hence, the choice of whether the DMUs in segment AB are preferable to the DMUs in segment CD is based on the firm's priority. For instance, segment AB had a good economic performance and a bad environmental performance while segment CD had bad economic performance and good environmental performance. Hence, the choice could differ according to different organizations. But for this study, the degree of performance co-efficient of segment AB is 0.75 which is higher than segment CD (0.5). This means that APRAL placed more importance in economic performance to environmental performance. On the other hand, any firm that values environmental sustainability more than economic sustainability will give segment CD more priority and hence, it will have a 0.75 degree of performance co-efficient while segment AB will have a lower degree of performance co-efficient of 0.5. This variation generally influences the choice of DMU and affects eco-efficiency evaluation. The DEA provided the operational efficiency scores of the different processes. High performing DMUs showed good operational efficiency scores and this formed part of the basis for eco-efficiency evaluation. It is an independent assessment and hence do not depend on the eco-enviro scores. Hence, it can also form an independent basis of decision especially if the firm is only interested in resource management. DMU 6 which was the best performing DMU in the eco-enviro assessment was also the efficient frontier in DEA. Hence, it could be stated that an efficient resource use process could achieve a good eco-enviro performance. An EES is a combination of the operational efficiency, economic and environmental scores. This provides an index for making an inform decision that incorporates the sustainability components.

It could be noted that the model and study do not only establish a joint relationship between the three sustainability components (economic, environment and resource efficiency) but also establishes a direct relationship of how a variation in any of the component affects others. This agrees with reports from the Food and Agriculture Organization of the United Nations (FAO) which explains that there is a strong relationship between resource use efficiency, productivity and sustainability (FAO, 2014).

### *5.5 Conclusions*

This study presents a five-step eco-efficiency-based methodology assessment for a small-scale food industry. The model was tested using a fruit processing plant in Honduras. This model does not only assess the various sustainability components, but it further provides a room for further improvement. One of the originalities of this model is that it incorporates resource use efficiency evaluated by the operational efficiency with the eco-enviro performance.

In this context, the model consists mainly of three independent assessments (LCA, LCC and DEA) and two dependent assessments (EEI and EES). The LCA and LCC in the model measures the environmental and economic performances of the processes (current process and virtual potential improved processes) referred to as decision-making units. The performances were plotted on an eco-enviro graph which is a two-dimensional (X, Y) cartesian system with four segments which represents different performance categories. The location of the DMUs on the graph gives a clear interpretation of their performances. The DEA calculates the operational efficiency which measures the input to output ratio linked to resource efficiency. The analysis identifies an efficient frontier which is the best performing among the compared DMUs. The closer the DEA score to 100% or 1, the closer it gets to being efficient. Organizations need to continuously evaluate the performance of their processes and products to be able to track inefficiencies associated with the processes and products and further improve the operations. This performance evaluation carried out by DEA gives a good reflection of the resource management efficiency of the processes and this has a direct effect on processing cost, economic sustainability and environmental impact. The EEI is an index of the environmental and economic performance while the EES is an index of the EEI and operational efficiency thus establishing the relationship between the three independent assessments and a score that combines both assessments for the organization.

This model acts as a guide to help organizations improve their processes and products. This helps them to incorporate good resource management options and technological developments in a bid to attain sustainable development. It takes into consideration food loss and waste which is fused in the environmental and economic profile of the processes. By testing hypothetical scenarios, firms can be able to compare the performances of these potential improved options with the current process before deciding to change the process and implementing a new process plan. By employing this joint evaluation and components, this eco-efficiency model assesses sustainability in the small-scale food industry which is important due to the dwindling natural resources and the increase in global food demand.

# 6 Summary, conclusions and suggestion for future studies

## *6.1 Summary and conclusions*

This study presented an environmental, economic and operational efficiency assessment for a small-scale food industry using APRAL processing plant, Honduras as a case study. The Life Cycle Assessment (LCA) methodology was used for the environmental assessment of the firm. The Life Cycle Cost (LCC) methodology was used for the economic assessment of the firm. The Data Envelopment Analysis (DEA) provided the operational efficiency scores. The study focused on the application of eco-efficiency concepts to assess sustainability in the food industry. Eco-efficiency in this context was viewed from a resource use perspective, environmental and economic efficiency. By sustainability, we considered the three dimensions of sustainability which are economic, environment and social.

