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Achieving Environmental Sustainability of Sugarcane Industry in Egypt: An Application of Life Cycle Assessment

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ACHIEVING ENVIRONMENTAL SUSTAINABILITY OF SUGARCANE INDUSTRY IN EGYPT: AN APPLICATION OF LIFE CYCLE ASSESSMENT

By

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Dissertation submitted in partial fulfillment of the requirements of the degree of
Doctor of Philosophy in Engineering
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PREFACE

"Sustainable development" was the target of my career since I received my Masters of Science in Environmental Engineering from the American University in Cairo in 1997. My work experience revolved around environmental management and finding of engineered solutions to pressing environmental issues in Egypt. Working for the Egyptian Ministry of Environmental Affairs and then shifting to providing consultancy work in the field of environmental degradation and enhancement has broadened my horizon and built a solid practical experience.

The PhD program came as a chance to contribute to the knowledge base of environmental management and preservation in Egypt. Solid waste management was one of the pressing national issues and realizing the fact that waste is an opportunity rather than a nuisance is the start. Hence, I wrote my first conference paper ***"Egypt's Biomass from an Environmental Landmine to an Energy Mine"*** that was presented as part of the Proceeding of the 6th International Perspective on Water Resources and Environment 2013 by the Environment and Water Resource Institute of the American Society of Civil Engineering (EWRI/ASCE) that took place in January 2013, in Izmir-Turkey. This was followed by the paper ***"Impact of Biomass in Egypt on Climate Change"*** which was published in the *Natural Science Journal*, Vol.5, No.6, 678-684, 2013 (http://dx.doi.org/10.4236/ns.2013.56083).

I was keen to introduce the concept of life cycle assessment as a methodology to assessing waste management options in Egypt. The issue of agricultural and agro-industrial residues and their reuse options was one of the vital topics. Episodes such as the "black cloud" resulting from the open burning of agricultural waste especially rice straw, emphasized the research topic. The sugarcane industry was the most appealing area and the Egyptian Sugar and Integrated Industries Company showed great cooperation in providing the data needed to establish life cycle inventories needed for the work. The objective became to use the LCA methods to assess the current situation of the sugarcane industry in Egypt and compare current practices and projects based on environmental performance. My research also contributed, through pilot scale experimentation, to investigating other waste management options including composting and silage making. The aim was to close the natural cycle by reaching a zero waste industry.

A number of papers were formulated as the work developed. The first was ***"Environmental Assessment of Utilization of Sugarcane Waste/By-products in Egypt"*** which was presented in the *EurAsia Waste Management Symposium* on May 2014 in Istanbul Turkey. The other was "***Environmentally Balanced Sugarcane Industrial Complex in Egypt***" which was included in the Proceedings of *Symbiosis 2014 International Conference* which was held in Athens on 19-21 June 2014. A poster was also presented on the same topic "***Environmentally Balanced Sugarcane Industry in Egypt***" during the *Youssef Jamil Summer School* which was held in Cardiff, Wales on 14-16 June 2014. Finally the paper ***"A Proposal to an Environmentally Balanced Sugarcane Industry in Egypt"*** was accepted and published in the *International Journal of Agricultural Policy and Research* Vol.2 (9), pp. 321-328, September 2014 (http://journalissues.org/ijapr-september-2014/).

I was also honored by my professor and supervisor Dr. Salah El Haggar to contribute to his latest book "*Sustainability and Innovation: The Next Global Industrial Revolution*" with Chapter 9 ***"Beyond Sustainability for the production of Fuel, Food & Feed".***

DEDICATION

To my Family,

I would like to dedicate this thesis and all my life achievements so far, to my dear parents, Eng. Adel H. Nakhla and Mrs. Amani B. Megally. Without their dedication, effort, support, care and love, I could have never made it so far. I am eternally indebted to them.

I would also like to express my sincere gratitude to my partner and friend, my husband Dr. Amir Anwar for his encouragement and back up and for his patience. Thank you for always believing in me and for being proud of my achievements.

I am also grateful to my jewels, my daughters, Sandra and Nadine for their understanding of how much this milestone has meant to me and for their continuous support and for cheerful encouragement.

Last, but never least, I am indebted to my soul mate and sister, Eng. Dina Nakhla, for her substantial assistance in proof reading my thesis and providing valuable comments and proposals. Thank you for always being here for me.

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There are several people who I wish to thank for their contribution and support. The completion of this thesis would not be possible without their assistance and support.

I would first like to thank Mr. Yousef Jameel for his generous contribution to the PhD program in Applied Sciences and Engineering and for the Fellowship Award I was granted for the four academic years. His generosity has made it possible to initiate a PhD program at the American University in Cairo which came to the benefit of Egyptian students especially qualified females who were not able to travel outside Egypt to pursue their studies and dreams. I am also grateful to the Office of the Dean for Graduate Studies for approving research and conference grants that covered most of the expenses of my research, conferences and publications.

I would like to express my sincere gratitude to my mentor and supervisor, Professor Salah El Haggar, Chairman of the Mechanical Engineering Department for his advice, guidance and support. Thank you for boosting up my confidence and for having faith in my capabilities. Thanks for always being there when I felt lost or was about to give up. Your doors, mind and heart were always opened for me and all your students, and for that, we are most grateful.

I would also like to thank my co-advisor, Dr. Bahgat Ali for his patience and time, for the expertise and for all the technical support that he provided. I am deeply grateful for the support that he and Dr. Yehya Ibrahim have provided with regards to composting.

Moreover, I am grateful to Dr. Bernhard Steubing, Institute for Environmental Engineering in Zurich, for his tutoring and guidance with regards to life cycle assessment and for the time and effort he put in reviewing the LCA related sections of my thesis.

I would like to acknowledge the former and current Chief Executive Officers of the Egyptian Sugar and Integrated Industries Company, Eng. Hassan Kamel and Mr. Mohamed Abdel Reheem, for approving my request to collaborate with their Company and for allowing me to conduct field visits and interviews in their mills to gather the required data. I am grateful to Eng. Abdel Latif Forgany, Eng. M. Elshazly, Eng. Nagy Naguib for the data they have provided. Special thanks to Eng. Noshy Sadek for his time and support during my field visits to the sugarcane fields and sugar mills in Upper Egypt.

I would also like to thank the Research Institute for a Sustainable Environment (RISE) for allowing me to set up my pilot experiment within their facilities and for the AUC Landscaping staff, Eng. Mahmoud Moharam and Eng. Tawheed Abdel Wahab for providing the manpower, equipment and support required for execution of my experimental work.

ABSTRACT

Sugarcane industry in Egypt goes back to the year 710 AD. Cane plantations are concentrated in the area of Upper Egypt. The total amount of cane cultivated in Upper Egypt is about 16 million tons per year. There are eight sugarcane producing factories in Egypt, most of them located close to the cultivations.

The sugarcane industry in Egypt can be currently defined as an open industrial system that consumes material and energy and creates products and wastes. The two main stages of sugarcane production are the agricultural stage and the industrial stage. The agricultural stage involves cane cultivation which involves the use of fertilizers, water and fuel for irrigation, and cane harvesting which results in the production of two main residues which are cane tops and dry leaves. The cane tops are collected and used by the farmers to feed their livestock. The dry leaves, on the other hand, are openly burnt resulting in pollution of the ambient air.

The cane is transported from the fields to the mills mainly by the sugarcane train. In the mill, the production process involves the consumption of chemicals, water and fuel to produce a number of by-products in addition to the main two products: raw sugar and molasses. The main residues or by-products are filter mud residing from the juice clarification process, bagasse from the cane squeezing and furnace ash in case the bagasse is burnt in the power house to provide steam and electricity for the mill. The filter mud and furnace ash are used in their raw form as soil additive due to their nutritional value. The bagasse, on the other hand, is either burnt in the mill power house to provide steam and electricity to the mill, or is directed to auxiliary factories to produce paper or fiberboard.

The main aspects that have contributed to the research motivation: (1) mismanagement of the considerable amounts of residues generated during sugarcane harvest and its associated negative environmental impacts, (2) lack of tools and data for assessment of waste management alternatives based on environmental criteria rather than economic ones, (3) lack of low cost sustainable waste management options for sugar cane industry to achieve environmental balance.

This research aims at assessing the environmental sustainability of the sugar industry in Egypt to achieve an environmentally balanced industry approaching zero waste. This is done by analyzing the current practices of reuse/recycling of by-products/residues generated from the sugarcane industry from its agricultural and industrial stages, as well as propose alternative environmental friendly practices for reuse of residues, such as composting and silage production.

To achieve this, the research is divided into stages; identification of main current and potential uses of residues in Egypt, data collection, and data analysis using Life Cycle Analysis approach. Primary data and information was collected through field visits, interviews and questionnaires. The data collected from secondary sources included books, journals, conference papers, governmental reports, international organizations' statistics and websites.

Pilot scale experimental composting and silage making was performed on a combination of agricultural and industrial residues of the sugarcane industry including green tops, dry leaves, filter mud, bagasse and furnace ash. Results of the different treatments were analyzed and recommendations on the best combinations were given in terms of the physical, chemical and biological characteristics of the produced compost or organic fertilizer.

Life cycle assessment (LCA) is used to evaluate the environmental performance of the sugarcane industry in Egypt including its agricultural and industrial stages. It is also used to identify the most environmental friendly options for the reuse of the residues generated from the sugarcane industry. Alternatives uses of bagasse, a cane milling residue, in the generation of steam and electricity, or production of paper, fiberboard or compost is investigated. It is also compared to processes that produce the same product but through other raw material. Recommendations and limitations of each option are presented and discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Ci,j	Characterization factor for species i and category j
Ej	Mass flow identified for species i in the inventory assessment
I	Overall life cycle impact assessment factor
Nj	Normalization indicator
Rj	Reference value
Sj	Category stress indicator for category j
Wj	Weighted indicator
Ωj	Weighing factors

Acronyms and Abbreviation

ADF	Acid detergent fiber
ADL	Acid detergent lignin
AP	Acidification potential
BOD_5	Biochemical oxygen demand
Ca	Calcium
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CDM	Clean development mechanism
CEO	Chief executive officer
CH_4	Methane
ClO_2	Chlorine dioxide
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COD	Chemical oxygen demand
CFC-11	Chlorofluorocarbon
1,4-DCB	1,4 dichlorobenzene
DALY	Disability adjusted life years
DFE	Design for the Environment
DM	Dry matter
DOMD	Digestible organic in dry matter
E	Egalitarian
EA	Economic allocation
EEAA	Egyptian Environmental Affairs Agency
EF	Ecological footprint
EP	Eutrophication potential
EIP	Eco-industrial Park
EPFL	Swiss Federal Institute of Technology - Lausanne
EPR	Extended producer responsibility
ESCWA	Economic and Social Commission for Western Asia
ESIIC	Egyptian Sugar and Integrated Industries Company
GWP	Global warming potential
H	Hierarchist
I	Individualist
IEIP	Integrated eco-industrial park

IS	Industrial symbiosis
IPM	Integrated pest management
IPCC	International Panel on Climate Change
K	Potassium
K_2O	Potassium oxide
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MA	Mass allocation
MDF	Medium density fiberboard
Mg	Magnesium
MSEA	Ministry of State for Environmental Affairs
MWRI	Ministry of Water Resources and Irrigation
N	Nitrogen
Na_2CO_3	Sodium carbonate
Na_2S	Sodium sulfide
NaOH	Sodium hydroxide
NDF	Neutral detergent fiber
NEIPS	Networked eco-industrial park system
NMVOC	Non Methane Volatile Organic Carbon Compound
NPK	Nitrogen, phosphorus, potassium
N_2O	Di-nitrogen monoxide or nitrous oxide
OM	Organic matter
P	Phosphorus
PDF	Potentially disappeared fraction
POCP	Photochemical ozone creation potential
POM	Polycyclic organic matter
PM	Particulate matter
PM_{10}	Particulate matter of 10 micrometers or less
$PM_{2.5}$	Particulate matter of 2.5 micrometers or less
P_2O_5	Phosphorus pentaoxide
RISE	Research Institute for a Sustainable Environment
RI	Respiratory inorganics
RO	Respiratory organics
SE	System expansion
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
UNIDO	United Nations Industrial Development Organization
USEPA	United States Environment Protection Agency
U235	Uranium 235
VFA	Volatile fatty acids
VOC	Volatile organic carbons
WRI	Water Research Institute
WBCSD	World Business Council for Sustainable Development

Chapter 1
INTRODUCTION

1.1 Background

Sugar is one of the main substrates of human diet. The five top sugar producing countries in the world are India, Brazil, Thailand, Australia and China. Their production accounts for 40% of the total global sugar production out of the 115 countries producing sugar in the world (Chauhan et al., 2011). Out of these countries, 67 produce sugar from sugarcane, 39 from sugar beet and 9 countries from both cane and beet. Thus, 70% of the sugar is produced from sugarcane and 30% from sugar beet and cassava (Chauhan et al., 2011).

Sugarcane is considered to act as a solar cell, converting solar energy to chemical energy. In 2009-10, it is estimated that 1683 million tons of sugarcane was planted worldwide, which amounts approximately to 22.4% of the total world agricultural production (Chauhan et al., 2011).

Sugar industry in Egypt goes back to the year 710 AD. (Hassan and Nasr, 2008). Sugar production depended mainly on sugar cane until 1981 when sugar beet was introduced to cover the increasing local demand for sugar. Beet was cultivated as it was not possible to expand the sugarcane plantations which were considered high water consumers in light of the National water policy encouraging water conservation (Hamada, 2011). Cane plantations are concentrated in the area of Upper Egypt specifically in Menia, Sohag, Qena, Luxor and Aswan. According to Hamada (2011), the total amount of cane cultivated in Upper Egypt is about 16 million tons per year. Egypt is therefore considered the largest producer of sugarcane among Arab countries followed by Sudan, at 7.5 million tons annually (ESCWA, 2009).

There are eight sugarcane producing factories in Egypt, most of them located in Upper Egypt close to the cultivations. The Governorates hosting the sugar cane mills are:

- El Menia; Abou Korkas mill
- Sohag; Gerga mill

- Qena; Nagaa Hamadi, Deshna and Kous mills
- Luxor; Armant mill
- Aswan; Edfu and Komombo Mills

There are also three sugar refineries located in Lower Egypt.

The sugarcane production season lasts for 5 months in Egypt, starting in December and ending in May. The mills operate 24 hours a day 7 days a week throughout the 5 months. Due to the tight schedule and the high costs of production, high efficiency is a vital issue that needs to be maintained and constantly improved.

1.2 Research Motivation

Three main aspects have contributed to the research motivation: (1) mismanagement of the considerable amounts of residues generated during sugarcane harvest and its associated negative environmental impacts, (2) lack of tools and data for assessment of waste management alternatives based on environmental criteria rather than only the economic one, (3) lack of low cost sustainable waste management options for sugar cane industry to achieve environmental balance.

1.2.1 Sugarcane harvest residues and its negative impacts

The sugarcane industry generates considerable amount of residues during harvesting. Sugarcane is a perennial crop, and is planted as a summer and autumn crop. The crop is harvested from December until April at an average age of 12 months. Cane is cut manually and not detached from the land. The cane tops and dry leaves are peeled off as they contain little sucrose and high starch thus reducing the sugar yield required by the mills. The leaves also have high silica content which causes mill role wear. Cane tops and dry leaves amount to about 20%-25% of the harvested cane weight (MSEA, 2003) estimated as approximately 2.5-3 million tons per the five month of harvest from the cane plantations in Upper Egypt.

Cane green tops are collected by the laborers responsible for harvesting to be used as animal feed. However, it is not totally utilized as the animals consume only a portion of it. The remaining dry portion is mixed with animal manure and left to decompose. Decomposition of the dry cane tops with manure leads to emissions of greenhouse gases, such as methane, and loss of organic content of the cane tops that could have been utilized as fodder or fertilizer.

As for the dry leaves, they are left behind in the field and in cooler Governorates are used to protect the stubbles from winter frost during the months of December and January and early February. However, during March and April it is daily burnt as it is believed by the farmers that the practice of burning the green leaves in the field eliminates weed population and kills all the different life cycle stages of pest insect species (MSEA, 2003). Burning of the cane dry leaves in the fields during the five months of harvest, have the following detrimental environmental impacts:

- Degradation of the air quality in the field area and downwind the fields due to the emission of partial combustion products such as, carbon monoxide (CO) and volatile organic carbons (VOC), which contribute to photochemical ozone creation potential (POCP), as well as acidification and eutrophication effects (Chauhan et al., 2011).
- Negative health impacts on the neighboring communities as a result of air pollution.
- Loss of the organic content of the leaves and nutrients that are burnt.
- Production of fly ash, which damages the soil microbial diversity (Chandel et al., 2012) as shown in Figure 1.1.

Figure 1.1. Ash in the fields after burning of the dry leaves

1.2.2 *Lack of Environmental Assessment Tools of Waste Management Options*

During the sugar production process in the mill, a number of residues are generated with large quantities: bagasse, which is the fibrous material remaining after chopping and milling from juice extraction, molasses as a co-product from sugar production and filter mud resulting from cane juice filtration. According to interviews conducted with the operation managers of a number of sugar mills in Upper Egypt, the percentage of residues generated during the sugar production process are as follows; 30% bagasse, 4% molasses and 3.5% filter mud (cachaza). These percentages amount to an annual production of about 3 million tons of bagasse, 370 thousand tons of molasses and 316 thousand tons of filter mud.

Molasses produced from the sugar mills is a very valuable co-product. Its moisture content is 78-80% with sugar content of 50-55% of the solid matter. Molasses produced from the sugar mills of Upper Egypt is utilized in fermentation processes, aerobic processes to produce bread and fodder yeast and carbon dioxide used in food industry, as well as in the production of alcohol used in other industries, such as vinegar production, perfumes, medical solutions.

The filter cake/mud, which is a dark spongy solid, is continuously collected and sold to contractors to be used as soil amendment or fertilizer, due to its richness in nutrients. Filter mud has been applied on soil to decrease soil degradation from erosion and compaction, as it prevents crusting and cracking, adjusts the pH, improves drainage and encourages growth of bacteria and microorganisms (George et al., 2010). However, due to the high moisture content of the filter cake (about 70%) and its composition, it is hard to handle and transport and may result in the following environmental impacts (George et al., 2010):

- The cake is smelly and attractive to insects and pests and easily ignitable when exposed to sunlight.
- It has a high BOD_5 (55 kg/m^3) which is a potential of water pollution in case it reaches a water body through direct contact or leaching. In addition, the high phosphorous and nitrogen content of the cake can cause water eutrophication.
- Fresh filter cake will undergo decomposition contributing to greenhouse gas emissions when carbon is converted to carbon dioxide and methane.

Bagasse, on the other hand, is used for different purposes in different sugar mills. It is used for steam and power generation in Nagaa Hamadi- Qena sugar mill, in the manufacture of fiberboard in Deshna- Qena mill and in pulp and paper manufacture in Kous- Qena sugar mill as it is composed of about 50% cellulose. Each of these uses has its environmental advantages as well as its drawbacks.

Bagasse has a gross calorific value of 19,250 kJ/kg at 0% moisture and 9,950 kJ/kg at 48% moisture (Nemerow, 1995). The bagasse burnt in the boiler provides the steam needed for electricity generation of the mill and for heating the sugar production processes. Bagasse is considered a renewable, reliable and cheap source of energy and its combustion is carbon dioxide neutral as it is of biogenic origin. It also results in lower combustion emissions as compared to fossil fuels. However, direct burning as a fuel to generate steam and electricity has the following major negative impacts (El Haggar and El Gowini, 2005):

- Contamination of the ambient air quality of the surrounding environment by the fly ash generated from burning bagasse in its loose bulky form. Sugar mills require expensive scrubbers and filters to collect these emissions. The installed pollution control devices are not always working effectively as shown in Figure 1.2.
- Loss of resources as the ash generated in burning is lost to the atmosphere and cannot be obtained due to the bulkiness of bagasse and the lack of control over the burning process. The fly ash is rich in nutrients, which can be processed and used efficiently as a fertilizer.
- Energy inefficiency due to the bulkiness of bagasse causes it to have low energy content per unit volume and leads to a low burning efficiency of 60%. In addition, due to the uncontrolled burning, approximately 30% of the bagasse by weight, does not burn in sugar mills. This bulk is disposed in dumpsites instead of being utilized.
- Bagasse is usually supplemented by another fuel such as fuel oil to enhance the burning efficiency, which aggravates the air polluting emissions due to high sulfur content of the fuel oil.

Figure 1.2. Air pollution caused from bagasse and heavy oil burning

As for utilizing bagasse in fiberboard manufacturing, it avoids impacts associated with growing and harvesting wood trees to manufacture wooden board, i.e. avoids use of virgin wood and decreases energy use since there is less processing and drying required when bagasse is used. However, the following environmental impacts are generally associated with fiberboard manufacturing:

- Dryers release wood dust, carbon monoxide, carbon dioxide, nitrogen oxides, fly ash, volatile organic carbons (resins and fatty acids) and formaldehyde compounds (due to the use of urea formaldehyde).
- It is an energy demanding industry for generation of electricity and steam.
- The pith produced from the depithing process that is burnt in the sugar mill boilers contributes to fine particles emitted from stack boilers and leads to loss of nutrients that could be used as animal fodder.
- Fermentation of bagasse stored in wet form may cause emissions of foul smells to the neighboring environment.

Moreover, manufacture of pulp and paper from non virgin material such as bagasse consumes less water, energy, chlorine and raw material, and generates less greenhouse gases and methane emissions than virgin material or wood (Poopak and Reza, 2012). The environmental impact due to bagasse pulp production is more controlled compared to rice straw pulping, due to the different chemical properties of the effluents (EEAA, 2003). Although rice straw is available at a minimal cost, the economic effectiveness is relatively low due to unavailability of proven technology for chemical recovery of silica content from the resulting black liquor (EEAA, 2003). Furthermore, a typical mill for soda or kraft pulp using bagasse in Egypt generates energy in the form of steam and electricity from recovery boilers (EEAA, 2003).

Nevertheless, a number of significant environmental impacts are associated with pulp and paper manufacture from bagasse due to air emissions from the recovery boiler, the lime kiln and any auxiliary boiler consisting of particulates, sulfur compounds derived from fuels, process chemicals in sulfate pulping and nitrogen oxides from combustion processes. Moreover, foul smelling emissions (reduced sulfur compounds originating from the spent cooking liquor) arise from the fiber line washers and liquor tanks in a sulfate pulping line (EEAA, 2003). Wastewater is also generated in large quantities and if not efficiently treated could cause considerable pollution.

It is therefore essential to compare the environmental positive and negative impacts of the current waste/by-products reuse alternatives to highlight which ones are more viable from an environmental respective.

1.2.3 Lack of low cost sustainable waste management options

Agricultural and agro-industrial residues are rich sources of organic nutrients required to enhance the fertility of the soil and nutritional content of the animal fodder. Lack of natural fodder and fertilizer is one of the pressing issues in Egypt and reuse of residues in their production is considered one of the most sustainable reuse options. However, its implementation requires that the following factors must be taken into consideration:

- Seasonal availability of the waste
- Inconsistency in the composition of waste
- Need for initial investment
- Operation and maintenance cost of equipment
- Transportation and storage costs, in case reuse is not carried out on site.

Usually, low-cost simple options that are relying on natural biodegradation of organic material offer the most sustainable options. This research will propose options for transforming the residues generated during sugar cane harvesting and milling into silage and compost.

The choice of treatment, reuse or recycling method for each by-product or waste depends not only on its economic viability but also on its environmental sustainability. The ideal situation is to transform the sugar cane industry into an environmentally balanced industry with the aim of achieving zero pollution or waste. The sugar industry in Egypt is already on the road of achieving environmental balance as it established major industries such as fiberboard and pulp and paper to utilize its residues. However, sustainable performance of the industry could be achieved by closing the cycle of the sugar cane production process and integrating the residues resulting from the harvesting and sugar production stages in the creation of more environmental products with minimal cost and technology.

1.3 Research Aim and Objectives

The aim of this research is to (1) assess the environmental sustainability of the sugarcane industry in Egypt, (2) develop an assessment methodology for evaluation of current and proposed strategies for reuse/recycle methods of the agricultural and agro-industrial waste/residues of the industry, and (3) achieve an environmentally industry that approaches zero pollution or waste.

To achieve this aim, the research is divided into the following main objectives:

- Identification of the main current and potential uses of the sugar cane by-products and residues in Upper Egypt
- Data collection of current waste management options in selected number of sugar mills in Upper Egypt to develop life cycle inventories based on the practices of the Egyptian sugar industry
- Experimental composting and silage making of a number of combinations of residues (agriculture and industrial) to valorize the waste with the aim of closing the waste cycle to reach zero waste industry

- Analysis of current and proposed waste management options using Life Cycle Assessment approach
- Proposing scenarios for achieving environmentally balanced sugar industry in Egypt with the aim of reaching sustainable management.

1.4 Research Approach and Methodology

A number of research methods were utilized to achieve research objectives. Literature review is one of the most important methods used in this thesis at an early stage of research in order to form the research aim, scope and collect part of the baseline data. The data collected from secondary sources included books, journals, conference papers, governmental reports, international organizations' statistics and websites.

Primary data and information was collected through field visits, interviews and questionnaires. As sugarcane plantations and industries are located in Upper Egypt, the following field visits were carried out in February 2013:

- Cane plantations in Maharza village, Nagaa Hammadi, Qena Governorate
- Nagaa Hammadi Sugarcane Factory, Qena Governorate
- Qena Paper Mill, Kous Sugarcane Factory, Qena Governorate
- Nagaa Hammadi Fiberboard, Deshna Sugarcane Factory, Qena Gvernorate

During the field visits, interviews with a number of stakeholders directly involved in the sugarcane industry took place including land owners and farmers, mills' operators as well as health, safety and environment officers. The whole life cycle of cane from plantation to harvesting, transportation and milling to produce sugar and molasses was reviewed including management of residues and by-products resulting from the different phases. The secondary production processes of fiberboard and paper production from bagasse was also examined and discussed.

Questionnaires were also prepared and applied to get more detailed information about the production inputs and outputs with regards to sugarcane milling, fiberboard and paper making. The questionnaires were distributed to the production unit in each mill through the office of the Chief Executive Officer (CEO) of the Egyptian Sugar and Integrated Industries Company (ESIIC) in Cairo. A number of meetings were held with the CEO of the ESIIC and his associates to introduce them to the research objectives and receive their consent on their cooperation and provision of information on the sugarcane industry in Egypt. Letters from the Department of Mechanical Engineering in the American University in Cairo requesting approval on field visits to the ESIIC mills and on provision of specific information on the mills, showing approval from the ESIIC CEO are included in Appendix A. The questionnaire format and content was based on the requirements of the software selected for carrying out the LCA which is LCA software SimaPro.

The data collected from primary and secondary sources were compiled into a life cycle inventory to be analyzed by the LCA software package SimaPro version 7.3.3. A free Faculty license was granted to the researcher by Pre Consultants. The SimaPro software stands for “System for Integrated Environmental Assessment of Products”, developed by Pre Consultants, the Netherlands.

Finally, a pilot scale experiment was set up to investigate the feasibility of producing silage and compost from the residues generated from the different stages of the sugarcane industry including harvesting and milling. Results and recommendations of the pilot experiment were used as input to the LCA exercise to assess and identify the most environmentally sound residue management options.

Figure 1.3 illustrates a flowchart for the used research methodology.

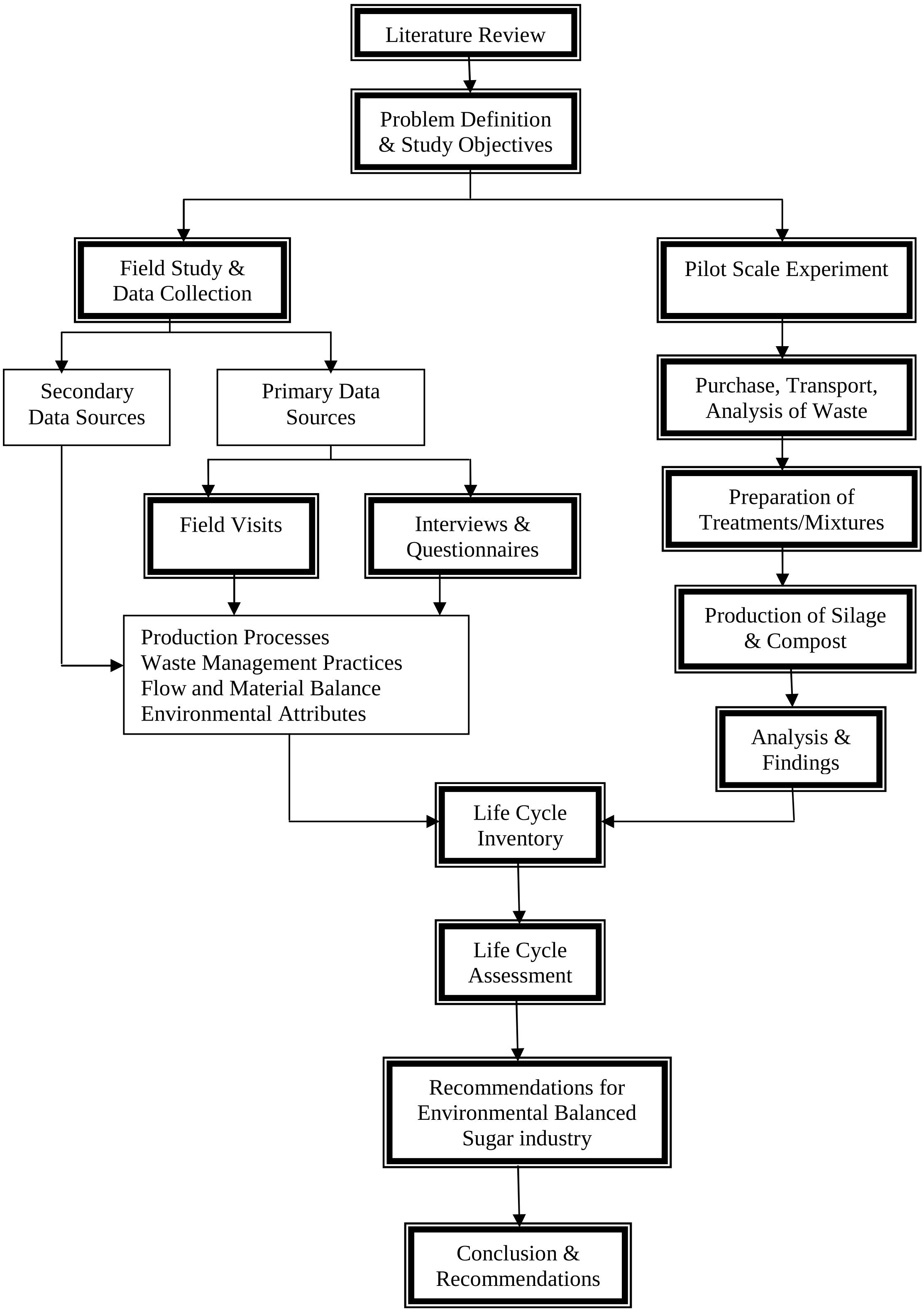


Figure 1.3 Research methodology

1.5 Thesis Outline

Chapter 2 gives a background about sugarcane industry in Egypt for the different stages of production of sugar from sugarcane. It starts with describing the process, inputs and outputs to the sugarcane plantation and harvesting stage and then discusses the sugar cane milling process that is generally followed in the mills located in the region of Upper Egypt, also stressing on its inputs, as well as the residues and by-products generated throughout the process. The Chapter then reviews the different options for reuse of the produced by-products and residues as practiced in Egypt and those proposed in other sugar cane producing countries. It also introduces the concept of sustainable industries including green industries, eco industrial parks and environmentally balanced industrial complex and how it was applied to a number of industrial sectors including sugarcane.

Chapter 3 outlines the theoretical and experimental considerations relevant to the production of silage and to the aerobic digestion of organic matter and production of compost. It then describes the pilot scale experimental set-up, material and methods used for the production of silage and compost from different combination of residues of the sugarcane industry. It also includes the results and discussion of the experimental work of silage and compost production, to evaluate which combination of residues achieved the best quality of silage or compost.

Chapter 4 introduces the concept of Life Cycle Assessment (LCA), its phases and assessment methodologies. It also contains a summary of the LCA studies that were carried out related to the sugarcane industry in sugarcane producing countries.

Chapter 5 defines the goal, scope and boundaries and life cycle inventory for the sugar cane industry in Egypt including sugarcane agricultural and industrial stages as well as current and proposed reuse or waste management options of the residues generated from the industry throughout its life cycle including dry leaves, filter mud, bagasse and furnace ash. Moreover, LCA is carried out for the reuse options of the bagasse which are production of paper, fiberboard, steam and electricity or compost. The Chapter concludes with the results and analyses of outcomes of the life cycle assessment for the different options and proposes scenarios for implementation of the concept of environmentally balanced industrial complex to the sugar cane industry.

Chapter 6 presents the conclusion of the research based on the experimental results and those of the LCA. Moreover, recommendations for further research and work continuation are highlighted.

Chapter 2
LITERATURE REVIEW

2.1 Introduction

This Chapter gives a background of sugarcane industry in Egypt for the different stages of production of sugar from sugarcane starting with cane cultivation, harvesting stage and ending with the milling stage. The Chapter then reviews the different options for reuse of the produced by-products and residues as practiced in Egypt and those proposed in other sugarcane-producing countries. It also introduces the concept of green industries and environmentally balanced industrial complex and how it was related to the sugarcane industry.

2.2 Sugarcane Cultivation

Sugarcane industry is one of the oldest in Egypt. Cane plantations are concentrated in the area of Upper Egypt specifically in Menia, Sohag, Qena, Luxor and Aswan. Sugarcane is produced and harvested in Egypt for four purposes: production of cane sugar in the large scale mills, production of black honey in smaller scale factories, use as seed for subsequent plantings and squeezed in juice shops to make cane juice. The sugarcane distribution, cultivated areas and its uses are shown in Table 2.1. According to this table, the total amount of cane cultivated in Upper Egypt is about 16 million tons per year.

As sugar industry is based on the availability of the canes, sugar factories or mills are situated within the cane growing areas normally within 25 km distance from the farms (Chauhan et al.,2011). There are eight cane sugar producing mills in Egypt as shown in Figure 2.1, most of them are located in Upper Egypt close to the cultivations. All eight mills are owned and managed by the Egyptian Sugar and Integrated Industries Company (ESIIC).

Table 2.1. Sugar cane distribution, cultivated area and its uses (Hamada, 2011)

Governorate	Area (hectare)	Yield (ton/hectare)	Area of Sugar Cane in each use (hectare)			
			Sugar Mills	Black Honey Factories	Seed	Juice
El Menia	15336	122.909	4163	3316	402	7455
Sohag	6722	125.694	3570	0	71	3081
Qena	62894	126.802	59417	2209	1102	166
Luxor	9687	127.348	9511	0	166	10
Aswan	32895	129.079	32032	0	765	98
Total	127534		108693	5525	2506	10810

Sugarcane is a perennial crop, and is planted as a summer and autumn crop in Egypt. The cane is grown from stem cuttings called setts or buds, which when planted are known as a planted cane crop. After the harvest of the mature plant crop, the buds on the underground rootstock germinate and this gives rise to a second crop. This crop is known as a “ratoon” crop and farmers may take up to six ratoon crops. In Egypt it is usually four crops. The crop is harvested during December- May at an average age of 12 months.

Ratooning of sugar cane minimizes costs as the farmer only has to plant every five to seven years depending on the fertility of the land. Ratoon crops give better juice quality and sugar recovery in relation to the plant crop. Typically, one hectare in Upper Egypt produces 125 tons of sugar cane. But the productivity can increase depending on the soil fertility and cane type. The stages of crop growth are germination, tailoring, boom stage (June-September) needing high temperatures, maturity (October-January) where sucrose is being accumulated and finally deterioration and over maturity (mid February- mid April) where sucrose is being tuned to fructose and glucose.

Irrigation is done by one of the following methods depending on the location of the land: flooding or spraying, drip irrigation or using perforated pipes. To increase the sugar content, the cane should not be watered for a few months before harvest.

Cane farmers utilize animal wastes as an organic soil fertilizer to build up organic content of the soil. The major disadvantage of this practice is the possibility of spread of weed-seeds, and transfer of nematodes and some soil born-diseases by microbes and bacteria. Synthetic fertilizers are also added to fulfill the soil's requirements of the NPK components (nitrogen, phosphorus and potassium). These include urea or ammonium nitrate, triple phosphate or mono phosphate and potassium sulfate.

In Egypt, especially in sugarcane areas, integrated pest management (IPM) is practiced to rationalize pesticide use. IPM controls and limits insect populations in a given crop or given area using cultivation practices, mechanical methods, the use of tolerant varieties and biological control. Cultivation practices include rotation, cropping patterns, deep ploughing, control of irrigation and drainage. Mechanical methods mean removal of infected plants, hoeing, weeding and eradication. The sugarcane grown in Upper Egypt is resistant to smut (EEAA, 2005). The chosen cane variety and adoption of a rotation of 5 years sugarcane followed by one year of another also assists in the control of this insect pest that affects sugarcane.

As for the sugarcane borers of the *Chilo* species, it is controlled biologically by the release of the natural parasite *Trichogramma evanesces* at the rate of 20,000 individuals/feddan. This has lowered the infestation rates from 17.3% to 4.1%. Pesticide use on sugarcane is normally extremely low and normally all control of the sugarcane borer is by releasing the parasite *Trichogramma evanesces* during May and June every year (EEAA, 2005).

In case cane is infected by the soft-scale insect *Pulvinaria tenuivalvata*, which reduces yields by more than 50%, cane can be sprayed with Malathion and other biocides in addition to using powdered sulphur.

Figure 2.1. Location of cane sugar factories and refineries in Egypt

2.3 Sugarcane Harvesting

In Egypt, cane is manually cut in the field and the cane tops and dry leaves are manually peeled as they contain little sucrose and high starch, thus reducing the sugar yield required by the mills. The leaves also have high silica content which causes mill role wear (EPA, 1997). The cane is loaded on animals or small tractors to be then loaded on factory railcars or private trucks to be transported to the sugar mills.

The cane train consists of 25 carts. Each cart is loaded with 10-15 tons of cane. The carts are given numbers according to the cane owner. The carts are weighed in the factory and the weight of the cart is subtracted. The amount of waste leaves are calculated and also subtracted. The cane arriving in the mills is weighed and is immediately processed as sugarcane undergoes deterioration of the sucrose content if it is stored for later processing (EPA, 1997).

The residues of sugarcane consist of “green tops” (20% of the total harvest) and dry leaves (5% of the total harvest). It is estimated that these residues amount to 2.5-3 million tons per the five months of harvest.

Figure 2.2 to 2.7 show typical stages of cultivation and harvesting of sugarcane in Egypt.

Figure 2.2. Land preparation

Figure 2.3. Loading cane on animals

Figure 2.4. Manual harvest of cane

Figure 2.5. The cane train transport

Figure 2.6. Cane green tops **Figure 2.7. Cane dry leaves**

2.4 Sugarcane Milling

There are eight sugarcane producing mills located in five of Upper Egypt Governorates: El Menia, Sohag, Qena, Luxor and Aswan. The location, areas, capacities, inputs and outputs of the factories of Upper Egypt are shown in Table 2.2.

Table 2.2. Areas, capacities, inputs and outputs of the sugarcane mills (Hamada, 2011)

Location	Factory	Area (Hectare)	Factory Design Capacity (tons)	Cane Processed in the Mill (tons)	Sugar Produced in the Mill (tons)	Percentage Contribution to Sugar Production
El Menia	Abou Korkas	4163	700,000	408,085	45,868	4.5
Sohag	Gerga	5188	900,000	531,633	60,107	5.9
Qena	Nagaa Hamadi	14280	1,700,000	1,435,137	166,296	16.4
	Deshna	8132	1,000,000	811,497	90,741	9.0
	Kous	16003	1,600,000	1,496,836	165,175	16.3
Luxor	Armant	13288	1,300,000	1,320,602	148,568	14.7
Aswan	Edfu	14054	1,100,000	1,199,351	136,775	13.5
	Komombo	19048	1,800,000	1,821,253	199,955	19.7
Total			10,100,000	9,024,394	1,013,485	100

At the mill, the cane is mechanically unloaded, and weighed. After weighing, the cane is conveyed to the crushers where its hard structure is broken using revolving knives, shredders and crushers. The crushed cane is conveyed from one mill to another and water is added to enhance the extraction of juice in a process called "inhibition" (EPA, 1997). At the last mill, crushed cane or bagasse exits. The extracted juice from the mills is strained to remove large particles and then clarified to remove non-sugar impurities.

Clarification is done using lime and small quantities of phosphoric acid which acts as a flocculating agent. The lime neutralizes the organic acids and temperature of the juice is raised to about 95°C. A heavy precipitate or 'mud' is formed and is separated from the juice by gravity or centrifuge. The mud is filtered and the 'filter cake' is washed with water.

The clarified juice goes to a series of evaporators to concentrate the juice. Steam from boilers is used to heat the first evaporator and steam generated from the first evaporator heats the second and so on. The temperature decreases from evaporator to evaporator and so does the pressure which allows the juice to boil at lower temperatures in the following evaporator. The syrup produced from the evaporator station is 65% solid and 35% water. The syrup is then clarified using lime, phosphoric acid and polymer flocculent, aerated and filtered.

From the clarifier, the syrup goes to the vacuum pans for crystallization. The syrup is evaporated in the pan boiling process until it reaches supersaturation where the crystallization process is initiated by "seeding" the solution. "Massecuite", which is a mixture of liquor and crystals, is formed in the evaporation pan and is discharged to the crystallizer to maximize the sugar removal from the massecuite. Then the massecuite is transferred to high speed centrifugals where "molasses" or mother liquor is centrifuged to the outer shell and the crystals remain in the inner centrifugal basket. The crystals are washed with water and the wash water is centrifuged from the crystals (EPA, 1997). The crystallization process produces three grades of molasses; A, B and C from the different stages of centrifugation. The crystals are cooled, packed and stored.

Molasses produced from the sugar mills is a very valuable co-product. It amounts to 4% of the weight of the cane entering the mill. Its moisture content is 78-80% with sugar content of 50-55% of the solid matter. Molasses produced from the sugar mills of Upper Egypt are utilized in fermentation processes, aerobic processes to produce bread and fodder yeast and carbon dioxide used in food industry, as well as in the production of alcohol used in other industries such as vinegar production, perfumes and medical solutions. In Brazil, ethanol is produced by fermenting sucrose from cane and in Australia, it is extracted from the fermentable sugars contained in molasses (Renouf et al., 2011).

Sugar production is a very energy intensive process requiring considerable amounts of steam and electricity. Sugar mills, therefore, self generate the steam and electricity needed for their industrial process. The fuel used is either fossil fuel (natural gas or fuel oil) or bagasse resulting from cane crushing.

Figure 2.8 shows a schematic diagram of the sugarcane milling process.

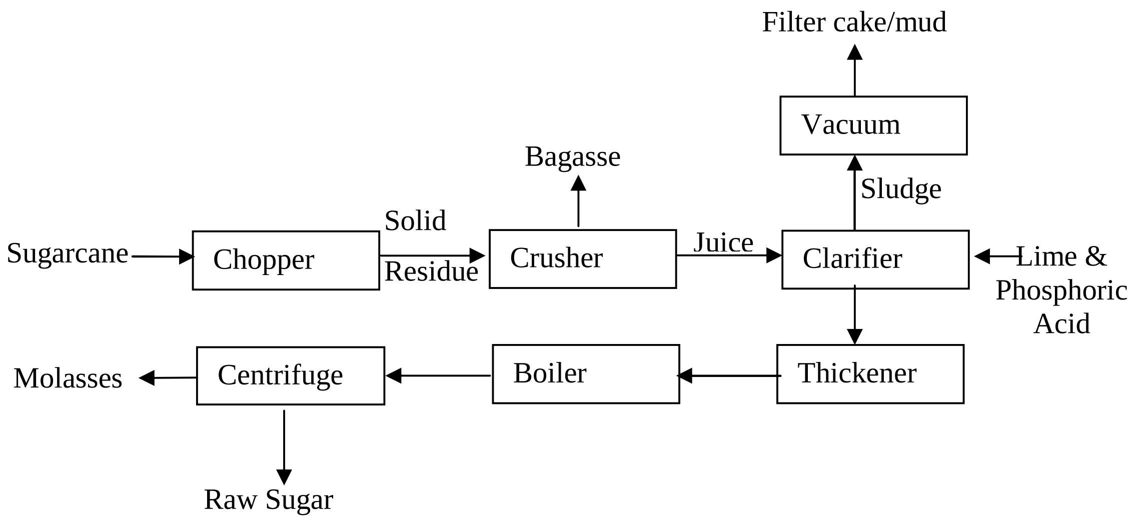


Figure 2.8. Sugar cane production process (Krishnan, 1996)

During the sugar production process in the mill, a number of by-products and residues are generated. These are:

- Bagasse, which is the fibrous material remaining after chopping and milling from juice extraction.
- Filter mud/cake resulting from cane juice filtration.
- Furnace ash, in case the bagasse is burnt in the boiler for steam and electricity generation.

Photos of sugarcane milling residues generated from Nagaa Hamadi Sugarcane mill are presented in figures 2.9 to 2.12.

Figure 2.9. Bagasse chopping

Figure 2.10. Filter mud/cake

Figure 2.11. Molasses

Figure 2.12. Furnace Ash

The percentage of by-products and co-products generated during the sugar production process are as follows (El Haggar, El Gowini, 2005):

- 30% bagasse
- 3.5% filter mud/cake
- 0.4% furnace ash

Based on the above estimates and the amount of cane detailed in Table 2.2., the amounts of residues produced from the sugar cane factories of Upper Egypt are shown in Table 2.3.