As regards building a sustainable eco-efficient food system, the focus should be in process improvement, increasing economic and environmental efficiency. These three components are embodied in the model as they can assess real and virtual processes referred to as decision making units (DMU). These virtual DMUs are options for potential improvements which are first tested by the model before implementation. The model hence presents the profiles of all the DMUs at all levels (independent and dependent assessments) which acts as a guide for decision making for stakeholders or researchers. The assessments in the model can be applied in all the life cycle stages of a product, it hence offers a good prospect to access any food product or process. The first phase of the study assessed the economic and environmental profile of a typical fruit juice processing plant in order to reveal the economic and environmental profiles of the system under study. In the next stage, a framework and model were developed, tested and validated using the APRAL processing plant. The workflow is a five-step methodology starting from inventory to the eco-efficiency implementation. The first three assessments in the model are independent assessments which could form basis for decisions for the two main sustainability components (environment and economic) and then an additional resource use component. The two other assessments in the model are dependent on the three independent assessments. For instance, the economic-environmental assessment is a combination of the two sustainability components while the eco-efficiency assessment is a combination of all the three independent assessments.

Deductions from this study show that:

1. An approach to a sustainable development in small scale food industry should include increasing operational efficiency, environmental and economic efficiencies of the firm.
2. Environmental and economic efficiency are two independent sustainability components. Having a good environmental performance does not guarantee a good economic performance.
3. Operational efficiency scores reflect the actual resource use efficiency of the small-scale firms.
4. It is possible to measure the efficiency of the current process and that of potential alternatives.
5. It is possible to generate a single eco-efficiency score based on economic, environmental and operational efficiency.
6. For a comprehensive decision, the eco-efficiency assessment which generates a single score for the three independent assessments offers a better basis for decision making.
7. The approach towards driving a sustainable development should be focused on process improvement.

### *6.2 Suggestion for future studies*

1. The model developed in this study is applicable for small-scale food industry; perhaps for a larger scale food industry involving a more complicated process, a bigger model with the same framework could be developed.
2. Apart from resource utilization, there are other factors that could be used to drive sustainability in the food industry. This study only focused on resource use management. Other studies could identify other factors and build a model that incorporates the factor(s).
3. Perhaps, a more sophisticated equation can be added to the one used in calculating the eco-efficiency in this study. An equation that could be able to cover the inputs and outputs in a single expression. The operational efficiency in the model only generates a single score for the input-output efficiencies.
4. A model that incorporates an output-oriented approach or a joint input and out-put oriented approach could form the basis of a future study.

5. A model that can be applied to a multi-functional system with many products can be developed in future studies.

# Appendix A. System boundary and processing stages for lime, tamarind and passion fruit

## *A.1 Fruit juice processing*

**Figure A.1** presents GaBi flow chart for processing one tonne of passion fruit. **Figure A.2** shows the processing and packaging stages for the fruit juice. **Figure A.3** presents the storage conditions for the fruit juice. **Fig. A.4** shows the contributions of inputs to the impact category while **Fig. A.5** shows the percentage contributions of these inputs.