Table 2.3. Amount of waste generated during sugarcane manufacturing process

Governorate	Factory	Cane Processed in the Factory (tons)	Amount of Bagasse (tons)	Amount of Molasses (tons)	Amount of Filter mud/cake (tons)	Amount of Furnace Ash[1] (tons)
El Menia	Abou Korkas	408,085	126,506	16,731	14,283	1,632
Sohag	Gerga	531,633	164,806	21,797	18,607	2,127
Qena	Nagaa Hamadi	1,435,137	444,892	58,841	50,230	5,741
	Deshna	811,497	251,564	33,271	28,402	3,246
	Kous	1,496,836	464,019	61,370	52,389	5,987
Luxor	Armant	1,320,602	409,387	54,145	46,221	5,282
Aswan	Edfu	1,199,351	371,799	49,173	41,977	4,797
	Komombo	1,821,253	564,588	74,671	63,744	7,285
Total		9,024,394	2,797,562	370,000	315,854	3,6098

[1] In case the bagasse used as fuel in the sugar mill for generation of steam and electricity

2.5 Current Uses of Sugarcane Residues in Egypt

2.5.1 Agricultural Residues

Cane green tops, which represent 80% of these residues, are collected by the labor responsible for harvesting to be used as animal feed. However, the animals do not consume the whole amount of tops and the remaining portion is left to decompose with the animal manure. This is considered as Egypt is facing severe shortage in the supply of natural animal fodder.

Dry leaves are left behind in the field and used to protect the stubbles from winter frost during the months of December and January and early February in some Governorates. However, the usual practice is that it is burnt daily as it is believed by the farmers that the practice of burning the green leaves in the field eliminates weed population, kills all the different life cycle stages of pest insect species, destroys plant disease and returns nutrients to the soil including calcium and potassium (MSEA, 2003). However, this practice has detrimental environmental impacts on the local air quality of the area due to the emission of partial combustion products such as carbon monoxide (CO) and volatile organic carbons (VOC), impacts health of neighboring communities and leads to the loss of valuable biomass.

2.5.2 Bagasse

Bagasse was historically utilized as a primary source of fuel in sugar mills to generate steam and electricity required by the sugar mills due to its high calorific value. In other sugar mills and due to its high cellulose and fiber content (as shown in table 2.4), bagasse is used as raw material for the manufacture of other products such as fiberboard and pulp and paper.

Table 2.4. Composition of bagasse (Dasgupta 1983)

Component	Composition (%)
Cellulose	46
Hemicelluloses	24.5
Lignin	19.9
Fats and Wax	3.5
Carbon	48.7
Hydrogen	4.9
Nitrogen	1.3
Phosphorous	1.1
Silica	-
Ash	2.4
Fiber	40.8

a. Steam and Electricity Generation

Bagasse is used for steam and electricity generation in sugar mills worldwide as it is a free, secure and reliable fuel generated originally as a waste product. Its use within the sugar mill eliminates also the cost of fuel transmission and distribution. It also produces lower greenhouse emissions and other combustion gases associated with fossil fuels (WADE, 2004). The Clean Development Mechanism (CDM) of the Kyoto Protocol encourages the use of bagasse cogeneration by giving a monetary value to CO_2 emission reduction (WADE, 2004).

Bagasse is used in its loose bulky form as a boiler fuel as it has a net calorific value of 7500 kJ/kg at 50% moisture content, as compared to 42,000 kJ/kg fuel oil and 50,000 kJ/kg of natural gas (Patauru, 1982). Reduction of the moisture content of bagasse improves its calorific value and reduces atmospheric pollution by particulates. The calorific value of bagasse is raised to 12,500 kJ/kg when the moisture content is reduced to 25% (Cheesman, 2005).

The high-pressure steam generated by the bagasse-burning boiler is used to drive the turbine generator and the low-pressure (back pressure) steam is utilized by the sugar manufacturing process. Bagasse as fuel is complemented with other fossil fuels such as fuel oil or natural gas to fulfill the power requirements in case of low bagasse intake as shown in Figure 2.13.

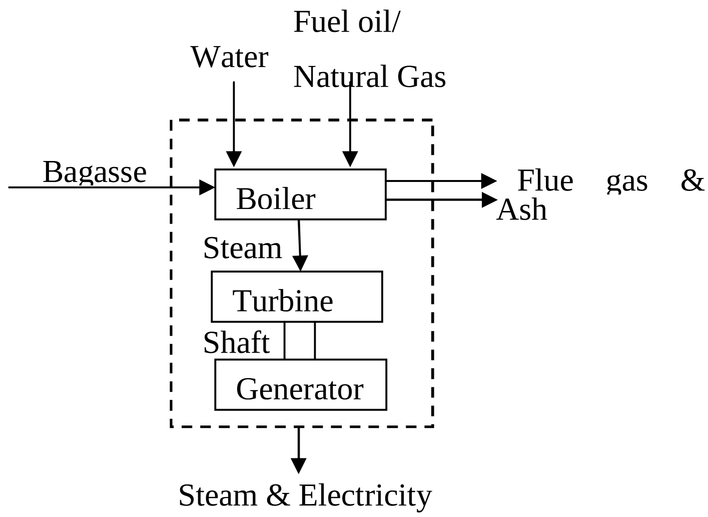


Figure 2.13. Use of bagasse in power generation (Krishnan, 1996)

Use of bagasse as a fuel source has the advantage over fossil fuels in that it is considered as a renewable source of energy and its combustion is carbon dioxide neutral and results in lower sulfur dioxide emissions. However, it causes air quality pollution with fly ash as it is burned in its loose bulky form and requires expensive scrubbers and filters to collect the fly ash. Also the bulkiness of the bagasse decreases its burning efficiency and can result in more than 30% of the bagasse is not burnt and needs to be disposed.

b. Fiberboard Production

The process of making fiberboard starts with depithing the bagasse, where the cellulose is separated from the pith along with the broken fiber. The pith is removed since it is a sponge-like material that absorbs water and will lower the quality of the fiber. Depithing is done in a centrifugal vertical machine with hammers and perforated sides (6-7 mm). The pith exits from the side perforations amounting to 25-30% of the bagasse weight. The pith is transferred back to the sugar factory boiler as it has a calorific value of 4,000 kcal/kg and a moisture content of about 53%.

The depithed bagasse, mainly cellulose, still contains 11-12% pith that will be further reduced at later stages. Bagasse is stored to assure continuous feeding to the plant all over the year as crushing sugar cane is seasonal. The depithed bagasse can be stored dry or wet. Dry storage requires large space to allow for ventilation of the stacked bagasse and is a fire hazard. Therefore, most of the factories storing bagasse for board or pulp production use wet storage. The depithed bagasse is mixed with water and pumped out with a solid content of 3-4%. This is done to get rid of any sugar in the bagasse. The bagasse slurry is then spread on concrete flooring that is sloped to a drain that collects water leaching from the slurry. The bagasse will eventually reach 70-80% moisture content. This method saves storage space 5 times as much as dry storage. To retard the action of fungus and bacteria, the bagasse should be kept at low temperature and so is constantly sprayed with water from the Nile (pH 7-8). The amount of water needed for 80 ton of bagasse/hr is 1,000-1,300 m^3/hr. The bagasse temperature is monitored using large thermometers.

Before using the bagasse, it is washed to remove any dust and stones. Bagasse is soaked in water and agitated (6 mixers) to remove another percentage of the pith and any broken fiber. The heavy particles are separated and the water is filtrated and recycled. The bagasse slurry is placed on a belt conveyor that drains the water to lower the moisture content from 85% to 70-75 %, as the moisture content affects the product.

The bagasse is then passed to a dewatering mill to further reduce the moisture content to 52-55%. The fibers are separated from the bagasse (defiberation) through cooking it with steam in a digester at 5-6 kbar pressure and 160-180°C. The bagasse is retained in an auger to raise its bulk density. The raw material is refined to obtain the basic fiber. This is a critical process where the bagasse undergoes centrifugal action between a stator and rotor rollers and more steam is applied and paraffin wax is added. Paraffin wax reduces the absorption of the fibers (tested using swell test). The moisture content is still 55-60%.

This is followed by the gluing process where adhesives are added to the fibers including urea formaldehyde (UF) in the glue station. One m^3 of board requires 90-100 kg of solid UF (60% solid content).

The glued fibers are dried to reach the suitable moisture content of fiber for manufacturing. The glued fibers are then passed in the blow line, which is a 100-120 m long tube where it is dried with a 130,000 m^3/hr fan and 300,000 m^3/hr flue gases. The fibers are dried to 7-8% moisture content. The fibers are then fed in the form of mats with regular density and suitable thickness for each board thickness. It is then pre-pressed under vacuum for cold forming to get rid of air gaps inside the mat and decrease the size of the mat. Hot pressing follows where the mat is pressed under high temperature to transfer the adhesive from the liquid to the solid state forming the required boards. The boards are then cooled to increase the bond between the adhesive and the fiber. The boards are then finished by trimming to the required dimension, sanding and smoothening its surface and finally packaging. The process is shown in Figure 2.14.

As mentioned in Chapter 1, utilizing bagasse in fiberboard manufacturing have a positive effect on deforestation as it avoids the use of virgin wood. This process also consumes less energy than that required in case of virgin wood. However, fiberboard manufacturing releases a number of air pollutants such as particulate matter, fly ash, volatile organic carbons and formaldehyde compounds. It is also energy demanding for generation of steam and electricity and results in pith waste, from bagasse depithing, which is directed back to the sugar mill to be burnt in its power house contributing to more air emissions.

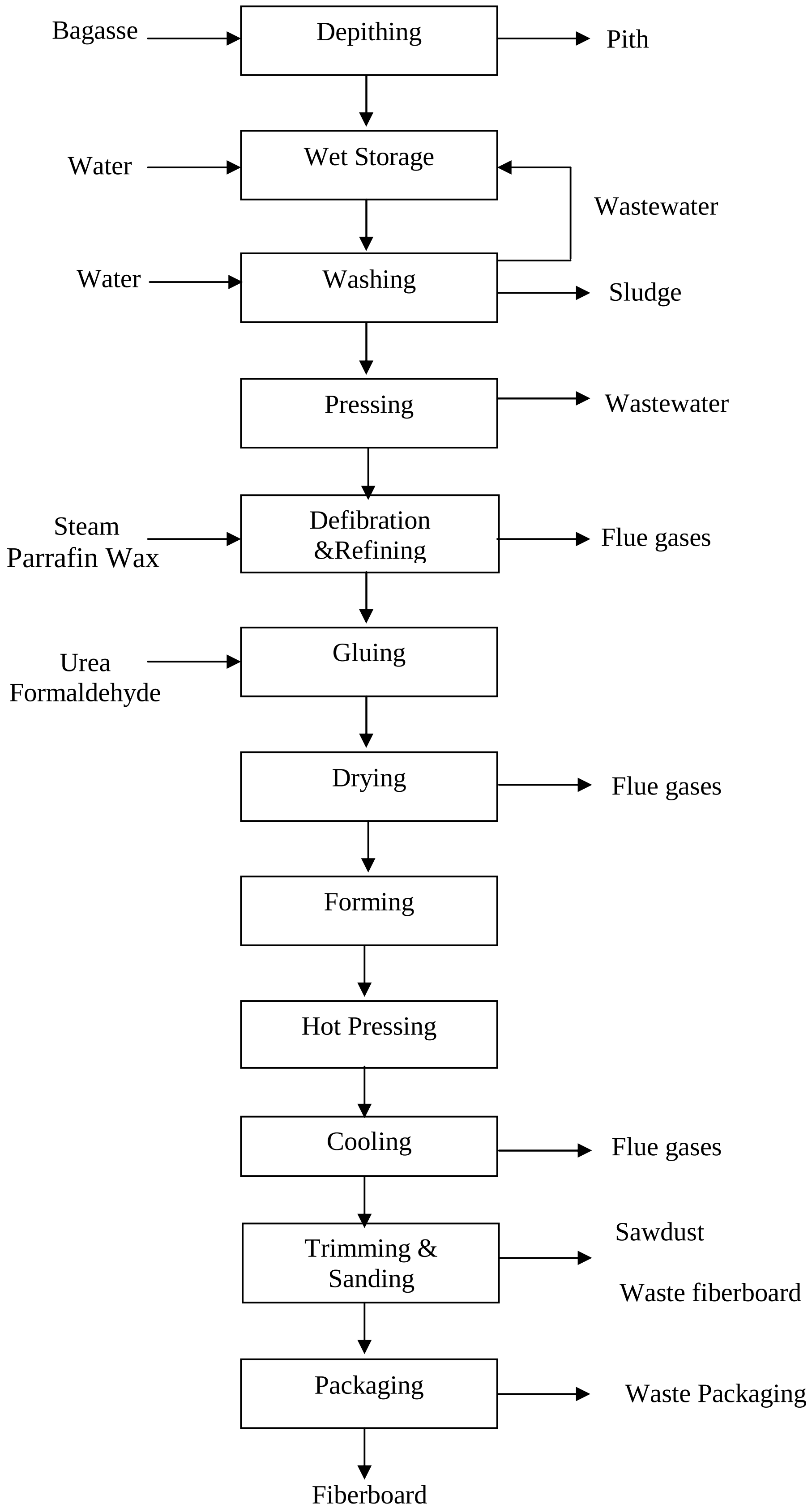


Figure 2.14. Use of bagasse in fiberboard production

c. Pulp and Paper Production

Production of bagasse paper in Egypt started in the year 2000 producing 144,000 ton/year of paper and newsprint, with bagasse representing 70-85% of its raw material (ESCWA, 2009). Paper production from bagasse undergoes three major processes: preparation of the bagasse, pulping and paper making. Qena Paper mill uses the technology of "soda" pulping.

Bagasse coming out of the sugarcane mill is mainly composed of 65-68% fibers, 25-30% pith, 2% sugar and 1-2% minerals. The process also begins with the depithing operation to separate the cellulose from the pith along with the broken fiber. The pith, amounting to about 125,000 ton/year, is transferred back to the sugar factory boiler to be combusted for power as it has a calorific value of 4000 kcal/kg. The depithed bagasse is then stored as a wet bulk on a concrete flooring. To retard the action of fungus and bacteria, the bagasse should be kept at low temperature and so is constantly sprayed with water from the Nile (pH 7-8). The amount of water needed for 80 ton of bagasse/hr is 1000-1300 m^3/hr. The bagasse temperature is monitored using large thermometers. The bagasse eventually reaches 70-80% moisture content (EEAA, 2003).

The wet bagasse is then conveyed to the pulp mill to undergo cooking, pulp washing, pulp screening, cleaning, thickening and bleaching. Washing and lignin separation is done by steam and sodium hydroxide. Black liquor containing sodium lignate is produced. The weak black liquor (15%) is concentrated by evaporation to "strong black liquor" (60-80%) in multiple-effect evaporators. The strong black liquor from the evaporators is burned in a recovery boiler for energy and the process chemicals are removed from the mixture in molten form. Molten inorganic process chemicals (smelt) is recausticized to remove impurities left over from the furnace and to convert sodium carbonate (Na_2CO_3) into active sodium hydroxide (NaOH) and sodium sulfide (Na_2S). This is done by mixing of smelt with "weak" liquor to form green liquor, named for its characteristic color. Contaminant solids are removed from the green liquor which is mixed with lime (CaO). After the lime mixing step, the mixture, now called white liquor, due to its new coloring, is processed to remove a layer of lime mud ($CaCO_3$) that has precipitated. The primary chemicals recovered are caustic soda (NaOH) and sodium sulfide (Na_2S). The remaining white liquor is then used in the pulp cooking process. The lime mud is treated to regenerate lime in the calcining process. In the calcining process, the lime mud removed from the white liquor is burned to regenerate lime for use in the lime mixing step (EEAA, 2003). The resulting lime mud powder is considered solid waste and is disposed in a designated landfill.

The produced cellulose is bleached with chlorine dioxide (ClO_2) to produce white pulp. The white pulp is mixed with long fiber raw pulp. The processed pulp is converted into a paper product via a paper production machine. The pulp slurry is placed on a moving wire belt. Water is removed by gravity, vacuum chambers, and vacuum rolls. This wastewater is recycled to the slurry deposition step of the process due to its high fiber content. The continuous sheet is then pressed between a series of rollers to remove more water and compress the fibers into paper (EEAA, 2003). The process, inputs and outputs resulting from the pulp and paper production is shown in Figure 2.15.

Pulp and paper mill energy generation is provided in part from the burning of liquor waste solids in the recovery boiler and from power house run on fossil fuel. Power boilers at pulp and paper mills are sources of particulate emissions, sulfur dioxide (SO_2), and nitrogen oxides (NOx).

Pulp and paper industry is a large consumer of water although the amount used for bagasse pulp is much less than that of wood pulp (Poopak and Reza, 2012). Wastewater generated from the pulp and paper mill is also polluting, if not properly treated, as it has high BOD, COD and suspended solids content.

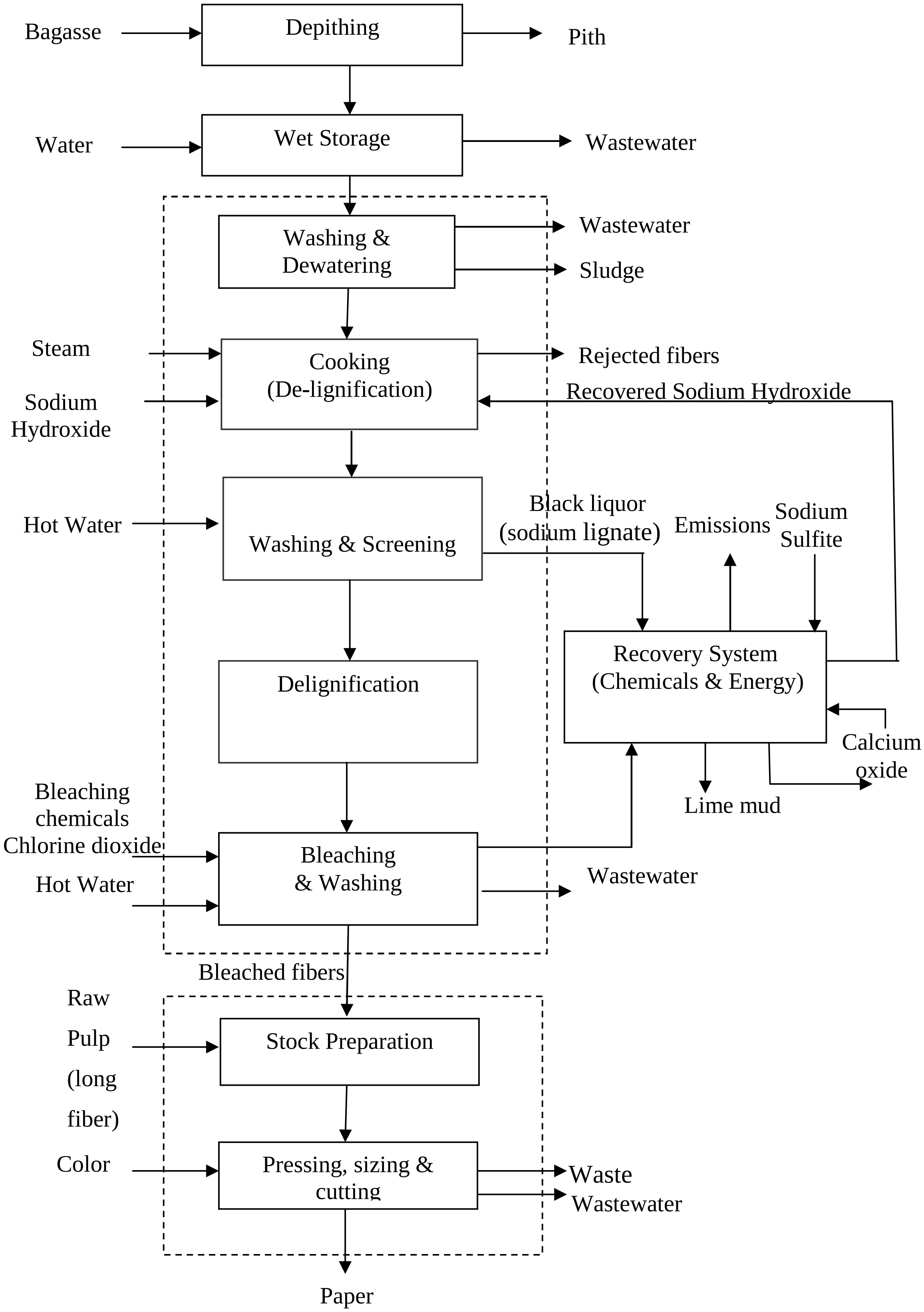


Figure 2.15. Use of bagasse in pulp and paper production

2.5.3 Filter cake/mud

The filter cake, which is a dark spongy solid, is continuously collected and sold to contractors to be used as soil amendment or fertilizer due to its richness in nutrients as shown in table 2.5. Filter cake has been applied on soil to decrease soil degradation from erosion and compaction as it prevents crusting and cracking, adjusts the pH, improves drainage and encourages growth of bacteria and microorganisms (George et al. 2010).

Table 2.5. Composition of filter cake (Dasgupta 1983)

Component	**Constituent (%)**
Cellulose	8.9
Hemicelluloses	2.4
Lignin	1.2
Fats and Wax	9.5
Carbon	32.5
Hydrogen	2.2
Nitrogen	2.2
Phosphorous	2.4
Silica	7.0
Ash	14.5

However, filter cake has high moisture content (70%) and its composition makes it hard to handle and transport. It is also smelly and attractive to insects and pests and easily ignitable when exposed to sunlight. It has a high BOD_5 (55 kg/m^3) which may cause water pollution in case it reaches a water body through direct contact or leaching. The high phosphorous and nitrogen content of the cake can cause water eutrophication. Direct application of the filter cake on land may contribute to greenhouse gas emissions when carbon is converted to carbon dioxide and methane.

2.5.4 Furnace ash

The furnace ash is also collected and sold to contractors to be used as a soil conditioner due to their richness in nutrients as presented in table 2.6.

Table 2.6. Composition of furnace ash (Dasgupta, 1983)

Component	Composition (%)
Organic Matter	17.13
Total Potassium	12.5
Total Phosphorus	1.24
Iron	0.181
Manganese	0.006
Copper	0.0121
Zinc	0.009
Calcium	0.4133
Magnesium	0.0127

2.6 Other Proposed Reuse Options for Sugarcane Residues

There are also a number of uses proposed worldwide for the reuse of the sugarcane industry residues. Some of those options for reuse are outlined below.

2.6.1 Agricultural Residues

Sugarcane agricultural residues can be used to generate steam and electricity in sugar mills. However, it is dispersed in the fields and thus an effective collection mechanism is required if it is to be employed in the sugar factory for cogeneration. Instead, its reuse options in the field could be more feasible. It could be converted into charcoal powder and briquettes.

Another option is the mulching of the dry leaves to improve soil properties, water use efficiency, nutrient uptake and assist in weed control (Balakrishnan and Batra, 2011).

Cane tops can be ensilaged to produce animal feed or can be combined with other sugar cane residues, such as filter mud and molasses, also to produce livestock fodder (Cheeseman, 2005).

2.6.2 Bagasse

a. Briquetting for Combustion

As mentioned in 2.4.1, direct combustion of bagasse is inefficient due the low energy value per unit volume and because it is not easy maintaining a steady fire and controlling the combustion process. It was therefore recommended by Nemerow (2007) to densify the bagasse into solid fuel pellets, or briquettes. Briquetting of the bagasse before combustion has the following advantages (Nemerow, 2007):

- Increasing the efficiency of combustion from 60% to 80%, due to lowering the moisture content and increasing the density of the fuel.
- Compacting the bagasse in the form of briquettes increases the energy per unit volume and specific weight, which makes it easier to handle and transport thus giving the sugar mills the option of selling it as fuel.
- The percentage of ash precipitating is higher, thus reducing its emission to the ambient air and resulting in more ash that has high nutritious value.

It was also proposed to add filter cake to the bagasse briquettes to enhance its properties. However, the proportion of the filter cake should not exceed 10% (Nemerow, 2007).

b. Bagasse Charcoal

A number of countries produce charcoal from bagasse. Preparation of charcoal briquettes from bagasse is done in three stages: (1) carbonization of bagasse bales, (2) mixing of the resulting charcoal with molasses and extrusion of briquettes from this mixture and (3) carbonization of the briquettes (Paturau, 1982).

Charcoal can be also obtained by the destructive distillation of the bagasse. The main products derived from this process are charcoal, combustible gases, methyl alcohol, acetic acid and tar (Paturau, 1982).

c. Production of Methane

Anaerobic fermentation or digestion of organic matter will yield methane gas, or biogas, which is considered a valuable fuel. As bagasse is composed of cellulose and lignin, it is not easily degraded by fermentation. It was proposed by Dasgupta (1983) to mix bagasse with filter cake/mud at a ratio of 2.4:1 to get a high gas yield. The anaerobic digestion of the bagasse/mud mixture generates methane gas, digested filter cake and filtrate. The filtrate is recirculated to the digester to enhance the digestion process and the gas can be burnt in the boiler to produce steam and electricity. The digested cake is suitable as organic fertilizer.

d. Production of Bioethanol

Sugarcane bagasse can be used as a feedstock for ethanol production, due to its high carbohydrate content and relatively low lignin content. The size of the bagasse fibers influences the profile of lignocellulosic enzyme activity. Hydrolysis of the bagasse can be done by using dilute sulfuric acid or hydrochloric acid at elevated temperature and pressure. Pre-treatment of the bagasse may be necessary to enhance the sugar yield. It can be accomplished by methods such as steam explosion, liquid hot water pretreatment and pre-treatments with peracetic acid or with ammonia water (Nigam and Pandey, 2009).

e. Animal Feed

Bagasse can be used as animal feed due to its high fiber and carbohydrate content. Bagasse could be treated in a number of methods to become suitable animal fodder. The first process is mechanical as it involves shredding of the bagasse and soaking it in steam under high pressure and temperature. This process accelerates the digestibility of the fodder without giving it much time for complete digestion. The main drawback of this process is its high cost. The other process is chemical, as after bagasse shredding, urea or ammonia is added to the bagasse to increase its nutritional value and digestibility. This procedure is inexpensive due to the cheap price of urea and can be easily applied. The third method is biological where the bagasse is buried in soil in anaerobic conditions for two to three months. This is the least cost option (El Haggar, 2007).

f. Production of Chemicals

Bagasse is a potential raw material for the production of a number of chemicals such as furfural, alpha-cellulose and xylitol (Cheesman, 2005). Furfural is a colourless, inflammable, volatile, aromatic liquid that is used in the chemical industry to produce solvents used to refine vegetable oils, furfuryl alcohol, resins and tetrahydrofuran. As for alpha-cellulose, it is a purified insoluble form of cellulose used for dissolving pulp. Xylitol is an easily purified sugar alcohol that could be used as a sugar substitute.

2.6.3 Filter mud/cake

a. Fuels and chemicals

Residual sugar, wax and protein can be extracted from sugarcane filter mud (Balakrishnan and Batra, 2011). It has also been used as a substrate in solid state fermentation for production of citric and lactic acids.

Moreover, due to the high organic content of the mud, it can be anaerobically digested to produce biogas and digested sludge that could be used as fertilizer. In India, a sugar factory set up such facility that produces 165 L biogas/kg press mud with 60% methane content, which is piped to houses neighboring the factory (Balakrishnan and Batra, 2011).

b. Organic Fertilizer

As filter mud has adequate nitrogen and phosphorus, enrichment of press mud by composting has been studied by mixing with other wastes like cow dung, bagasse and sugarcane trash. Using filter mud as a fertilizer either directly or after biocomposting is a common practice (Balakrishnan and Batra, 2011).

Use of composted filter cake/mud as soil conditioner improves the soil organic content and provides nutrients that were depleted due to the extensive cultivation of sugarcane in the agricultural fields. The compost improves the soil tilth and water holding capacity implying reduction in irrigation needs. It also reduced the need for chemical fertilizers by 10 to 30%as it traps mineral and prevents their leaching from the soil. The filter cake compost is free from pests, pathogens, nematodes and weed seeds (Senthil and Das, 2004).

2.6.4 Furnace Ash

Bagasse furnace ash has a very high silica concentration and in smaller amounts; aluminum, iron, alkalis and alkaline earth oxides. Souza et.al. (2011) proved that it is feasible to use furnace ash in the ceramic industry by mixing the ash (up to 60 % by weight) with a clayed raw material. Faria et.al (2012), on the other hand, also proved the feasibility of using ash as a replacement of natural clay by up 20% weight, acting as a filler in clay bricks.

2.7 Sustainability of Sugarcane Industry

The sugarcane industry in Egypt can be currently defined as an open industrial system that consumes material and energy and creates products and wastes (El Haggar, 2007). For the sugarcane industry to become a sustainable industry or a green industry, its production process has to be closed over its lifecycle. Its wastes, residues and by-products should not be burned or disposed but should be rather treated as raw material for other industries. The sugarcane industry in Egypt needs to introduce the concept of green industries and industrial ecology.

2.7.1 Green industry

According to the United Nations Industrial Development Organization (UNIDO), green industry can be defined as "industrial production and development that does not come at the expense of the health of natural systems or lead to adverse human health outcomes". Green industry aims to reduce the significant impacts imposed on the human beings' health and conserve the environment's natural resources through the efficient use of resources, and efficient methods of production and manufacturing.

The UNIDO recommends that are two main methods to achieve green industry: either by greening the existing industries or by creating green industries as shown in Figure 2.16.

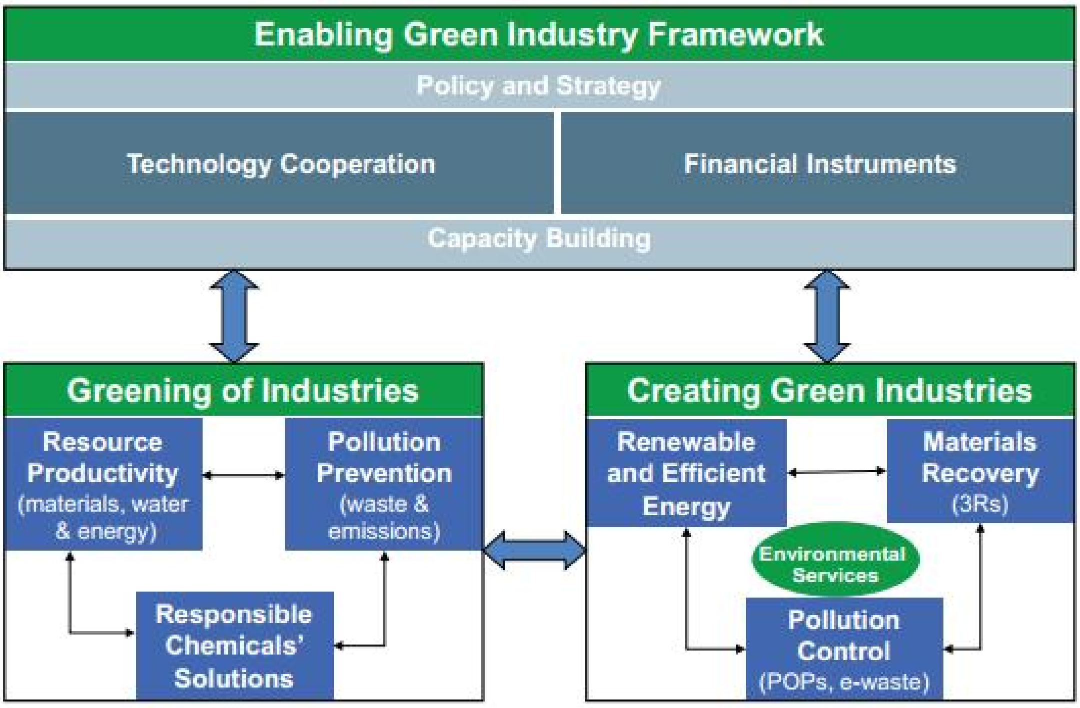


Figure 2.16. Green industry themes (UNIDO,2012)

Greening of existing industries means more efficient use of resources, expanding use of renewable energy sources, phasing out toxic substances and improving occupational health and safety at the industrial level. As shown in Figure 2.16, greening of industries requires resource productivity with regards to materials, water and energy, prevention of pollution caused by waste and emissions, as well as conscientious chemicals use.

As for the creation of green industries, it involves planning for the use of renewable and efficient energy, minimizing use of material through is recovery, recycling and reuse and finally control of pollution through environmental-friendly waste management plans.

Green industries have numerous benefits related to different aspects. The benefits of a green industry can be classified into three main categories, which are social, environmental and economic benefits (UNIDO, 2012) as illustrated in Figure 2.17.

Social Benefits	Environmental Benefits	Economic Benefits
- Better Health and well-being - Increase worker Productivity - Encourage Sustainable business practices	- Reduce Energy Consumption - Lower Greenhouse gas emissions - Conservation of resources - Water conservation	- Less operating costs - Creating jobs - Innovation and Growth

Figure 2.17 Benefits of green industry (UNIDO, 2011)

Social benefits of green industries include maintaining the health and well-being of labor due to the absence of harmful emissions and hazardous chemicals in manufacturing processes, which will reflect on the productivity of the workers and encourages sustainable business practices.

As for environmental benefits, green firms use less energy and resort to energy efficiency practices. Greenhouse gas emissions will hence be reduced significantly due to the reduction of fuel use for energy. Conserving resources will be achieved by using renewable resources and increasing the efficiency of resources, such as materials and energy. Water will also be conserved through water management, recycling and reuse.

Economic benefits, on the other hand, will include reduced operating costs due to less energy consumption and decreased costs of pollution to the environment. Green industries also increase job opportunities by promoting green jobs, such as those of material recycling. They also encourage innovation and promoting new value adding processes and finding creative alternatives to replace traditional practices.

2.7.2 Industrial Ecology

The concept of "industrial ecology", which started in the 1990s, encouraged "waste utilization" rather than "waste treatment" (Nemerow, 2007). Industrial ecology borrows from nature the notion of cycling. It promotes the idea that the industrial system should imitate the natural one by conserving and reusing resources entirely in production and consumption (Clini et al, 2008).

The objective of industrial ecology is to avoid environmental damage from the beginning “through systems analysis, through product, process, and facility design, and through technological innovation” (Clini et al, 2008). It increases eco-efficiency and preserves the environment by minimizing the environmental impacts to regulatory limits (El Haggar, 2007). Pollution control devices only transform the pollution from one type to another. For example, scrubbers installed on stacks replace air pollution from emitted dust to a solid waste disposal issue of the collected dust.

According to Clini et al (2008), the five elements of industrial ecology are: (1) design for environment (DFE), (2) life cycle analysis and assessment (LCA), (3) material flow analysis, (4) industrial symbiosis and (5) policy approaches.

Design for environment (DFE) means that the environmental dimension is included in the design of a product, process, or facility at an early stage without compromising performance, reliability, aesthetics, maintainability, cost, or time to market (Clini et al., 2008). The World Business Council for Sustainable Development (WBCSD, 2000) stated the following requirements associated with DFE:

- Reduce material requirements (total mass)
- Reduce energy intensity
- Reduce dispersion of toxic substances
- Enhance recyclability
- Maximize use of renewable resources (avoid depletion of finite resources)
- Extend product durability/product life
- Increase service intensity

Life Cycle Assessment (LCA) is “an analytical tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle” (Clini et al., 2008) while material flow analysis is used to quantify the flow of materials in an industry including energy and water inflows and outflows.

The perception of industrial symbiosis (IS) is based on the scheme of exchange of a facility’s waste in terms of energy, water or material with another facility and becoming its feedstock and Extended Producer Responsibility (EPR) means that the producers assume responsibility of their products even after use.

The main focus of industrial ecology is waste minimization and the conversion of by-products into reusable products or resources (Roberts, 2004). Industrial ecology is most effective when there is a cluster of industries that can exchange their waste and by-products. Proximity allows for savings and economies of scale and reduces operational costs due to sharing of common services or suppliers (Roberts, 2004). Agglomeration of industries with similar waste and by–product allows for concentrating and minimizing waste collection costs and encourages other industries to reprocess the waste and sell it to neighboring manufacturers to use it as raw material.

According to Roberts (2004), the principles of industrial ecology are:

- Establishing partnerships with communities and government in promoting the idea of sustainable industries
- Planning for industrial clusters to benefit from the concentration of by-products, waste material flows and energy surplus
- Co-location of industries involved in the trade or exchange of waste and by-products
- Valorization of waste and energy through recovery practices
- Innovation in the fields of cleaner production, waste management and sustainable industry development
- Provision of 'smart infrastructure' to sustain the growth of eco-industries
- Encourage innovation and marketing of new products developments through policies and incentives

Industrial ecology is a systems-orientated concept where the boundaries of the system can be defined at a number of levels as follows:

- *Micro-level or firms level*

  Industrial ecology at the firms level include actions like water recycling, co-generation of electricity and steam and reprocessing of waste material within the firm or industry. These measures can attain operational savings but there are limitations related to the scale and quality of waste and by-products that can affect recovery cost.

- Meso level or eco-industrial parks

  Eco-industrial parks apply the principles of industrial ecology, cleaner production and valorization of waste management. EIPs encourage co-location of industries having linked or independent processes and are able of utilizing waste material and energy of one industry to other industries in the same location. There are two types of EIPs: green industry parks and integrated eco-industry parks. Green industry parks are mainly composed of 'environmentally conscious' industries that are applying cleaner production technologies. It is a cluster of firms that share their commitment to cleaner production but with no exchange of material or energy among them. Integrated eco-industry parks (IEIPs), on the other hand, are designed to support the development of industrial ecologies centered on industrial clusters. The planning of IEIPs is complex as it requires detailed information about local and regional waste and emission flows to optimize the location and types of industries in the park.

- Macro-level or Regional and manufacturing centers

  Networked eco-industrial park system (NEIPS) is a group of EIPs linked to other EIPs across metropolitan regions. NEIPS share waste exchange system and markets as well as reprocessed products.

2.7.3 Eco industrial Parks (EIP)

Eco industrial parks are based upon industrial ecology principles promoting the clustering of industrial facilities with the aim of minimizing energy, water and material wastes through their exchange among the industries (El Haggar, 2007). EIPs close the material and energy flows within an industrial economy. EIPs are considered to be on the path of sustainable industrial development (Roberts, 2004).

EIP aims at achieving economic, environmental, social and government benefits. Economic benefits are achieved through the reduction of costs of raw material, energy, waste management and treatment, where environmental gain is attained through reduction in use of natural resources as well as emissions and waste that cause environmental degradation (El Haggar, 2007). Social benefits, on the other hand, ~~is~~ are recognized through the provision of new job opportunities and governmental profit is due to the reduction in cost of environmental degradation, demand on natural resources and infrastructure (El Haggar, 2007).

For planning of EIPs, the following “macro-level planning audit” should be done (Roberts, 2004):

- Estimation of total and segmented wastewater, material and energy volumes and flow patterns from all manufacture sources
- Assessment of waste volumes, sources and sinks
- Assessment of physical, environmental and economic aspects associated with each product use
- Spatial concentration and transportation of each waste type
- Identification of environmentally sensitive locations for waste materials, water and energy processing and reprocessing
- Take into consideration regional planning strategies especially of industrial estates
- Regulatory framework for material and waste management
- Assessment of government performance as related to application of environmental policies
- Appraisal of community reaction towards waste management industries and planning of mixed industrial development.

EIPs require networks of suppliers and distribution chains which depend on local material and energy flows (Roberts, 2004). If the disposal costs of waste are less than the market price of the reprocessed material there will be no incentive for by-product users.

There are two types of eco-industrial parks (Lambert and Boons, 2002):

- Greenfield complexes, which are newly established industrial parks developed according to well defined concepts of reduction of environmental impacts
- Brownfield complexes, which are existing parks that need restructuring based on regional requirements and taking into account environmental performance.

Allocation of recycling industries in the vicinity of existing process industries minimizes transportation cost and nuisance (Lamber and Boons, 2002).

Eco-industrial parks related to the sugar industry exist in China as one of the strategies for implementing sustainable development. In China, the Guitang Group Sugar Complex has implemented an approach of integrated life cycle management that link material life cycles into increasingly complex webs with the aim of developing an eco-industrial park.

Guitang group categorized the output material to any process as:

- Products which are the desired products of the process and represent the greater part of the value added.
- Co-products representing significant value, although not produced intentionally.
- By-products which are not intentionally produced, but they represent a modest positive value less than that of the original raw material.
- Residual products which are the process wastes including emissions to the atmosphere, soil and water. They represent a negative value as one has to pay for their disposal, treatment or processing.

The objective of sustainable management was to take full advantage of co-products and by-products, while reducing residual products. The proposed industrial ecosystem collaborated the environmental and economic benefits of a community of industries to manage energy, water, materials and other resources.

As shown in Figure 2.18, the eco-park is composed of two chains: the alcohol chain and the paper chain. The alcohol chain consists of the sugarcane farm, sugar refinery, an alcohol plant and a fertilizer. The down-stream plant utilizes the waste resulting from the up-stream plant as its raw material (Zhu and Cote, 2004). Molasses, a co-product of the sugar plant, is used by the alcohol plant, the residue of which is used in the production of fertilizer. The second chain adopts the same concept as the pulp plant uses the bagasse generated from the sugar refinery and sends its wastes of white sludge to cement factories.

The Guitang Group reduces the wastes generation, improves their financial performance, treats the residual products, and even partly achieves waste recovery. Examples of those measures are:

- The waste liquid from alcohol production is re-used after treatment to be used to produce fertilizer that is sold to the raw material producer, the sugarcane farmers.
- Wastewater produced during paper making is difficult to dispose and so it is reduced between 30% and 40% through improved water efficiency. The resulting wastewater is filtered in the boiler house using the boiler slag and further treated to meet national standards and is then discharged into rivers.
- The filter mud produced during sugar refinery is dried and is used as raw material for cement production.

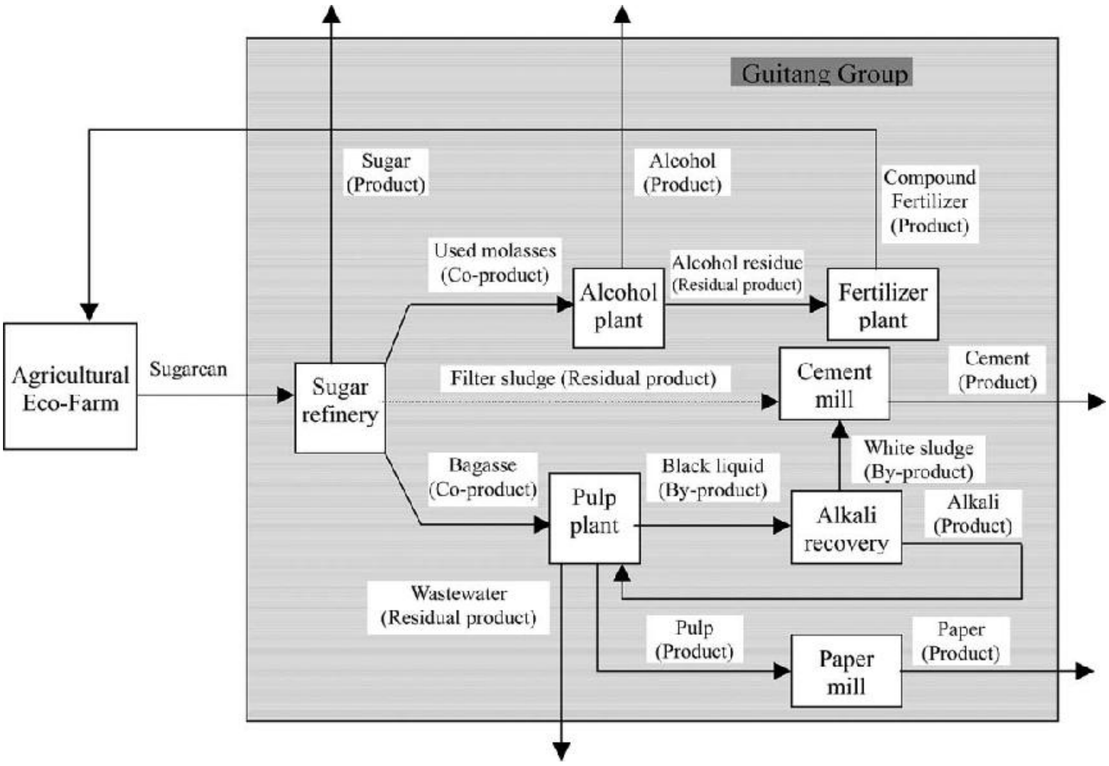


Figure 2.18. Integrated and internal green supply chain model of the Guitang Group (Zhu and Cote, 2004)

In India, on the other hand, Seshasayee Paper and Board Ltd. was established with the aim of supplying its raw material from a sugar mill that was set up (Lowe, 2001). Bagasse generated from the sugar mill was used as a raw material for paper-making and the produced molasses, was used in a distillery for the production of ethyl alcohol. Some of the water supplied for cultivation of the cane was the treated wastewater from the milling operations. Moreover, the bagasse pith resulting for the paper mill was combined with combustible agricultural wastes to be used as source of energy. Figure 2.19 shows the proposed Agro Industrial Eco-complex.

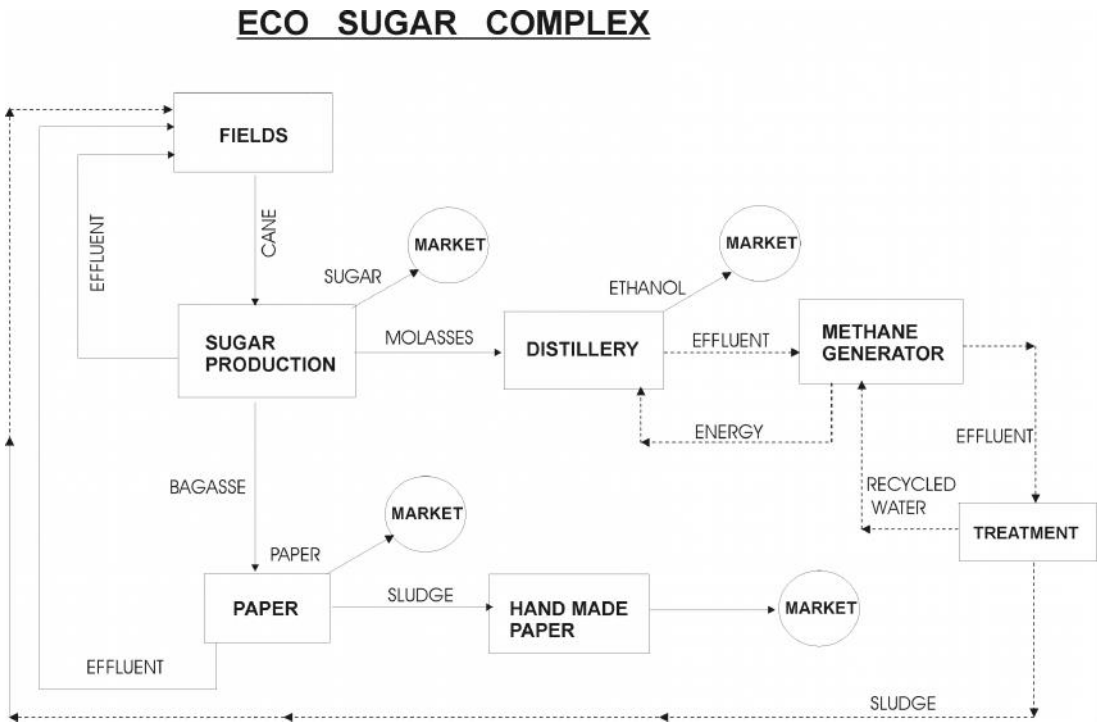


Figure 2.19: Agro Industrial Eco-Complex in India (Lowe, 2001)

2.7.4 Environmentally Balanced Industrial Complex

Another concept related to sustainable industries and the concept of zero pollution is that of environmentally balanced industrial complex (EBIC), as introduced by Nemerow and Dasgupta (1986). EBIC is a "selective collection of compatible industrial plants located together in a complex to minimize environmental impact and industrial production costs" (Nemerow, 1995). The waste of some industries is used as raw material of other industries, thus minimizing transportation, storage, disposal costs of waste and cost on virgin raw material.