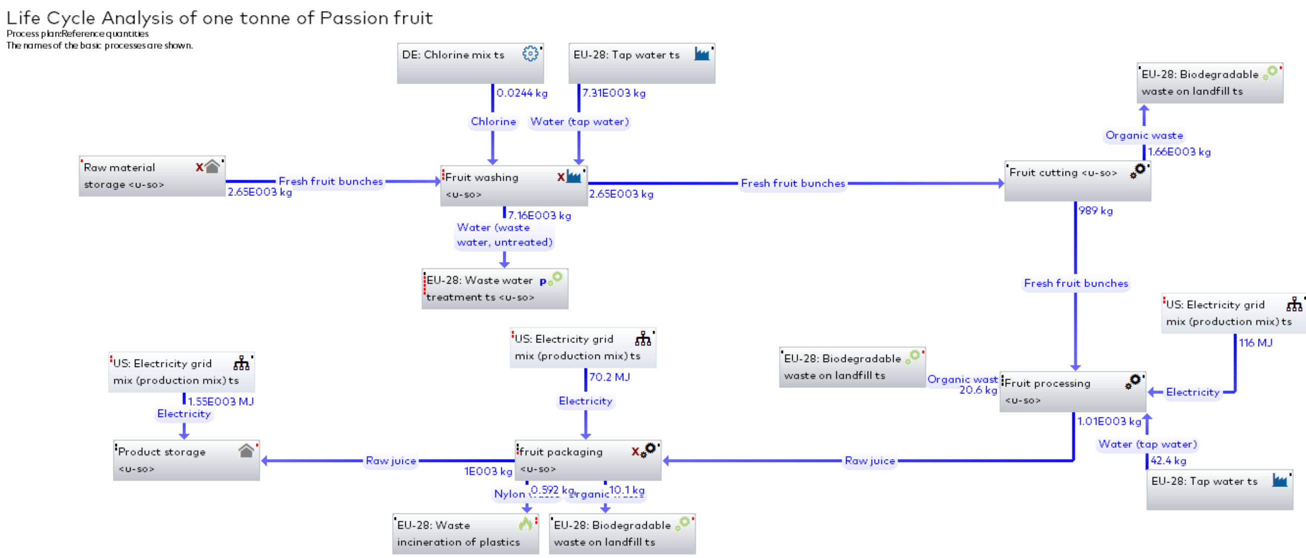


Figure A.1. GaBi flow chart for processing one tonne of passion fruit.

Figure A.2. Processing and packaging stages for the fruit juice

Figure A.3. Storage conditions for the fruit juice

| A | B | C | D | E | F | G | H | I | J | K | L | M | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Electricity | | | Waste water | | | Fruit waste | | | Chlorine | | |
| Impact Categories | Unit | Maracuya | Tamarind | Lime | Maracuya | Tamarind | Lime | Maracuya | Tamarind | Lime | Maracuya | Tamarind | Lime |
| Global warming potential | $kgCO_2$-eq | 275 | 629.5 | 484 | 0 | 0 | 0 | 1180 | 310 | 846 | 0.0246 | 0.0616 | 0.246 |
| Acidification potential | $kgSO_2$-eq | 0.601 | 1.3771 | 1.06 | 0.0646 | 0.0167 | 0.0698 | 1.62 | 0.424 | 1.16 | 5.47E-05 | 1.37E-04 | 5.47E-04 |
| Eutrophication potential | kgN-eq | 0.0359 | 0.0794 | 0.0632 | 2.7 | 0.7 | 2.92 | 0.927 | 0.242 | 0.663 | 7.14E-06 | 1.79E-05 | 7.14E-05 |
| Ecotoxicity (air) | CTUe | 5.52 | 6.09 | 9.71 | 5980 | 1550 | 6460 | 6.06 | 1.59 | 4.33 | 1.84E-04 | 4.60E-04 | 1.84E-03 |
| Human Toxicity (cancer) | CTUh | 4.43E-08 | 4.88E-08 | 7.79E-08 | 1.27E-04 | 3.29E-05 | 1.37E-04 | 3.70E-07 | 9.69E-08 | 2.65E-07 | 1.05E-11 | 2.63E-11 | 1.05E-10 |
| Human Toxicity (non cancer) | CTUh | 2.52E-06 | 3.33E-06 | 4.44E-06 | 1.05E-03 | 2.71E-04 | 1.13E-03 | 3.70E-07 | 9.71E-06 | 2.65E-05 | -9.80E-11 | -2.45E-10 | -9.80E-10 |
| Resources, Fossil fuels | MJ surplus | 228 | 521.8 | 401 | 0 | 0 | 0 | 223 | 58.3 | 159 | 0.0194 | 0.0485 | 0.194 |