Nemerow (1995) suggested that EBICs are best suited for large waste consuming and waste producing industries such as fertilizer plants, cement plants or sugar plants. The waste of the large industry may be suitable to be reused by other small scale industries that could prepare this waste to be used as raw material by other ones in the complex. Solid waste is only "misplaced raw material" as it can be used to replace the raw material of some industry and make a valuable product (Nemerow, 1995).

But before matching industries, the following issues need to be addressed:

- The physical distance between the waste producer and consumer
- The economics of joining the two industries
- The degree of compatibility of the waste material to be used as raw material of the other.

Nemerow and Dasgupta (1986) proposed a number of environmentally balanced sugar cane complex or a "closed loop" complex that would result in zero waste. One of the EBICs that he proposed was the "sugarcane-power-alcohol complex" that includes: (1) a sugarcane refinery; (2) a power plant producing both steam and electricity; (3) agricultural land for growing sugarcane and (4) an optional alcohol production plant. The core of this complex is an anaerobic digester, which treats the main residues; bagasse and filter cake. The four major products of the complex are: refined sugar, electrical energy, molasses and alcohol (optional), in addition to fermentation mash, digested and filtered sludge, digester gas, and steam (Nemerow, 2007). The proposed zero-waste complex is shown in Figure 2.20. Another optional unit was an Algae

Growth Basin utilizing the runoff of fertilizer and pesticide residues mixed and reused with excess water from the growth basin of sugarcane growing area.

The other complex that was proposed involved the compressing of bagasse and filter cake at high temperature into density packed briquettes. The cake acts as a binding agent due to its fat and wax content. The resulting briquettes acted as fuel for boilers as they have a calorific value of 15000 [kJ/kg] (El Haggar, 2007). The precipitating ash in the boiler can be used as fertilizer. The proposed sugar cane-briquettes-fertilizer complex is demonstrated in Figure 2.21.

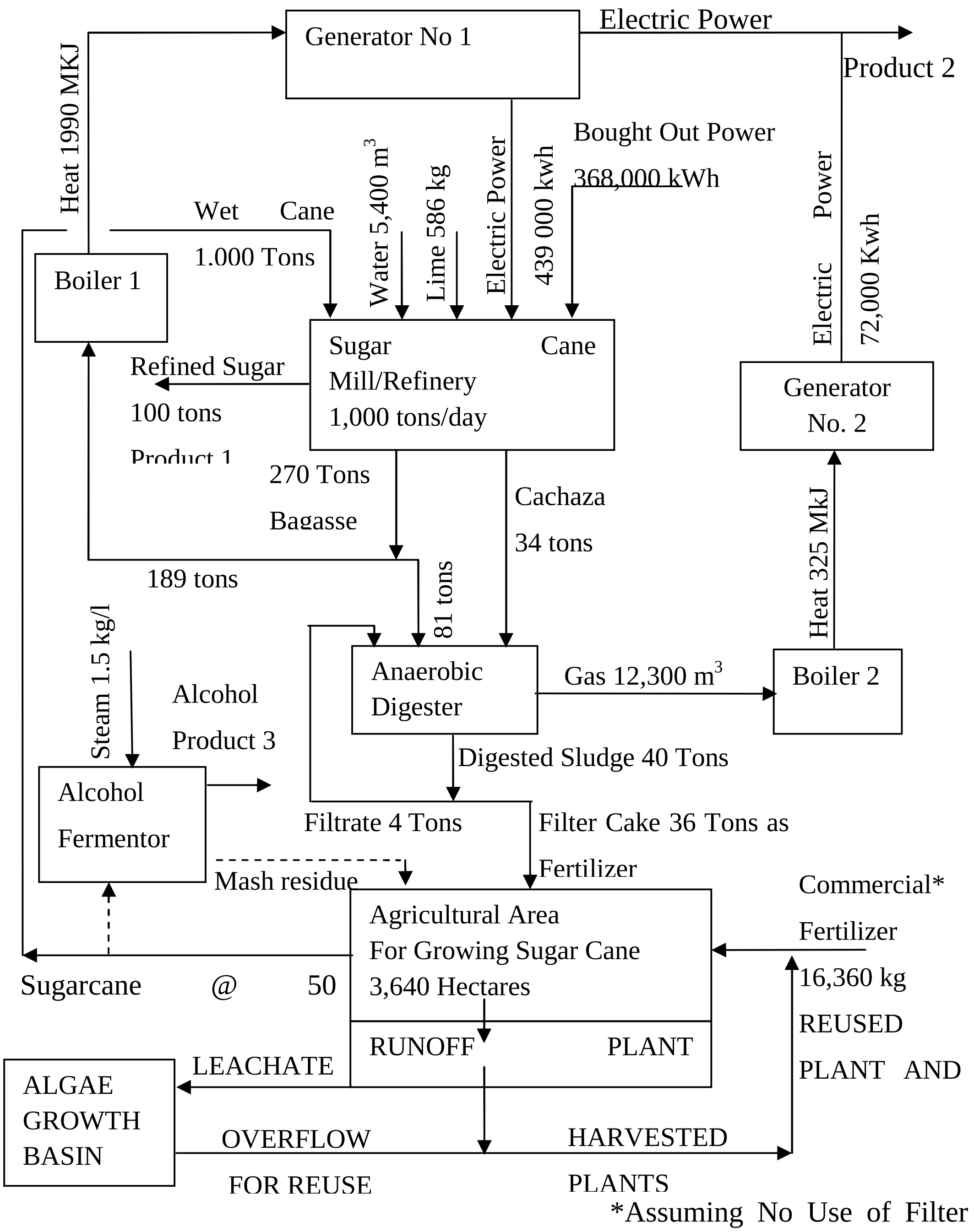


Figure 2.20. Sugarcane Power Alcohol Complex (Nemerow, 2007)

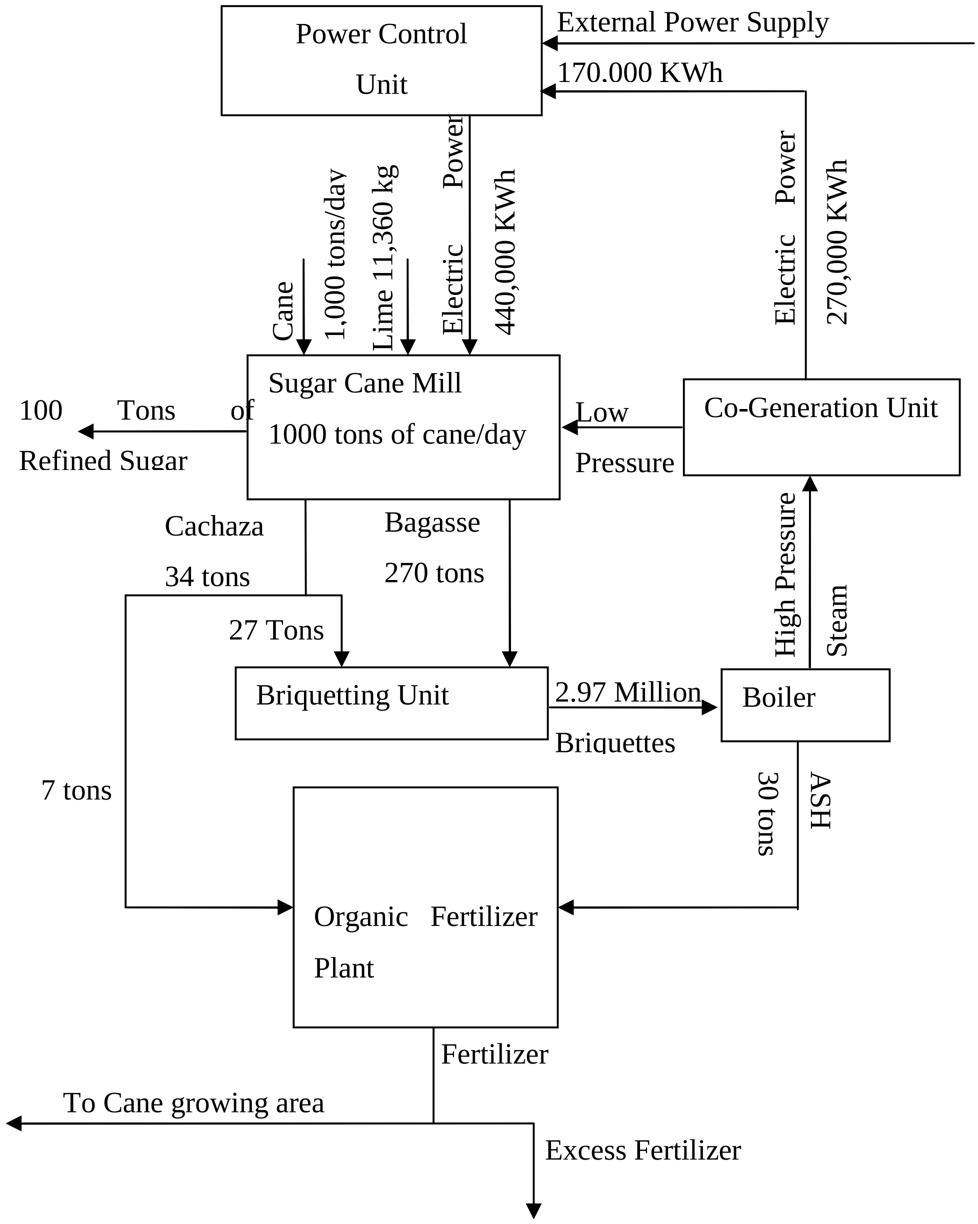


Figure 2.21. Sugarcane Briquettes Fertilizer Complex (El Haggar, 2007)

2.8 Conclusion

The sugarcane industry in Egypt needs to work on the closing of its material cycle to reach sustainability. The wastes and residues generated from the harvesting process are not efficiently used but rather burnt or disposed. Re-using the agricultural residues to produce useful products that can be returned to the field will achieve sustainability in the first phase of sugarcane production, which is cultivation and harvesting. This research will investigate the option of reusing the cane tops and dry leaves to produce animal feed and organic fertilizer to be returned to the cane cultivation phase. The reuse methods proposed are simple, low cost and could be applied by the farmer on a small scale.

As for the sugarcane milling stage, the material cycle can also be closed by reusing in a sustainable manner the industries main by-products which are bagasse, filter cake and furnace ash. Bagasse current reuse options in power generation and production of paper and fiberboard will be assessed using life cycle assessment to identify the best option in terms of the environmental perspective. More simple low cost option for reuse of bagasse will be investigated, which is the production of compost or organic fertilizer in combination with the filter cake and ash and the production of animal fodder. The output from the fertilizer or fodder option will also close the natural cycle as it will be returned to the farmers and cane fields.

Chapter 3
SILAGE AND COMPOST PRODUCTION FROM SUGARCANE RESIDUES

3.1 Introduction

The objective of this part of the research is to test for the possibility and feasibility of producing organic fertilizer and animal fodder from the waste streams generated from the agricultural and industrial phases of sugarcane manufacture, as an environmentally friendly reuse alternative.

As discussed in Chapters 1 and 2, the main residues generated from the sugarcane industry are green tops and dry leaves from the harvesting process as well as bagasse, filter cake/mud and furnace ash from the cane milling process. The green tops are directly fed to the farmers' livestock in its raw form but it is not completely consumed due to size and form. The unconsumed portion wilts and dries and is left to deteriorate. Green tops are also available as fodder only during the sugar harvesting season which is from January to April. As for the dry leaves, it represents a burden due to its volume and fire hazard and so it is daily burnt in the fields causing considerable air pollution. Bagasse, on the other hand, is currently used as fuel to generate the mill's steam and electricity or as fiber to make fiberboard and paper. However, as natural gas is replacing bagasse as fuel, bagasse will be available in large quantities in the factories that are not currently utilizing it for fiber. In addition, filter cake/mud and furnace ash are currently applied directly on reclaimed lands to act as soil additive. However, direct incorporation of raw agro-industrial waste into the soil may cause undesirable outcomes as "phytotoxicity and soil nitrogen immobilization" (Meunchang et al., 2005).

It is thus proposed to produce silage from the green tops and bagasse to provide the farmer with a secure supply of natural fodder that is of acceptable quality. It is also anticipated to make compost from a combination of dry leaves, bagasse, filter mud and ash to produce organic fertilizer that is more safe and environmental friendly than chemical or artificial fertilizers.

A pilot scale experimental setup for experimental production of silage and compost was set up within the facility of the Research Institute for a Sustainable Environment (RISE) and aid was provided from the AUC Landscaping team who supplied manpower for raw material handling, sample preparation, compost mixing and monitoring, as well as product sampling.

Residues of the sugarcane harvesting, including green tops and dry leaves, generated in one of the agricultural fields of El Menia Governorate were collected, baled and transported to the AUC New Cairo Campus for processing as shown in Figure 3.1. The dry leaves were shredded in the fields to reduce its size to allow its baling. Clover, that was proposed to be added to some silage samples, was also acquired from El Menia Governorate. As for the bagasse, filter mud and furnace ash, which are residues of the sugarcane milling process, they were purchased from Abou Korkas sugarcane mill also located in El Menia Governorate. Due to the large volumes of raw material, they were delivered to the composting area at AUC New Campus in three consecutive days as shown in Figures 3.1 and 3.3. Cow dung that was added to some mixtures was purchased from a livestock farm in Menofeya Governorate.

Samples of raw materials were taken and analyzed in the laboratories of the Soil, Water and Environment Research Institute of the Agricultural Research Center, Ministry of Agriculture and Land Reclamation. The physical, chemical and microbiological characteristics of these materials are presented in Tables 3.1 and 3.2.

Figure 3.1. Sugarcane agricultural residues

Figure 3.2. Bagasse residues

Figure 3.3. Filter mud/cake

Table 3.1. Characteristics of sugarcane residues generated during harvesting and milling

Parameters	Harvest Residues		Milling Residues		
	Dry Leaves	**Green Tops**	**Bagasse**	**Filter Mud**	**Furnace Ash**
Density (kg/m^3)	110	-	112	650	195
Moisture content (%)	18	68	53	76	41
pH (1:10)	-	-	5.46	5	8.39
EC (1:10) (ds/m^2)	-	-	2.13	1.9	1.46
Total nitrogen (%)	0.54	1.26	0.35	1.84	0.42
Ammoniacal Nitrogen (ppm)	-	-	-	53	Nil
Nitrate Nitrogen (ppm)	-	-	-	28	Nil
Organic matter (%)	89.47	91.23	98	67.74	46.22
Organic carbon (%)	51.90	52.92	56.84	39.29	26.81
Ash (%)	10.53	8.77	2.00	32.26	53.76
C/N ratio	96:1	42:1	162:1	21.4:1	63:1
Total phosphorus (P_2O_5) (%)	0.06	0.19	0.04	1.98	1.00
Total potassium (K_2O) (%)	0.54	1.07	0.1	0.28	0.99
Calcium (mg/kg)	9270	5791	906.8	47961	17047
Magnesium (mg/kg)	1881	1211	397.8	2296	6850
Iron (mg/kg)	809.7	841.1	471.2	5627	5774
Manganese (mg/kg)	50	37.6	17.2	177.3	143.9
Copper (mg/kg)	11.3	55.8	7.7	44.8	40.4
Zinc (mg/kg)	47.2	17.9	7.7	52.7	40.6
Total Coliform Bacteria(Cfu/g)	Nd	Nd	Nd	40 x 104	Nd
Fecal Coliform Bacteria(Cfu/g)	Nd	Nd	Nd	20 x 104	Nd
Salmonella & Shigella Bacteria (Cfu/g)	Nd	Nd	Nd	nd	Nd

All the analysis is done on oven dry basis except density and moisture content

Nd: Not detected Cfu: Colony forming unit

Table 3.2. Analysis of materials additives to silage and compost

Parameters	Clover	Animal Dung
Density (kg/m^3)	-	530
Moisture content (%)	89	22
pH (1:10)	-	9.58
EC (1:10) (ds/m^2)	-	5.78
Total nitrogen (%)	2.71	0.82
Ammoniacal Nitrogen (ppm)	-	679
Nitrate Nitrogen (ppm)	-	35
Organic matter (%)	86.16	27.59
Organic carbon (%)	49.98	16
Ash (%)	13.84	72.41
C/N ratio	18:1	19.5:1
Total phosphorus (P_2O_5) (%)	0.48	0.22
Total potassium (K_2O) (%)	1.68	1.35
Calcium (mg/kg)	19890	8960
Magnesium (mg/kg)	1680	5220
Iron (mg/kg)	901.3	4149
Manganese (mg/kg)	35.3	86
Copper (mg/kg)	17.8	15.1
Zinc (mg/kg)	12.6	43.4
Total Coliform Bacteria (Cfu/g)	Nd	22×10^5
Fecal Coliform Bacteria (Cfu/g)	Nd	13×10^5
Salmonella & Shigella Bacteria (Cfu/g)	Nd	230

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected Cfu: Colony forming unit

3.2 Silage Production

3.2.1 Theoretical Background

Silage is "ensilation of surplus feed" for use in periods of feed deficiency. The ensilage process is a technique that preserves the foddering plants through acid fermentation as lactic acid bacteria convert soluble sugars to lactic acid (Carneiro et al. 2006). Common methods used for ensiling included silage pit, stack, silo, bales, or silage wrapping (Hill laboratories, 2014). During the ensiling process, plant sugars are converted to a range of acids including lactic acid which is responsible for preserving the silage until use.

Silage fermentation results from the activity of aerobic and anaerobic bacteria. Aerobic activity occurs during silo filling and emptying. Minimizing aerobic activity reduces dry matter losses and oxidation of energy rich sugars produces excess heat, which can damage forage protein (Seglar et al., 2003). Anaerobic activity, on the other hand, converts water soluble carbohydrates to silage aids reducing the pH and avoiding spoilage. There are two types of anaerobic fermentation that are essential for silage fermentation; hetero- and homo-fermentation. Hetero-fermentation converts water-soluble carbohydrates to various fermentation end products at the expense of energy as dry matter is decreased. As for homo-fermentation bacteria (lactic-acid bacteria), it converts water-soluble carbohydrates to lactic acid, while consuming little energy and reducing dry matter loss (Seglar et al., 2003).

Silage fermentation undergoes 6 phases (Seglar et al., 2003) as shown in Figure 3.4.

- Phase 1 begins when the plant is harvested as the native aerobic organisms convert water-soluble carbohydrates to carbon dioxide, water, and heat. The plant's enzymes support the hydrolysis of starch and hemicellulose to monosaccharides. The neutral detergent fiber content increases slightly after ensiling, mainly because the water-soluble carbohydrate content is reduced. If the forage is properly sealed, aerobic activity should last only a few hours and aerobic spoilage organisms are avoided.
- Phase 2 starts after oxygen depletion, as the products work under anaerobic hetero-fermentation bacteria producing short-chain volatile fatty acids

(acetate, lactate, and propionate), ethanol, and carbon dioxide from the fermentation of water-soluble carbohydrates, including hexoses (glucose and fructose) and pentoses (xylose and ribose). This phase lasts for no longer than 24 to 72 hours and experiences a drop in pH.

- Phase 3 is a short transitional phase that lasts about 24 hours, where the decline in pH promotes increased populations of efficient homo-fermentative lactic-acid bacteria. These bacteria reduce silage pH faster and more efficiently by producing predominantly lactic acid. Heat is lost and pH continues to decrease, the action of phase 3 lactic-acid bacteria decreases and the activity of phase 4 lactic-acid bacteria increases.

- Phase 4 is a continuation of phase 3 as silage temperature stabilizes due to the homo-fermentative lactic-acid bacteria fermenting water-soluble carbohydrates to lactic acid.

Phases 2, 3, and 4 are the longest fermentation phases in ensilage and continue until forage pH is sufficiently low to reduce, but not destroy, the growth potential of all organisms. Unassisted natural fermentation carried out only by epiphytic organisms takes 10 days to 3 weeks depending on the buffering capacity, moisture, and maturity of the crop to be ensiled.

- Phase 5 is the storage phase or the stable phase. However, changes can take place depending on environmental conditions and penetration and the number and types of aerobic organisms (yeasts, molds, and aerobes) on the crop at harvest. It also depends on the types of fermentation acids present in the silage in phase 5.
- Phase 6 is the last fermentation phase related to silage feeding from the storage structure. This phase is also critical as up to 50% of dry-matter losses result from secondary aerobic spoilage on the surface of the silage during storage and feeding.

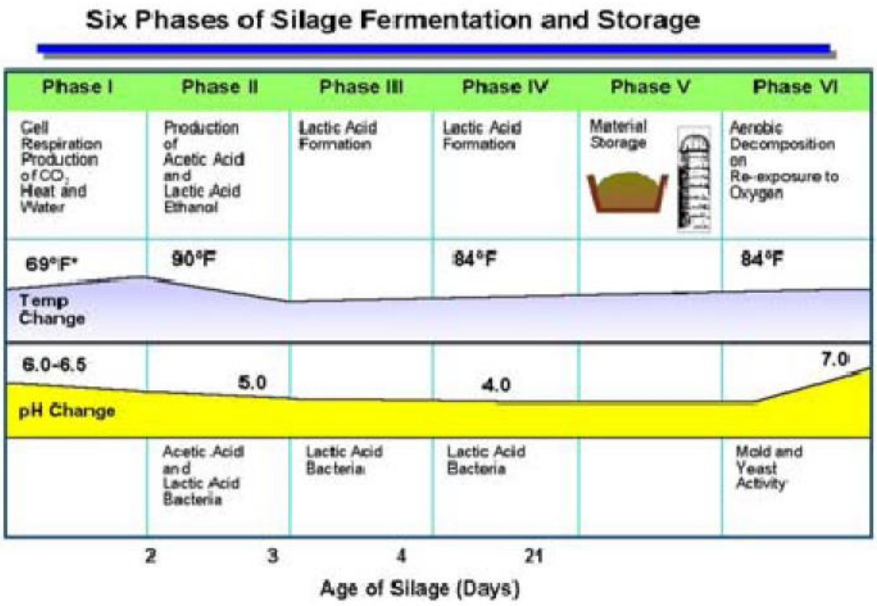


Figure 3.4. Silage Fermentation and Storage Phases (Seglar, 2003)

The quality of silage is directly related to the quality of the forage harvested and the success of the fermentation. The quality of the silage includes pH, dry matter (%), crude protein (%), acid detergent fiber (%), neutral detergent fiber (%), digestibility (% DOMD), metabolisable energy (MJ ME/kg DM), NH_4:Total N (%), volatile fatty acid profile (%) (Hill laboratories, 2014). Feed quality values of some typical forage are given in Table 3.3.

Table 3.3. Feed quality for forage samples (Hill Laboratories, 2014)

Feed Type	Dry Matter (%)	Crude Protein (%)	Acid Det. Fiber (%)	Neutral Det. Fiber (%)	Digestibility (% DOMD)	Metabolisable Energy (MJ/kg)
Mixed Pasture	12-25	20-30	20-30	30-45	65-80	9-12
Pasture Silage	25-30	14-20	20-35	30-45	65-75	9-11
Cereal Silage	35-40	8-12	25-40	35-60	55-65	8.5-10.5
Maize Silage	25-35	6-9	25-35	35-50	60-70	9.5-11
Lucerne Forage	15-25	20-30	25-30	35-45	60-70	9-12
Lucerne Hay	85-90	18-25	25-35	35-45	55-65	8-11

A loss of about 8% of the forage dry matter is expected throughout the ensilaging process. As for crude protein, it is directly related to the nitrogen content of silage. Acid detergent and neutral detergent fiber indicate structural carbohydrate levels and their increase decreases digestibility (Hill Laboratories, 2014).

Acid detergent fiber (ADF) is a measure of cellulose and lignin, and neutral detergent fiber (NDF) is a measure of hemicellulose, cellulose and lignin. As ADF decreases, the digestibility and the energy content increases. High fiber forages fill the stomach faster meaning that the animal eats less and needs more ration supplements.

Ammonium nitrogen is the product of protein decomposition. Protein breakdown will occur normally but poor preservation or slow rate of fermentation will increase its breakdown. Silage makers try to achieve a ratio of 10% ammonium nitrogen to total ammonia. Levels of 12-15% indicate that the pH is also high and considerable protein decomposition has occurred, thus reducing the storage life of the silage (Hill Laboratories, 2014).

Fermentation of the forage lowers the pH, due to the formation of Volatile Fatty Acids (VFA), to preserve the forage. Lactic acid is the strongest and most efficient volatile fatty acid and generally predominates in the best-quality silage (more than 60% of the total volatile fatty acids). It is present at levels as high as 3% to 6% of dry matter (Hill Laboratories, 2014). The presence of lactic acid will drop the pH more than the other volatile fatty acids. Lactic acid has a mild odor and does not volatilize upon exposure to air. Lactic acid creates efficient fermentation because it is stronger than the volatile acids.

Other volatile fatty acids (VFA), such as acetic, propionic and butyric acids, evaporate easily when introduced to air and give silages their characteristic smell. The volatile fatty acids provide aerobic stability properties. Acetic acid gives silages a vinegar odor and taste and is usually the predominant acid produced during fermentation for maintaining aerobic stability. Its presence is usually less than 3% in silages, as more than that implies inefficient hetero-fermentative fermentation. Propionic acid, on the other hand, produces a sharp sweet smell and taste. It is found at less than 1.0% in normal silages. As for butyric acid, it emits a rancid butter smell and taste. It is usually present at less than 0.1% in quality silage. Table 3.4 shows typical VFA profiles for different silages.

Table 3.4. VFA profiles for typical silages based on percentage dry matter content of silage (Hill Laboratories, 2014)

	Lucerne silage 30-35% DM	**Lucerne silage 45-55% DM**	**Grass silage 25-35% DM**	**Maize silage 25-35% DM**	**Maize silage 35-45% DM**	**Cereal silage 35-40%**
pH	4.3-4.5	4.7-5.0	4.3-4.7	3.8	3.7-4.2	3.7-4.5
Lactic acid	7-8	2-4	6-10	4.9	4-7	4-7
Acetic acid	2-3	0.5-2.0	1-3	1.4	1-3	1-3
Propionic acid	<0.5	<0.1	<0.1	N/A	<0.1	<0.1
Butyric acid	<0.5	0	<0.5	0.25	0	0
NH_4-N: TN	10-15		8-12		5-7	5-10

As for aerobic microbial counts including yeast, mold, and bacillus population counts, expressed in colony forming units per gram of feedstuff (cfu/gm), these indicate silage bunk life and aerobic instability from air penetration.

Ash content, on the other hand, is the total inorganic matter or minerals in the feed.

3.2.2 Use of Sugarcane Residues as Silage

In Brazil, Carneiro et al. (2006) experimented with producing silage from sugarcane while evaluating the microbiological quality and chemical composition of silage with and without nutritional additives (1% ammonium sulfate and 1% urea) after 30 days of fermentation. Biological analysis included yeasts, filamentous fungi and distinct groups of bacteria and the chemical analyzes comprised dry matter, crude protein, fiber content, lignin, and pH. It was concluded that the addition of ammonium sulphate and urea has decreased the microbial load after 30 days but it has increased the total crude protein concentration. Additives also affected neutral detergent fiber, acid detergent fiber and lignin (Carneiro et al. 2006).

In India, Tiwari et al. (2013) treated sugarcane bagasse and chopped green tops with urea in order to increase the crude protein content as these agricultural residues are a poor source of protein and have high fiber content. Urea is a source of ammonia that is suitable for chemical treatment of lingo-cellulosic materials as it improves their protein content and improves the energy availability since it increases the digestibility of the feed. It was found that treatment of bagasse with 5% urea at 40% moisture content for four weeks enhanced the crude protein content from 2.17 to 14.35% and hemicellulose content from 16.22 to 24.85 %. As for the sugarcane tops, treatment with 3 % urea at 40 % moisture content for 3 weeks gave the optimum result as it increased the crude protein from 4.91 to 13.76 % and neutral detergent fiber and acid detergent fiber content from 72.44 to 80.39% and 41.20 to 47.11 %, respectively (Tiwari, et al, 2013).

Shahowna et al. (2013) carried out an experiment to study the effect of fermentation and poultry litter level of nutritive value of bagasse as animal feed. The tested poultry litter ratios were 0%, 10%, 20% and 30%. The experiment concluded that addition of poultry litter to bagasse and fermentation improved crude protein content (CP), dry matter and organic matter digestibility, which contributes positively to the animal nutrition (Shahowna et al., 2013).

3.2.3 Materials and Methods

Sugarcane residues that could be potentially ensilaged to produce animal fodder were fresh cane tops and bagasse. Fresh cane tops are currently used to feed livestock in their fresh form but making silage out of them should enhance their nutritional properties and allow for its storage. Bagasse is also added as fiber filler in fodder-making in one of the sugarcane mills in Upper Egypt but was not used solely as fodder. It is thus intended to test the viability of producing silage from cane tops and bagasse. Cane tops are also mixed with clover (barseem) to enhance the quality of the produced silage.

Plastic boxes of one cubic meter capacity, lined with textile and plastic sheets, were used for anaerobic fermentation of the cane residues. The treatments used in this experiment were as follows:

1. The sugar cane tops were shredded and loaded in the first plastic lined box and compacted by means of a mechanical press. About 150 kg of shredded cane tops were compacted filling a volume of approximately 0.8 m^3. The silage was well wrapped, covered and stored under the pressure of the press so that it works under anaerobic conditions.

2. The second silage box was composed of a mix of green tops and clover (barseem) at a weight ratio of 3:1. The clover, added to increase the nutritional value of the silage, was first spread in the sun and air-dried to reduce its moisture content. It was then shredded and mixed with the shredded cane tops. The mix was also loaded, pressed, sealed and stored under pressure in anaerobic conditions. The starting weight was 150 kg of mix occupying a volume of about approximately $0.8m^3$.
3. The third mix was composed on bagasse which is a residue of the sugar cane squeezing process in the mill. Bagasse was purchased from Abu Kourkas Sugar mill and transported to the American University in Cairo in New Cairo. Bagasse was also loaded pressed, sealed and stored under pressure in anaerobic conditions. The starting weight was 165 kg of mix occupying a volume of about $0.8\ m^3$.

Figure 3.5 to 3.8 demonstrate the steps of preparation of the silage silos.

Figure 3.5. Chopping the green tops

Figure 3.6. Filling the silage bags with raw material

Figure 3.7. Ensiling the raw material

Figure 3.8. Pressing the silage bag

The physical and chemical characteristics of raw material(s) used in silage making are shown in Table 3.5 as analyzed by laboratories of the Soil, Water and Environment Research Institute of the Agricultural Research Center, Ministry of Agriculture and Land Reclamation. The initial analysis shows that the treatments of green tops, and green tops mixed with clover have high calcium, magnesium and iron, which is considered nutritional as animal feed. Bagasse also contains micro-nutrients but in lower concentrations.

Table 3.5. Initial analysis of raw material used for silage production

Parameter	**Treatments**		
	Green Tops	**Green Tops: Clover 3:1**	**Bagasse**
Moisture content (%)	68	70	53
Dry Matter (%)	32	30	47
Total nitrogen (%)	1.26	1.13	0.35
Organic matter (%)	91.23	88.17	98
Organic carbon (%)	52.92	51.14	56.84
Ash (%)	8.77	11.83	2.0
Total phosphorus (P_2O_5) (%)	0.19	0.10	0.04
Total potassium (K_2O) (%)	1.07	0.09	0.1
Calcium (mg/kg)	5791	5900	906
Magnesium (mg/kg)	1211	1633	397.8
Iron (mg/kg)	841	669.6	471.2
Manganese (mg/kg)	37.6	50.3	17.2
Copper (mg/kg)	55.8	10	7.7
Zinc (mg/kg)	17.9	10.5	7.7

All the analysis is done on oven dry basis except density and moisture content

3.2.4 Results and Discussion

After approximately 8 weeks of storage under anaerobic conditions, the pressure was relieved and the silage bags were opened and samples were taken from each box to be analyzed as shown in Figures 3.9 and 3.10.

Figure 3.9. Opening of silage box

Figure 3.10. Silage from bagasse

Analysis of the products was carried out at the Regional Center for Food and Feed as well as the Soil, Water and Environment Research Institute of the Center of Agricultural Research, Ministry of Agriculture as well as the Micro Analytical Center of the Faculty of Science, Cairo University. Results of analysis are shown in Table 3.6.

Table 3.6. Analysis of silage product

Analysis	Treatments		
	Green Tops	**Green Tops: Clover 3:1**	**Bagasse**
Moisture Content (%)	36	36.5	45.4
Dry matter (%)	64	63.5	54.6
pH	4.6	6.15	6.1
Ammoniacal Nitrogen (NH_4-N) (ppm)	Nil	40	40
Nitrate Nitrogen (NO_3-N) (ppm)	Nil	Nil	Nil
Nitrogen content (%)	1.008	1.104	0.256
Crude Protein (%)	6.3	6.9	1.6
Silica content (%)	7.3	10.38	1.6
Crude fiber (%)	28.45 ± 0.7	27.11 ±0.65	36.40 ± 0.87
Neutral Detergent Fiber (NDF) (%)	69.31 ± 1.67	63.73 ± 0.77	83.66 ± 2.02
Acid Detergent Fiber (ADF) (%)	45.05 ± 0.78	46.89 ± 0.82	58.84 ± 1.03
Acid Detergent Lignin (ADL) (%)	9.09 ± 0.95	16.70 ± 1.75	13.34 ± 1.39
Hemicelluloses (%)	24.26	16.84	24.82
Cellulose (%)	35.96	30.19	45.5
Lignin (%)	6.15	10.1	10.97
Lactic Acid (%)	0.095	0.012	0.04
Acetic Acid (%)	Nil	0.0062	0.0232
Butyric Acid (%)	Nil	Nil	Nil
Propionic Acid (%)	Nil	0.004	Nil
Lactic /total acids (%)	100	65.93%	63.29%
VFA (% as acetic)	3.72	7.5	6.54

The **dry matter** increased by 100% of the initial amount in case of green tops and green tops and clover (3:1) as the moisture content decreased by the same amount, implying that the moisture drained down the silo during the silaging process. As for bagasse, dry matter increased by 16% of the original amount.

The **pH** of 4.6 of the green tops silage indicate that it was well preserved during the silaging process. However, the higher pH of the other two treatments indicates that it was badly preserved and this is also indicated by the presence of ammoniacal nitrogen. Ammoniacal nitrogen is an indicator of protein decomposition that might have resulted from poor preservation or having a slow rate of fermentation.

Results of crude **protein, crude fiber, neutral detergent fiber (NDF)** and **acid detergent fiber (ADF)** indicate that the silage made from green tops, as well as green tops and clover, are of good quality and acceptable digestibility. These are nutritional and suitable as animal feed. As for the bagasse, it is very poor in crude protein and has low digestibility as it is high in its fiber content. It can only be used as a feed filler or additive.

As shown in Table 3.6, **lactic acid** comprises 100% to 63% of all acids in the three silage treatments, which is desirable in silage fermentation. The other acids, whose presence is undesirable, are present at insignificant quantities. These include acetic, propionic and butyric acids.

3.3 Compost Production

3.3.1 Theoretical Background

Composting is one of the most recommended methods for recycling of organic waste, as it closes the natural cycle and returns back to soil its nutrients. It is considered the "highest form of recycling" (Epstein, 1997). Composting can improve soil conditions and plant growth, reduce potential for erosion and runoff and can add humus to the soil, if properly produced. Production of composted fertilizer from lignocellulosic residues of by-products of sugar industries maintains the health of plant and soil properties and protects the plant from soil borne diseases (Sardar et al., 2012).

Composting is the process of aerobic decomposition of organic materials by microorganisms under controlled conditions (Abou Hussein and Sawan, 2010). Some of the objectives of composting include the decomposition of putrescible organic matter into a stable matter that can be used for soil improvement and disinfection of pathogenically infected organic waste to a safe matter (Epstein, 1997).

Aerobic decomposition is a process that consumes oxygen, and releases carbon dioxide, water vapor and heat. The main factors that affect the composting process are moisture content and oxygen (aeration). The ideal moisture content is 60% and if it decreases below 40%, microbial activity slows down, while above 60% anaerobic conditions may develop (El Haggar, 2007). Aeration, on the other hand, is needed to recharge the oxygen supply for the micro-organisms.

Temperature is also an important factor of composting, as it is an indicator of the microbial activity. The ideal temperature range is from 32°C to 60°C, within which activity of microorganisms is ideal. The increase in temperature during composting kills weeds, nematode and plant pathogenic organisms.

As shown in Figure 3.11, composting undergoes two stages: intensive decomposition and curing. The intensive decomposition has two stages; the mesophilic stage (<45°C) and the thermophilic stage (>45°C). In the active or decomposition phase, easily decomposable and putrescible compounds are broken down and pathogens are eliminated. During curing, the compounds that are less susceptible to carbon mineralization are broken down along with fatty acids (Epstein, 1997).

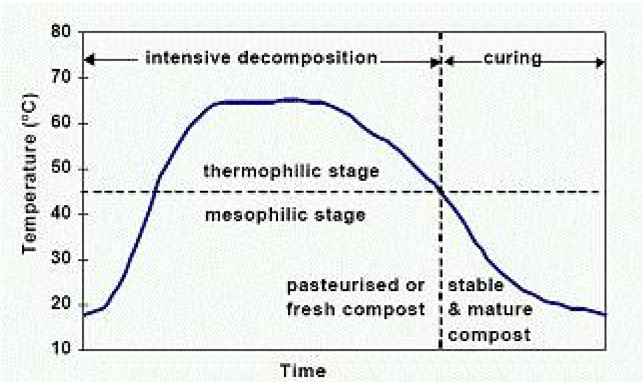


Figure 3.11. Phases of composting decomposition and curing as related to temperature (Epstein, 1997).

Other key factors are pH and carbon-to-nitrogen ratio, as carbon is the main source of energy and nitrogen is needed for cell synthesis. The ideal carbon-to-nitrogen ratio is 30:1 for microbes' best activity (El Haggar, 2007). If available nitrogen is low, microbial activity during composting will be slow but if nitrogen is in excess, it is lost from the system as ammonia gas (Meunchang et al., 2005).

Factors indicating maturation and stabilization of the compost include temperature, absence of odor and lack of attracting insects (Abou Hussein and Sawan, 2010).

Oxygen may be supplied to compost by different techniques. The most common composting techniques are natural or windrow composting, forced composting, passive composting and vermin-composting (El Haggar, 2007).

In natural or windrow composting, piles of compost are formed in parallel rows and continuously turned and moistened. This method needs considerable land and labor to manage the turning and watering process. Windrow composting is a low cost method that relies on natural ventilation but emits odors and requires a long time for maturation (El Haggar, 2007).

Passive composting involves placing parallel rows on perforated piping under the compost to provide air to the compost piles by natural convection (El Haggar, 2007). As this method does not require turning for aeration, it required less land and labor, takes less time for compost maturation, but includes the cost of installation and maintenance of the aeration system. Odor can be controlled by covering the piles with a top layer of finished product which causes the surface layer to decay killing all pathogens and seed weeds.

As for forced aeration, it works like passive composting but the piping is connected to blowers to force air through the compost at specific rate and velocity. Odor can be controlled in this method also by covering it and the compost takes less time to mature. However, it is a higher cost method due to the installation and maintenance of the blower system, and the need for source of electricity and skilled operating labor (El Haggar, 2007).

Vermi-composting, on the other hand, relies on worms transforming organic waste to fertilizer. It is considered an ecologically safe and economic method. Under appropriate aeration, humidity and temperature, worms feed on the organic waste and expel manure that breaks up the soil and provides aeration and drainage (El Haggar, 2007). This process is odorless, free of disease and creates an organic soil conditioner and natural fertilizer.

Compost could also be processed through in vessel composting, where the organic material is fed into a drum, silo or trench. This method allows close control of the temperature, moisture and aeration, as well as processing of large amounts of material without consuming as much space as the windrow method. This method also controls odors and allows minimal leachate. However, it needs manual labor for turning of the compost and could take more time for the microbial activity to stabilize and the pile to cool.

3.3.2 Compost Production from Sugarcane Residues

Sardar et al. (2012) produced compost from different ratios of filter cake/mud, molasses and rock phosphate. They also experimented with adding single super phosphate and sulfur mud to produce good quality fertilizer. They concluded that the compost produced reduces the hardness of the soil and made it more porous due to the presence of organic matter, phosphate, sulfur and other minerals. It also enhanced the fertility of land and increased the crop yield as it improved the nutrient conditions of the soil. Mixing compost with inorganic fertilizers also gave quality results according to the requirements of the different crops (Sardar et al., 2012).

In Thailand, composting was carried out to filter cake, and filter cake mixed with bagasse at a ratio of 2:1. It was recommended that the optimum C/N ratio for effective composting is between 25:1 and 40:1. Bagasse was added to the filter cake to increase the C/N ratio to conserve the nitrogen during composting. Mature compost was expected to have a reduced NH_4^+/NO_3^- and C/N in comparison to the original material and a high germination index. The final compost produced was found to be suitable for agronomic use, as they both contained appropriate pH, low phytotoxicity and were free of pathogens. They were also a good source of nutrients including nitrogen, phosphorus, potassium, calcium and magnesium (Meunchang et al., 2005).

According to Bernhardt and Notcutt (1993), filter cake/mud composting is recommended as it produces a marketable product, reduces offensive odors associated with rotting filter cake, reduces environmental pollution caused from its disposal as well as weight of the cake due to its drying and decomposition of organic matter, and increases the nutrient concentration of the cake due to the removal of water and cellulose. Composted filter cake is also free from pathogenic organisms and weed seeds, as they are eliminated by the high temperature juice clarification process requiring no further pasteurization process. Filter cake also has significant quantities of plant nutrients including nitrogen, phosphorus, potassium, calcium, magnesium and micronutrients (Bernhardt and Notcutt, 1993).

Bernhardt and Notcutt (1993) experimented composting filter cake/mud with four different treatment methods: (1) constructing a filter cake pile with alternative layers of bagasse 10 cm thick, with the intention of facilitating aeration through bagasse inter layers and not requiring turning, (2) forming filter cake pile that was aerated through manual turning once every four days, (3) mixing raw filter cake with starter culture of composted cake (2% by weight) and manually turning every four days, and (4) composting of filter cake using forced aeration pipe network and leaving the pile undisturbed for the duration of the experiment. Piles were monitored for six weeks for temperature, moisture, pH, nutrients (N, P, K, Ca, Mg) and carbon. Water was sprayed on the piles at intervals to prevent excessive dehydration. It was concluded that unpleasant smell characteristic of the raw cake disappeared within a week. Turning of the piles enhanced the composting activity than forced aeration or bagasse layers. All piles showed increase in percentage of nutrient content (N, P, K, Ca and Mg) and decrease in C/N ratio from 30.6:1 to 18.8:1 and 17:1 as the acceptable value for inclusion in soil is 20. The moisture content dropped from 80% to 50% and the pH changed from 7.2 to 8.3. A seedling growth test was performed on the most successful trials (2 and 3) and found that it compared to commercial compost (Bernhardt and Notcutt, 1993).

Cifuentes et al. (2013) tried composting a mix of waste sugarcane with filter cake/mud in large scale windrows mechanically turned. The composting process proceeded smoothly and the losses in organic matter ranged from 64 to 72 %. The C/N ratio of mature composts was between 10:1 and 20:1 and no signs of phytotoxicity were observed with black bean seeds which germinated between 95 and 100 %. Tomato seeds planted in a greenhouse experiment showed that compost made from waste sugarcane could be mixed with soil up to 50–60 % where tomato plant height and weight were at their maximum value.

Moreover, in India, a compost production unit was established in Rajshree Sugars to produce compost from a mixture of filter cake/mud and distillery spend wash which has a very high BOD (40,000 to 80,000 mg/L) and is acidic in nature. This approach solved the problems associated with treatment and disposal of the distillery spend and made use of its high nutritional value. The product was nutrient-rich compost that can contribute to improving soil fertility and agricultural productivity (Senthil and Das, 2004).

3.3.3 Material and Methods of Composting

Composting was carried out using two methods: in vessel composting and windrow composting. In vessel composting was carried out for five mixtures and windrow composting for two mixtures. Composting was also carried out in a 1 m^3 bag for a mixture due to the availability of its raw material in limited quantities.

Five wooden boxes of 4.5 m^3 capacity were constructed specifically for this research. The box was partially opened from three sides and closed from the fourth side to act as a gate as shown in Figure 3.12. The material mixes were proportioned based on weight, which was measured using a portable scale as shown in Figures 3.13 to 3.15. The compost mixtures were prepared in-vessel, bag or windrow as detailed in Table 3.7. The percentages of mixtures of the different raw material were chosen based on assumed scenarios as follows:

1. Dry leaves produced in the field has high C/N ratio (96:1) as shown in Table 4.1 and it was thus proposed to add animal dung, which is usually available in Egyptian agriculture lands (in limited amount), to act as a starter to the digestion process. The ratio 5:1 was calculated based on weight of leaves produced per feddan of land in proportion to assumed amount of dung generated from farmers' livestock.
2. Dry leaves were also mixed with filter mud generated from the cane mills so accomplish a good starting C/N ratio that is less than 40:1 as presented in Table 4.8.