**Table. A.1** shows the contributions of inputs to the impact category

| | | Electricity | | | Waste water | | | Fruit waste | | | Chlorine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Impact Categories | Unit | Maracuya | Tamarind | Lime | Maracuya | Tamarind | Lime | Maracuya | Tamarind | Lime | Maracuya | Tamarind | Lime |
| Global warming | $kgCO_2$-eq | 18.84% | 66.83% | 36.39% | 0.00% | 0.00% | 0.00% | 80.82% | 32.91% | 63.61% | 0.00% | 0.01% | 0.02% |
| Acidification potential | $kgSO_2$-eq | 26.24% | 75.66% | 46.29% | 2.82% | 0.92% | 3.05% | 70.74% | 23.30% | 50.66% | 0.00% | 0.01% | 0.02% |
| Eutrophication potential | kgN-eq | 0.98% | 7.71% | 1.73% | 73.57% | 67.96% | 80.00% | 25.26% | 23.50% | 18.16% | 0.00% | 0.00% | 0.00% |
| Ecotoxicity (air) | CTUe | 0.09% | 0.39% | 0.15% | 99.83% | 99.36% | 99.85% | 0.10% | 0.10% | 0.07% | 0.00% | 0.00% | 0.00% |
| Human Toxicity | CTUh | 0.03% | 0.15% | 0.06% | 99.22% | 99.40% | 99.28% | 0.29% | 0.29% | 0.19% | 0.00% | 0.00% | 0.00% |
| Human Toxicity (non cancer) | CTUh | 0.23% | 1.16% | 0.38% | 96.33% | 94.43% | 97.41% | 0.03% | 3.38% | 2.28% | 0.00% | 0.00% | 0.00% |
| Resources, Fossil fuels | MJ surplus | 50.33% | 89.81% | 71.35% | 0.00% | 0.00% | 0.00% | 49.23% | 10.03% | 28.29% | 0.00% | 0.01% | 0.03% |

**Table. A.2** shows the percentage contributions of these inputs.

# Appendix B. Data Envelopment Analysis

## *B.1 Operational Efficiency by Banxia Frontier Analyst*

**Figure B.1.** Operational Efficiency scores for the different DMUs for tamarind. **Figure B.2.** Input/output data for different DMUs for tamarind processing. **Figure B.3.** Analysis page for the 6 DMUs for lime processing. **Figure B.4.** Efficiency table for the 6 DMUs for lime processing. **Figure B.5.** Efficiency table for passion fruit processing

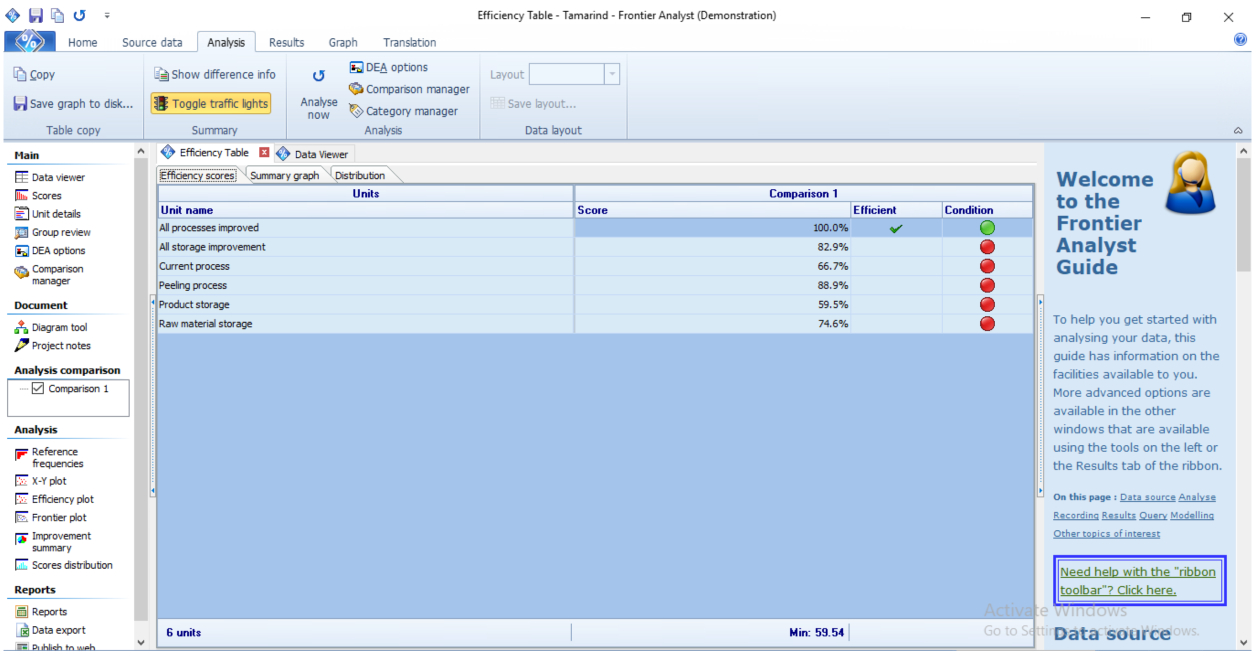


Figure B.1. Operational Efficiency scores for the different DMUs for tamarind

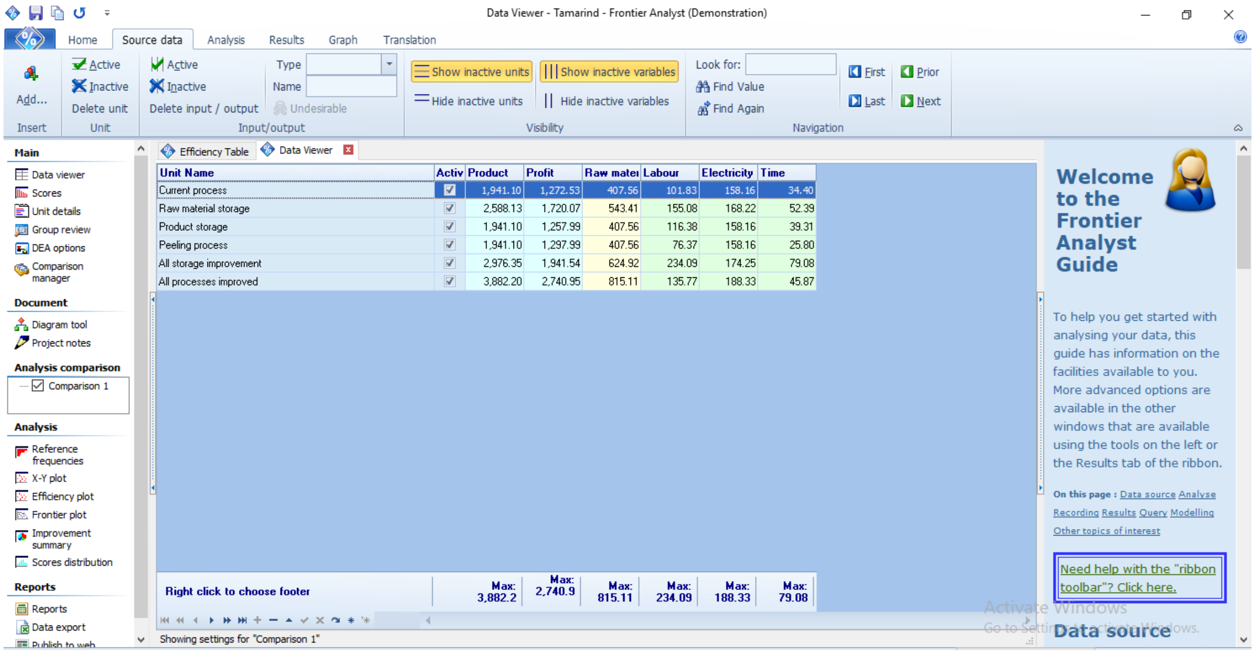

Figure B.2. Input/output data for