3. Bagasse, the main residue of sugar milling, also having a high C/N ratio was mixed with animal dung which was also intended to act as a starter to the digestion process and to test the feasibility of the composting mix.
4. Bagasse was mixed with filter mud with the same ratio as that produced from the sugar mill which is about 8:1, since as bagasse is generated with an amount of 30% of cane weight and filter mud as 3.5%.
5. Bagasse was mixed at a ratio of 1:1 with filter mud, assuming that 90% of the amount of bagasse is used for other uses such fiberboard or paper and only 10% are available for composting.
6. Bagasse was mixed with filter mud at a ratio of 1:2 to mimic the situation when most of the bagasse is burnt for power and so a limited quantity is available to be mixed with the filter mud.
7. Filter mud was composted alone to test for its properties and quality with and without being composted, as it was expected to give very high quality fertilizer after it is digested.
8. Filter mud was mixed with furnace ash at a ratio of 9:1 as this is the actual ratio of their production from the sugar mill if bagasse is burnt for power.

Figure 3.12. Composting vessels

Figure 3.13. Weighing raw material

Figure 3.14. Preparing composting mixtures

Figure 3.15. Preparing compost windrows

Table 3.7. Composition of the raw material mixtures used in compost production

Composition	Treatments							
	Dry Leave: Cattle Dung 5:1	Dry Leaves :Filter Mud 1:6	Bagasse :Cattle Dung 5:1	Bagasse : Filter Mud 8:1	Bagasse: Filter Mud 1:1	Bagasse: Filter Mud 1:2	Filter Mud	Filter Mud: Ash 9:1
Abbreviation	L:D 5:1	L:M 1:6	B:D 5:1	B:M 8:1	B:M 1:1	B:M 1:2	M	M:A 9:1
Treatment method	Vessel	Windrow	Vessel	Vessel	Windrow	Vessel	Vessel	Bag
Initial Total Weight (kg)	336	4200	600	630	4000	1170	2500	500
Initial Volume (m^3)	3.375	15	3.04	3.4875	13.5	3.375	3.15	0.85

Based on the analysis of the main raw material, the physical characteristics of the different compost treatments are presented in Table 3.8. The temperatures of the compost treatments were recorded on weekly basis to monitor the performance of the composting process. Every week, the compost was also discharged from of the box to be manually turned and watered and then packed again in the wooden box or bag. The windrows were also watered and turned using a loader. Reduction in the volume of the compost was noted after the maturation period. Figures 3.16 to 3.19 demonstrate the process of temperature monitoring and compost turning and watering.

Table 3.8: Characteristics of the compost treatments at the start of the experiment

Parameters	Treatments							
	Dry Leaves: Dung 5:1	**Dry Leaves: Mud 1:6**	**Bagasse :Dung 5:1**	**Bagasse :Filter Mud 8:1**	**Bagasse :Filter Mud 1:1**	**Bagasse :Filter Mud 1:2**	**Filter Mud**	**Filter Mud: Ash 9:1**
Abbreviation	L:D 5:1	L:M 1:6	B:D 5:1	B:M 8:1	B:M 1:1	B:M 1:2	M	M:A 9:1
Density (kg/m^3)	100	280	197	181	296	347	794	588
Moisture content (%)	57	63	61	63	60	69	76	72
pH (1:10)	7.39	7.15	7.65	5.12	5.8	5.45	5	5.52
EC (1:10) (ds/m^2)	2.20	1.4	0.83	0.66	0.2	0.9	1.9	1.93
Total nitrogen (%)	0.58	1.37	0.47	0.44	0.85	1.10	1.84	1.54
Ammoniacal Nitrogen (ppm)	112	357	119	63	378	441	53	25
Nitrate Nitrogen (ppm)	21	Nil	28	Nil	Nil	35	28	Nil
Organic matter (%)	79.58	75.62	80.45	96.18	87.77	82.71	67.74	63.12
Organic carbon (%)	46.16	43.87	46.66	55.76	50.91	47.97	39.26	36.61
Ash (%)	20.42	24.38	19.55	3.82	12.23	17.29	32.26	36.88
C/N ratio	79:1	32:1	100:1	127:1	60:1	43:1	21:1	24:1
Total phosphorus (P_2O_5) (%)	0.09	1.28	0.08	0.16	0.7	1.02	1.98	1.77
Total potassium (K_2O) (%)	0.67	0.37	0.41	0.11	0.16	0.19	0.28	0.43
Calcium (mg/kg)	9220	33923	2914	3730	16812	24682	47961	41329
Magnesium (mg/kg)	2415	2145	1599	512	1039	1357	2296	3273
Iron (mg/kg)	1343	3879	1388	781	2214	3076	5627	5659
Manganese (mg/kg)	56	131	34	27	71	98	177	170
Copper (mg/kg)	12	33	10	10	20	26	45	44
Zinc (mg/kg)	47	51	17	10	23	30	53	50
Free Nematode (Larve/200g)	Nd	Nd	80	20	Nd	20	Nd	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Total Coliform Bacteria (Cfu/g)	5×10^4	180×10^4	8×10^4	15×10^5	295×10^4	12×10^5	40×10^4	14×10^5
Fecal Coliform Bacteria (Cfu/g)	3×10^4	80×10^4	6×10^4	3×10^4	50×10^4	4×10^4	20×10^4	2×10^4
Salmonella & Shigella Bacteria (Cfu/g)	15	25×10^3	14	13×10^3	15×10^3	19×10^3	Nd	11×10^3

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected   Cfu: Colony forming unit

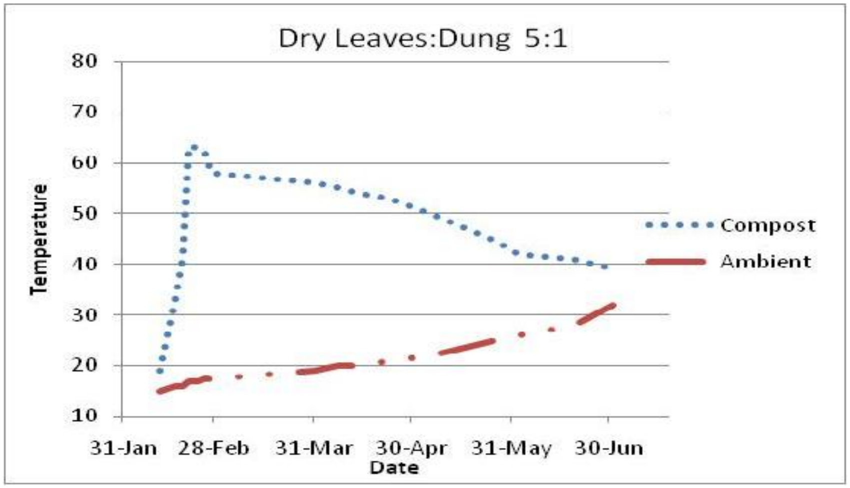
Figure 3.16. Manual mixing of compost **Figure 3.17. Monitoring of compost temperature**

Figure 3.18. Mixing of compost windrows **Figure 3.19. Watering of compost windrows**

3.3.4 Results and Discussion

After 20 weeks of watering, mixing of the compost and based on monitoring of temperature of the compost treatments and observation of the physical appearance of the compost, the composting process was terminated.

Results of temperature monitoring showed that all treatments passed through the mesophilic and thermophilic stages and were in the curing stage which results in stable and mature compost as shown in Figures 3.20 to 3.27.



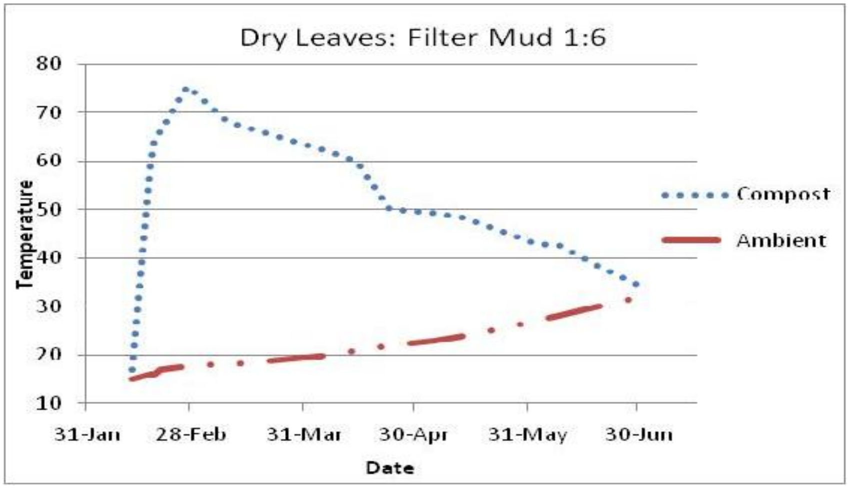
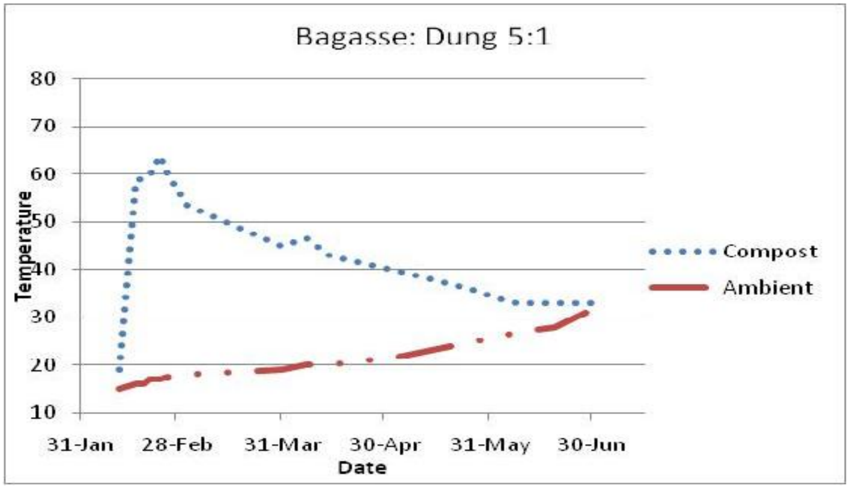


Figure 3.20. Temperature monitoring for L:D (5:1)

Figure 3.21. Temperature monitoring for L:M (1:6)



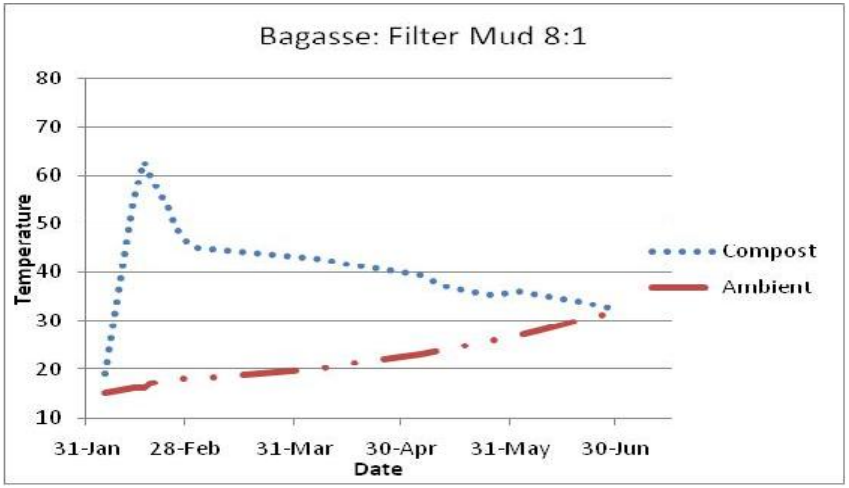


Figure 3.22. Temperature monitoring for B:D (5:1)

Figure 3.23. Temperature monitoring for B:M (8:1)

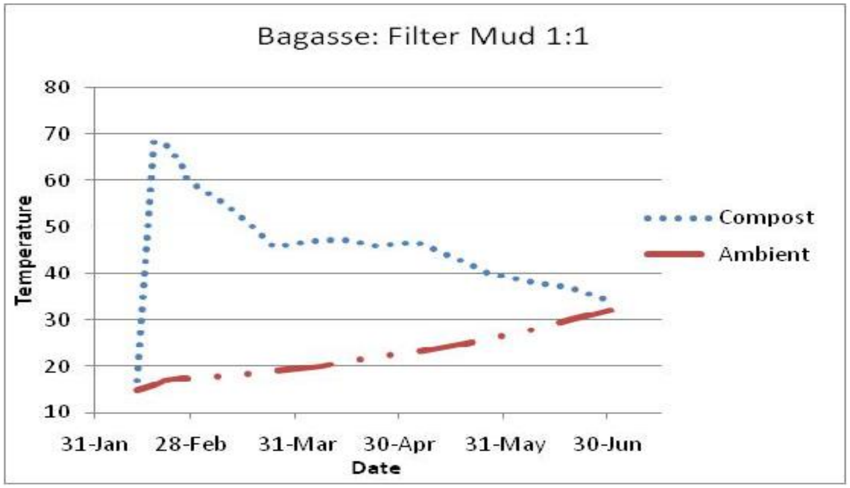


Figure 3.24. Temperature monitoring for B:M (1:1)

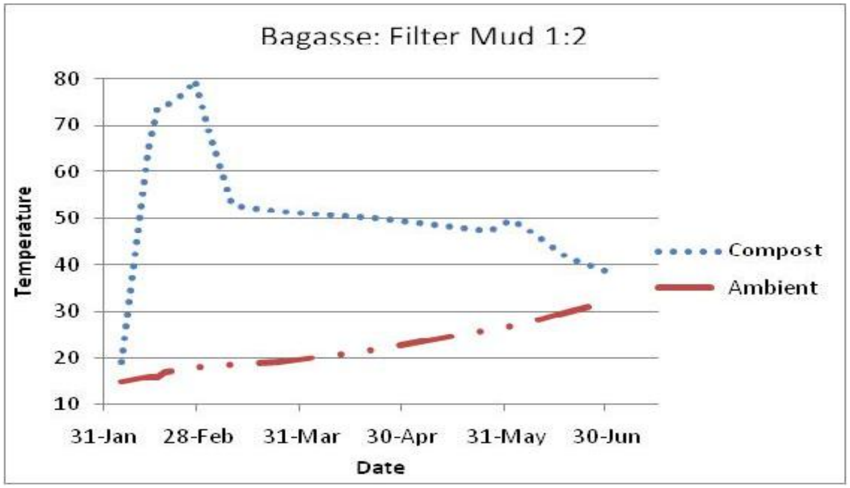


Figure 3.25. Temperature monitoring for B:M(1:2)

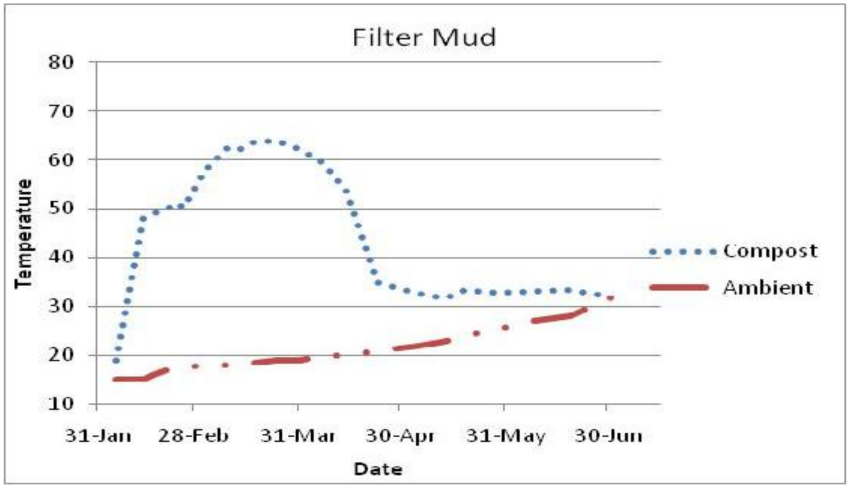


Figure 3.26. Temperature monitoring for M

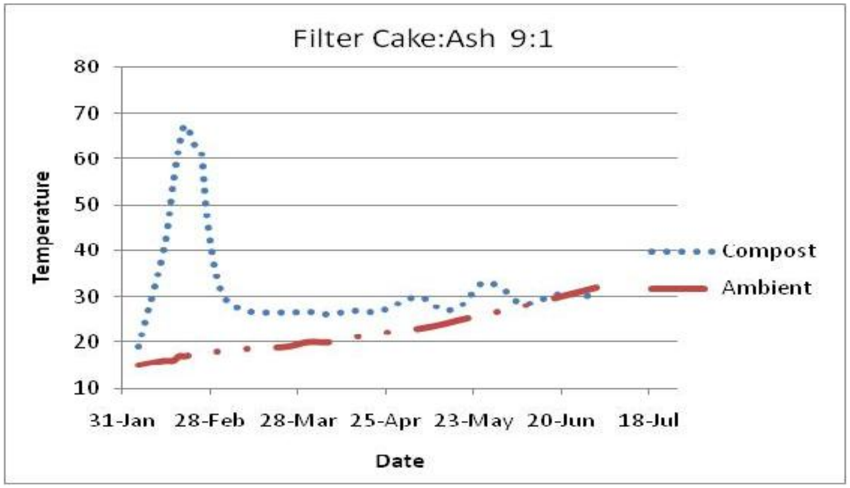


Figure 3.27. Temperature monitoring for M:A 9:1

The final volume of the treatments was taken and reductions in volume, density, and fresh weight were calculated as shown in the Table 3.9.

Table. 3.9. Change in the characteristics of compost mixtures

Composition	Treatments							
	Dry Leave: Cattle Dung 5:1	**Dry Leaves: Filter Mud 1:6**	**Bagasse : Cattle Dung 5:1**	**Bagasse : Filter Mud 8:1**	**Bagasse : Filter Mud 1:1**	**Bagasse: Filter Mud 1:2**	**Filter Mud**	**Filter Mud: Ash 9:1**
Abbreviation	L:D 5:1	L:M 1:6	B:D 5:1	B:M 8:1	B:M 1:1	B:M 1:2	M	M:A 9:1
Treatment method	Vessel	Windrow	Vessel	Vessel	Windrow	Vessel	Vessel	Bag
INITIAL TREATMENT								
Initial Weight (kg)	336	4200	600	630	4000	1170	2500	500
Initial Volume (m^3)	3.375	15	3.04	3.4875	13.5	3.375	3.15	0.85
Initial Density (kg/m^3)	100	280	197	181	296	347	794	588
Initial Dry Matter (kg)	273.28	1356	313	280	1420	370.5	600	137.5
FINAL PRODUCT								
Final Weight (kg)	288	1008	279	360	1213	401	536	114
Final Volume (m^3)	0.9	1.6	0.9	0.9	2.5	0.9	0.9	0.3
Final Density (kg/m^3)	320	630	310	400	485	445	595	380
Final Dry Matter (kg)	150	585	134	259	497	204	273	86
PERCENTAGE CHANGE IN THE BATCH CHARACTERISTICS								
Decrease in Volume	73%	89%	70%	74%	81%	73%	71%	65%
Increase in Density	221%	125%	57%	121%	64%	28%	-25%	-35%
Decrease in Dry Mass	45%	57%	57%	7%	65%	45%	54%	38%

Analysis of the compost produced after about 20 weeks of composting as compared to the analysis at the start of experiment are shown in Tables 3.10 to 3.17.

Table 3.10. Compost analysis of dry leaves and cattle dung (L:D 5:1)

	Raw Batch	**Compost Product**
Density (kg/m^3)	100	320
Moisture content (%)	57	48
pH (1:10)	7.39	7.01
EC (1:10) (ds/m^2)	2.20	3.66
Total nitrogen (%)	0.58	1.03
Ammoniacal Nitrogen (ppm)	112	67
Nitrate Nitrogen (ppm)	21	47
Organic matter (%)	79.58	53.07
Organic carbon (%)	46.16	30.78
Ash (%)	20.42	46.93
C/N ratio	79:1	30:1
Total phosphorus (P_2O_5) (%)	0.09	0.64
Total potassium (K_2O) (%)	0.67	1.14
Calcium (mg/kg)	9220	44235
Magnesium (mg/kg)	2415	9445
Iron (mg/kg)	1343	8340
Manganese (mg/kg)	56	178.5
Copper (mg/kg)	12	25.8
Zinc (mg/kg)	47	41.7
Free Nematode (Larve/200g)	Nd	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	5×10^4	Nd
Fecal Coliform Bacteria (Cfu/g)	3×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	15	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected Cfu: Colony forming unit

Table 3.11. Compost analysis of dry leaves and filter mud (L:M 1:6)

	Raw Batch	**Compost Product**
Density (kg/m^3)	280	630
Moisture content (%)	63	42
pH (1:10)	7.15	7.34
EC (1:10) (ds/m^2)	1.4	1.72
Total nitrogen (%)	1.37	1.6
Ammoniacal Nitrogen (ppm)	357	57
Nitrate Nitrogen (ppm)	Nil	143
Organic matter (%)	75.62	29.67
Organic carbon (%)	43.87	17.21
Ash (%)	24.38	70.33
C/N ratio	32:1	11:1
Total phosphorus (P_2O_5) (%)	1.28	2.32
Total potassium (K_2O) (%)	0.37	0.31
Calcium (mg/kg)	33923	66740
Magnesium (mg/kg)	2145	9010
Iron (mg/kg)	3879	20430
Manganese (mg/kg)	131	747.7
Copper (mg/kg)	33	122.8
Zinc (mg/kg)	51	406.5
Free Nematode (Larve/200g)	Nd	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	180×10^4	Nd
Fecal Coliform Bacteria (Cfu/g)	80×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	25×10^3	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected   Cfu: Colony forming unit

Table 3.12. Compost analysis of bagasse and cattle dung (B:D 5:1)

	Raw Batch	Compost Product
Density (kg/m^3)	197	310
Moisture content (%)	61	52
pH (1:10)	7.65	7.46
EC (1:10) (ds/m^2)	0.83	1.67
Total nitrogen (%)	0.47	1.08
Ammoniacal Nitrogen (ppm)	119	57
Nitrate Nitrogen (ppm)	28	38
Organic matter (%)	80.45	63.92
Organic carbon (%)	46.66	37.07
Ash (%)	19.55	36.08
C/N ratio	100:1	34:1
Total phosphorus (P_2O_5) (%)	0.08	0.88
Total potassium (K_2O) (%)	0.41	0.82
Calcium (mg/kg)	2914	22485
Magnesium (mg/kg)	1599	4400
Iron (mg/kg)	1388	5070
Manganese (mg/kg)	34	106.8
Copper (mg/kg)	10	22.1
Zinc (mg/kg)	17	49
Free Nematode (Larve/200g)	80	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	8×10^4	Nd
Fecal Coliform Bacteria (Cfu/g)	6×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	14	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected   Cfu: Colony forming unit

Table 3.13. Compost analysis of bagasse and filter mud (B:M 8:1)