different DMUs for tamarind processing

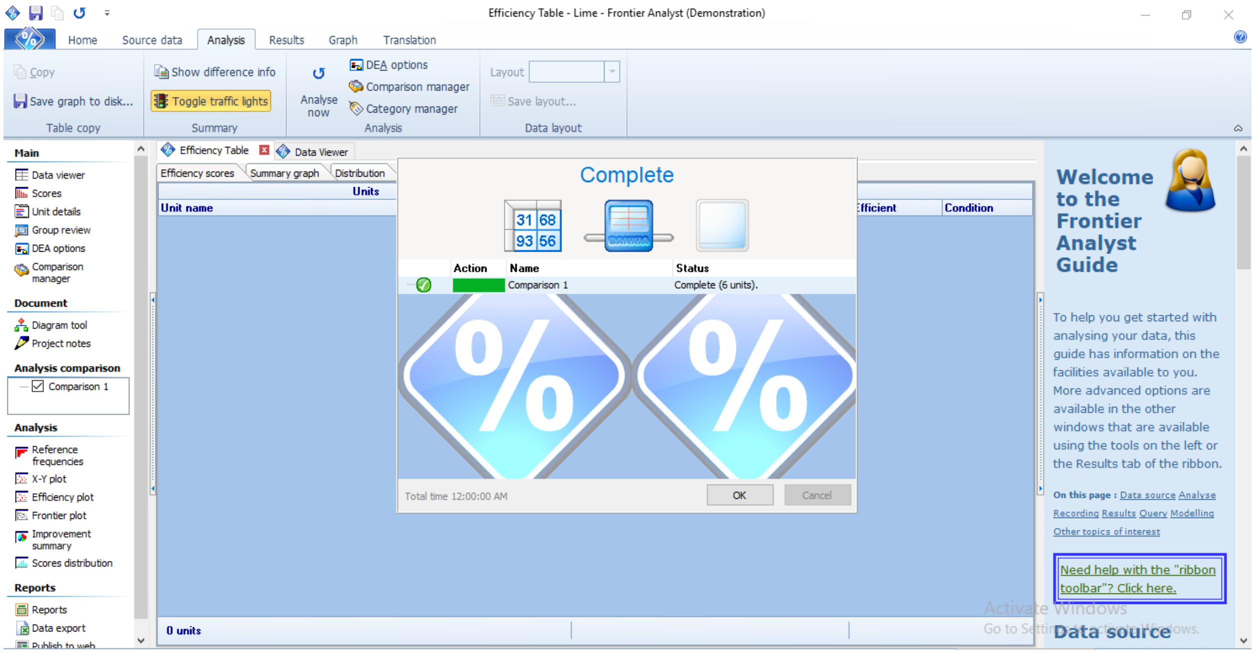

Figure B.3. Analysis page for the 6 DMUs for lime processing

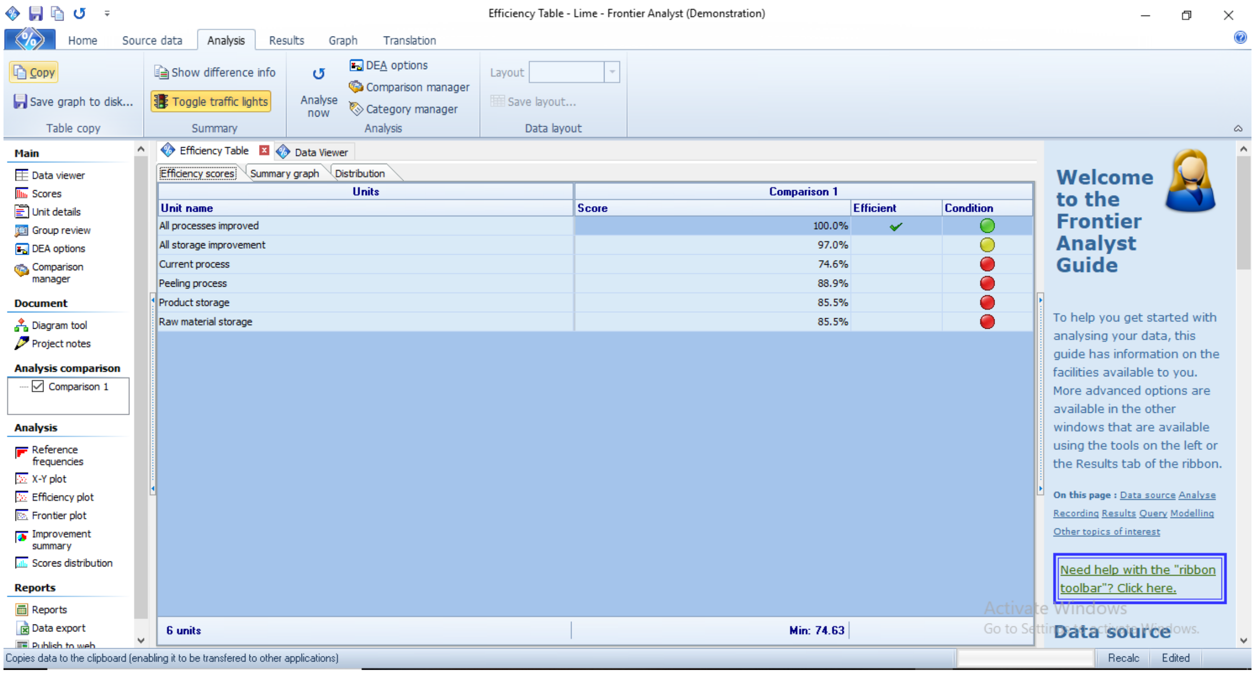


Figure B.4. Efficiency table for the 6 DMUs for lime processing

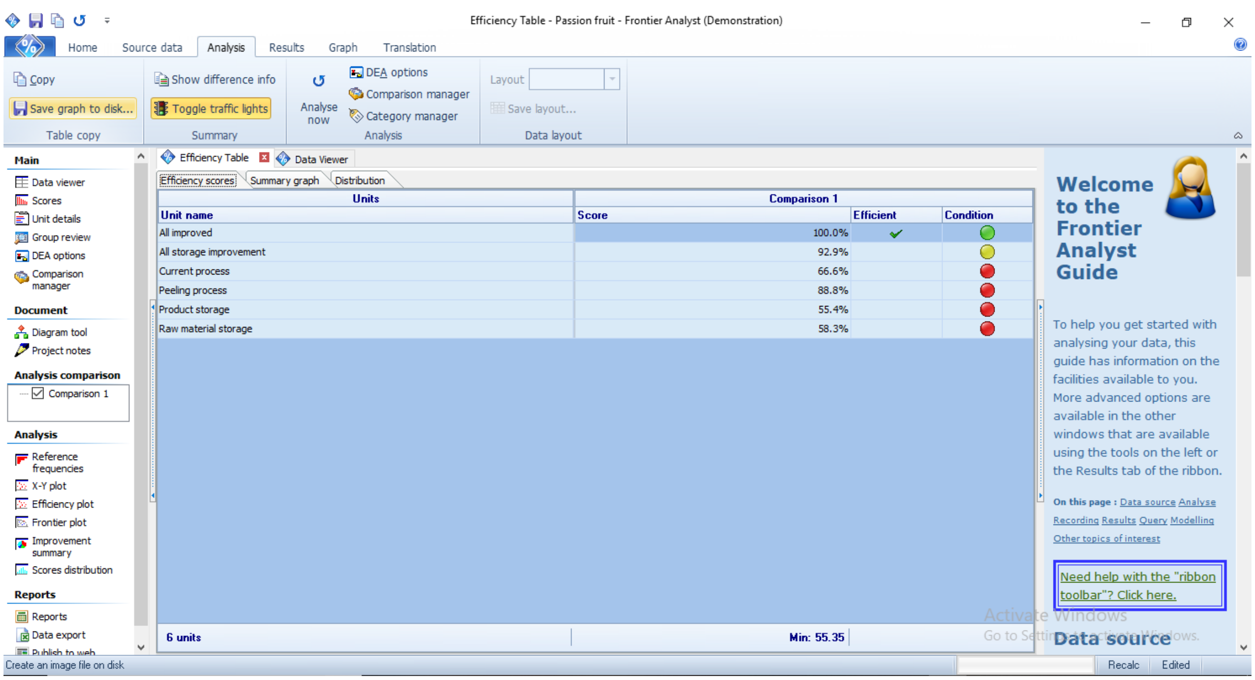


Figure B.5. Efficiency table for passion fruit processing

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