	Raw Batch	Compost Product
Density (kg/m^3)	181	400
Moisture content (%)	63	28
pH (1:10)	5.12	7.11
EC (1:10) (ds/m^2)	0.66	0.45
Total nitrogen (%)	0.44	0.78
Ammoniacal Nitrogen (ppm)	63	38
Nitrate Nitrogen (ppm)	Nil	Nil
Organic matter (%)	96.18	42.4
Organic carbon (%)	55.76	24.59
Ash (%)	3.82	57.60
C/N ratio	127:1	32:1
Total phosphorus (P_2O_5) (%)	0.16	0.79
Total potassium (K_2O) (%)	0.11	0.27
Calcium (mg/kg)	3730	15895
Magnesium (mg/kg)	512	1875
Iron (mg/kg)	781	3005
Manganese (mg/kg)	27	50.7
Copper (mg/kg)	10	18.7
Zinc (mg/kg)	10	21.8
Free Nematode (Larve/200g)	20	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	15 x 10^5	Nd
Fecal Coliform Bacteria (Cfu/g)	3 x 10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	13 x 10^3	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected   Cfu: Colony forming unit

Table 3.14. Compost analysis of bagasse and filter mud (B:M 1:1)

	Raw Batch	**Compost Product**
Density (kg/m^3)	296	485
Moisture content (%)	60	59
pH (1:10)	5.80	6.88
EC (1:10) (ds/m^2)	0.2	0.58
Total nitrogen (%)	0.85	1.4
Ammoniacal Nitrogen (ppm)	378	47
Nitrate Nitrogen (ppm)	Nil	Nil
Organic matter (%)	87.77	50.58
Organic carbon (%)	50.91	29.34
Ash (%)	12.23	49.42
C/N ratio	60:1	21:1
Total phosphorus (P_2O_5) (%)	0.7	2.04
Total potassium (K_2O) (%)	0.16	0.12
Calcium (mg/kg)	16812	51210
Magnesium (mg/kg)	1039	3465
Iron (mg/kg)	2214	8420
Manganese (mg/kg)	71	288.9
Copper (mg/kg)	20	66.6
Zinc (mg/kg)	23	147
Free Nematode (Larve/200g)	Nd	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	295×10^4	Nd
Fecal Coliform Bacteria (Cfu/g)	50×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	15×10^3	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected   Cfu: Colony forming unit

Table 3.15. Compost analysis of bagasse and filter mud (B:M 1:2)

	Raw Batch	Compost Product
Density (kg/m^3)	347	445
Moisture content (%)	69	49
pH (1:10)	5.45	6.9
EC (1:10) (ds/m^2)	0.9	2.48
Total nitrogen (%)	1.10	1.44
Ammoniacal Nitrogen (ppm)	441	47
Nitrate Nitrogen (ppm)	35	152
Organic matter (%)	82.71	57.08
Organic carbon (%)	47.97	33.11
Ash (%)	17.29	42.92
C/N ratio	43:1	23:1
Total phosphorus (P_2O_5) (%)	1.02	2.7
Total potassium (K_2O) (%)	0.19	0.33
Calcium (mg/kg)	24682	47420
Magnesium (mg/kg)	1357	4850
Iron (mg/kg)	3076	9565
Manganese (mg/kg)	98	261.5
Copper (mg/kg)	26	56.8
Zinc (mg/kg)	30	129.6
Free Nematode (Larve/200g)	20	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	12×10^5	Nd
Fecal Coliform Bacteria (Cfu/g)	4×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	19×10^3	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected Cfu: Colony forming unit

Table 3.16. Compost analysis of filter mud (M)

	Raw Batch	Compost Product
Density (kg/m^3)	794	595
Moisture content (%)	76	49
pH (1:10)	5	6.56
EC (1:10) (ds/m^2)	1.9	3.91
Total nitrogen (%)	1.84	1.55
Ammoniacal Nitrogen (ppm)	53	76
Nitrate Nitrogen (ppm)	28	143
Organic matter (%)	67.74	45.46
Organic carbon (%)	39.26	26.37
Ash (%)	32.26	54.54
C/N ratio	21:1	17:1
Total phosphorus (P_2O_5) (%)	1.98	3.87
Total potassium (K_2O) (%)	0.28	0.36
Calcium (mg/kg)	47961	75145
Magnesium (mg/kg)	2296	8065
Iron (mg/kg)	5627	18370
Manganese (mg/kg)	177.3	443.7
Copper (mg/kg)	44.8	146.9
Zinc (mg/kg)	52.7	169.2
Free Nematode (Larve/200g)	Nd	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	40×10^4	Nd
Fecal Coliform Bacteria (Cfu/g)	20×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	Nd	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected Cfu: Colony forming unit

Table 3.17. Compost analysis of filter mud and furnace ash (M:A 9:1)

	Raw Batch	Compost Product
Density (kg/m^3)	588	380
Moisture content (%)	72	25
pH (1:10)	5.52	6.47
EC (1:10) (ds/m^2)	1.93	4.98
Total nitrogen (%)	1.54	1.24
Ammoniacal Nitrogen (ppm)	25	105
Nitrate Nitrogen (ppm)	Nil	152
Organic matter (%)	63.12	42.42
Organic carbon (%)	36.61	24.61
Ash (%)	36.88	57.58
C/N ratio	24:1	20:1
Total phosphorus (P_2O_5) (%)	1.77	2.74
Total potassium (K_2O) (%)	0.43	0.56
Calcium (mg/kg)	41329	73670
Magnesium (mg/kg)	3273	7235
Iron (mg/kg)	5659	13890
Manganese (mg/kg)	170	501.9
Copper (mg/kg)	44	115.6
Zinc (mg/kg)	50	147.8
Free Nematode (Larve/200g)	Nd	Nd
Pathogenic Nematode (Larve/200g)	Nd	Nd
Total Coliform Bacteria (Cfu/g)	14×10^5	Nd
Fecal Coliform Bacteria (Cfu/g)	2×10^4	Nd
Salmonella & Shigella Bacteria (Cfu/g)	11×10^3	Nd

All the analysis is done on oven dry basis except density and moisture content
Nd: Not detected   Cfu: Colony forming unit

The **bulk density** for all treatments except the filter mud (M) and filter mud ash mixture (F:A 9:1) increased with composting by amounts ranging from 221% to 28%, as presented in Table 3.9 and demonstrated in Figure 3.28. The change in bulk density depends on the physical characteristics of the mixture. The higher the fiber content of the mixture, the more it increases in density with time. The fiber structure breaks with time and the particle size decreases causing the porosity of the mixture to decrease. The opposite effect was observed with treatments composed of filter mud as the bulk density decreased by 25% and 35%. The filter mud produced from the mill is heavy due to its high moisture content but as the moisture content decreases and the material is aerated; it becomes more porous and light.

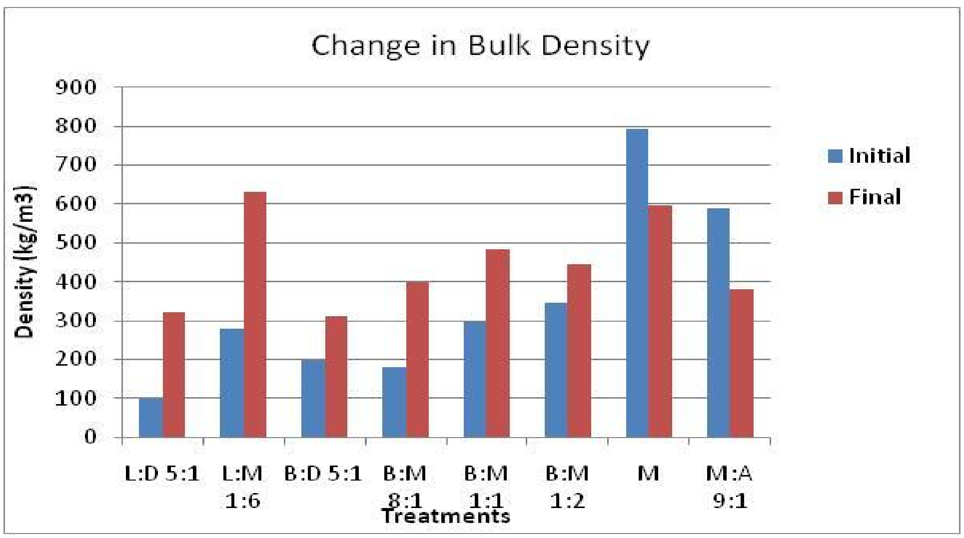


Figure 3.28. Change in bulk density of different compost treatments

The **pH** of mature compost typically approaches neutral, which is the case in all treatments as shown in Figure 3.29. The treatments composed with filter mud started off with low pH and so did some of the treatments composed of filter mud and bagasse. However, the ones mixed with animal dung or filter ash started the experiment with higher pH due to their alkali nature.

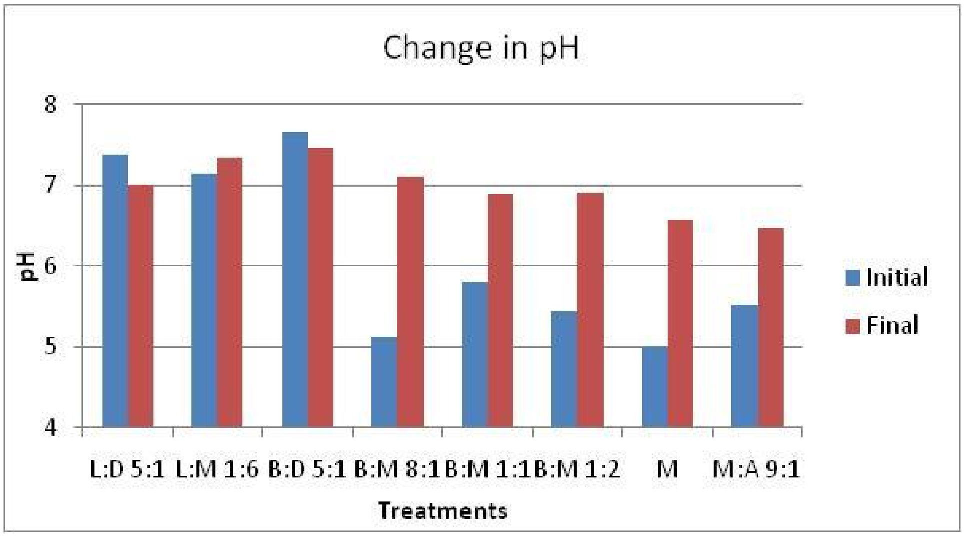


Figure 3.29. Change in pH of different compost treatments

The electrical conductivity **(EC)** increased in all treatments except for the B:M 8:1, which witness a decrease in electrical conductivity, as shown in Figure 3.30. The increase in conductivity could be attributed to the high concentration of nutrient ions released during the mineralization of organic matter.

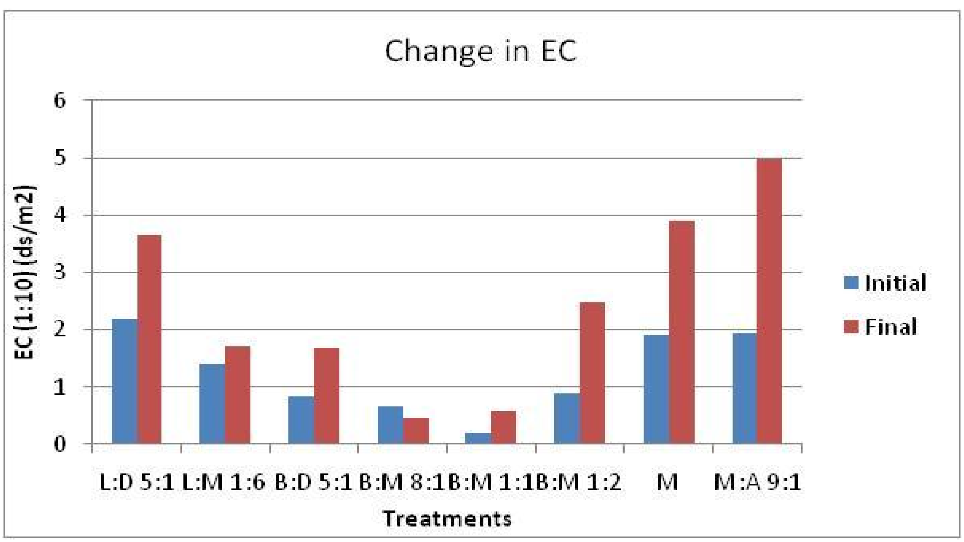


Figure 3.30. Change in electric conductivity of different compost treatments

The percentage as well as mass of **organic content** and **organic carbon** decreased resulting from the loss of carbon dioxide during composting as shown in Figure 3.31. The percentage ash content thus increased.

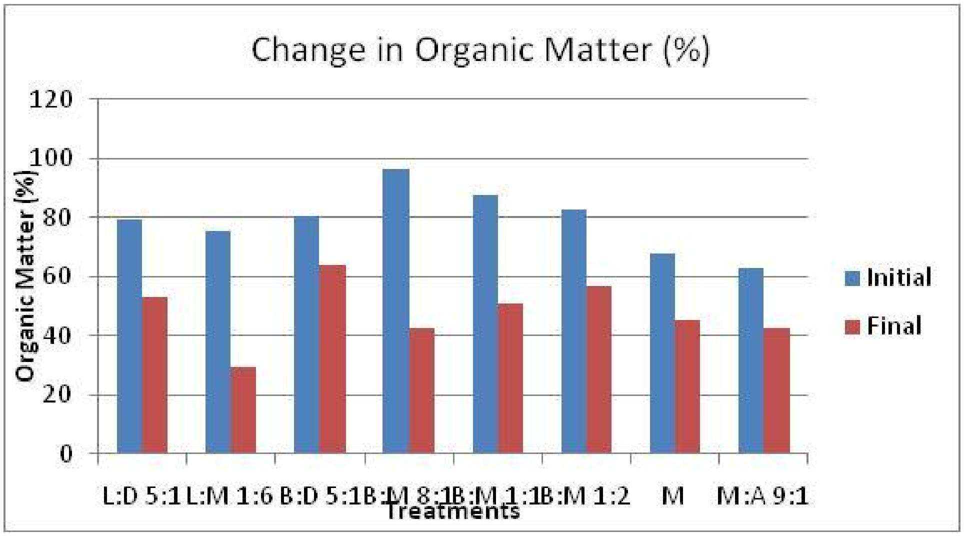


Figure 3.31. Change in percentage of organic matter in different compost treatments

The **nitrogen content,** as percentage of dry matter, increased for the treatments containing dry leaves or bagasse as they contained cellulosic material but decreased in the treatments containing mainly filter mud as shown in Figure 3.32. However, the nitrogen content in terms of mass decreased for all treatments except for the one that had the highest bagasse content mixed with the lowest amount of filter mud which is B:M 8:1 as presented in Figure 3.33. The significant drop in the nitrogen content in kg of nitrogen in L:M 1:6 could be attributed to excessive watering of the windrow which lead to leaching of the nutrients.

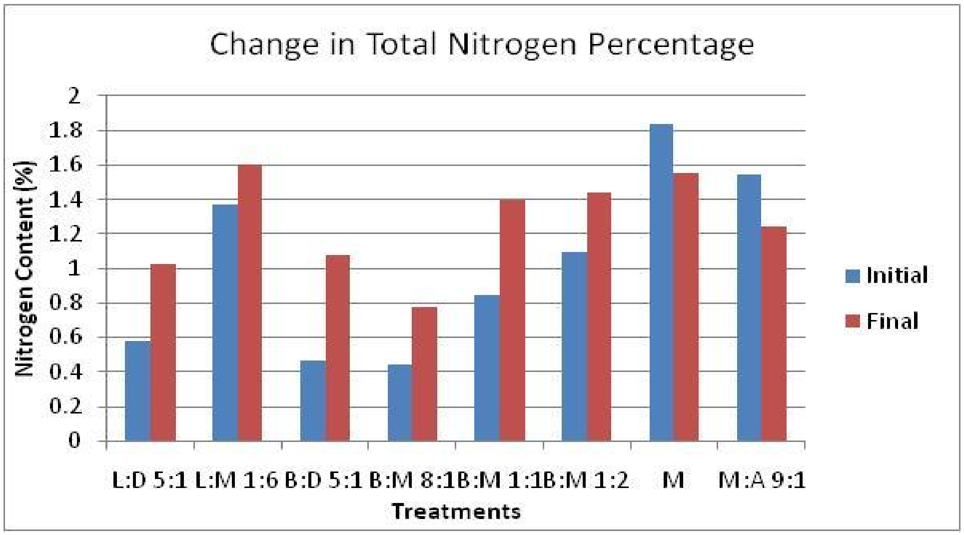


Figure 3.32. Change in the percentage of total nitrogen in different compost treatments

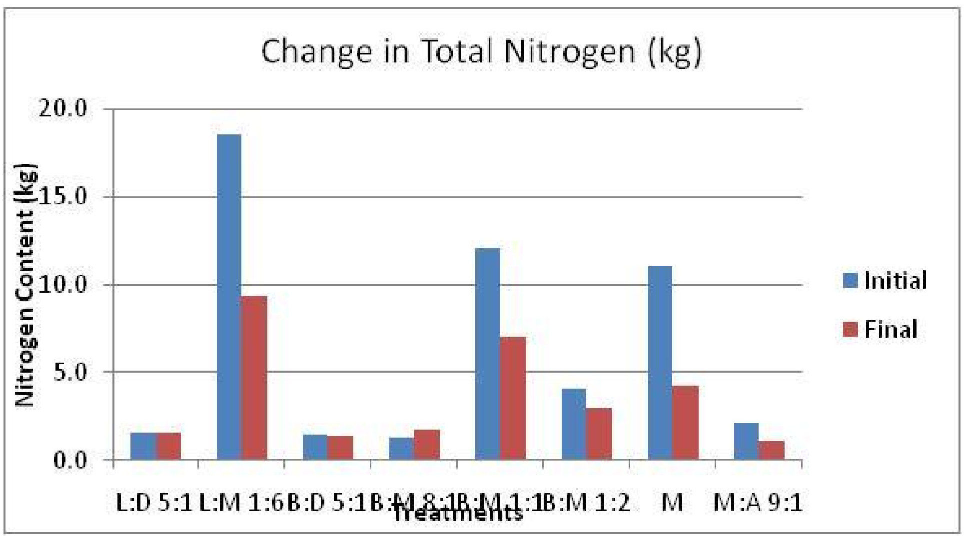


Figure 3.33 Change in the mass of total nitrogen in different compost treatments

The large decrease in **ammoniacal nitrogen** and increase in **nitrate nitrogen** during composting was related to the nitrogen transformation that occurred during composting. In treatments L:D 5:1, L:M 1:6 and B:D 5:1, the ammoniacal nitrogen decreased and the nitrate nitrogen increased but the ammoniacal nitrogen remained higher than the nitrate nitrogen. The same occurred with treatment B:M 1:2, however, the nitrate nitrogen reached higher values that the ammonium nitrogen. In treatments M and M:A 9:1 both the ammoniacal and nitrate nitrogen increased. Treatments B:M 8:1 and B:M 1:1 had no nitrate nitrogen before and after composting and its ammoniacal nitrogen decreased during composting. Figures 3.34 and 3.35 show these trends.

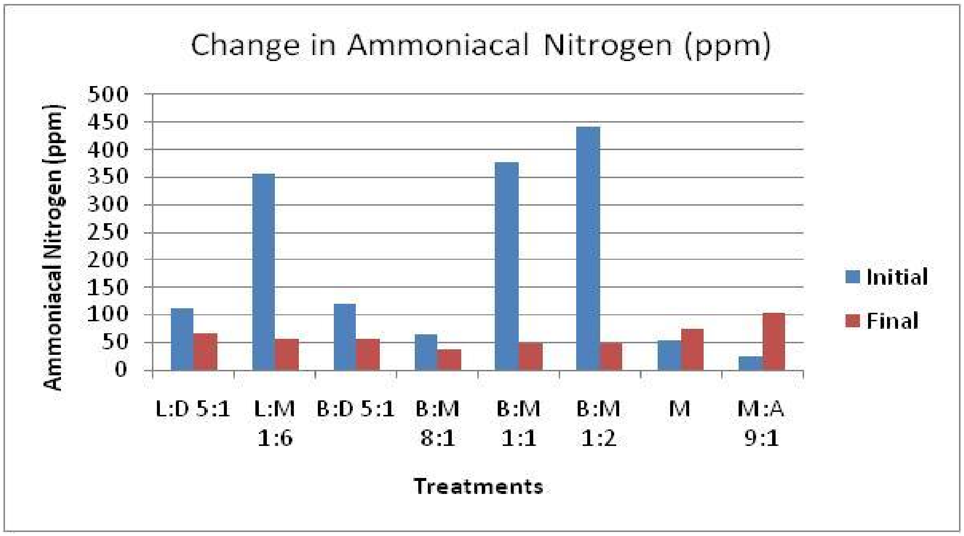


Figure 3.34 Change in ammoniacal nitrogen of different compost treatments

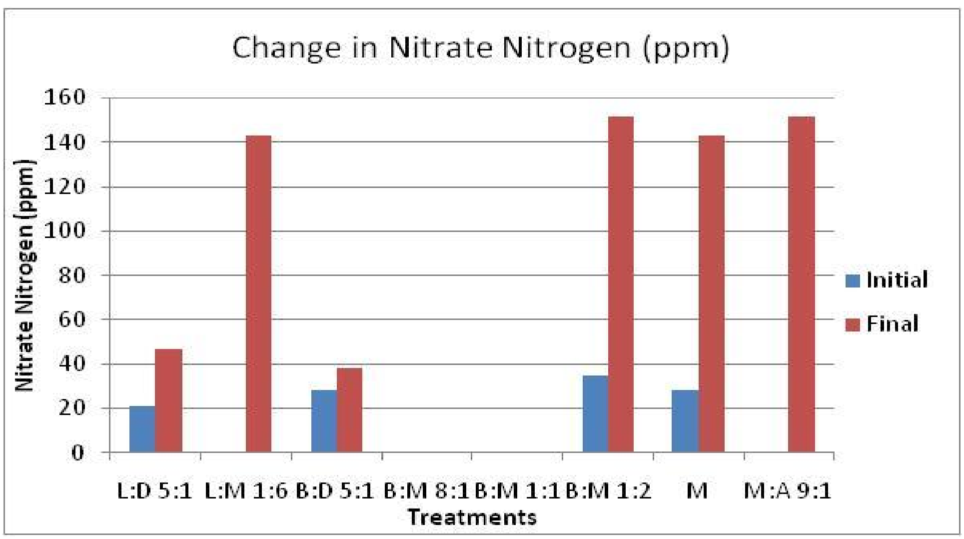


Figure 3.35 Change in nitrate nitrogen of different compost treatments

The treatments that were high in fiber content started with very high C/N ratio such as with treatments L:D 5:1, B:D 5:1, B:M 8:1 and L:M 1:6, which had C/N ratios of 79:1, 100:1, 127:1 and 60:1 respectively. These were followed by B:M 1:2 and L:M 1:6 having C/N ratios of 43:1 and 32:1, respectively, as they had lower fiber and more filter mud. The treatments with no fiber at all, started off with low C/N ratio of 21:1 and 24:1 which were M and M:A 9:1. However, by the end of the composting procedure, the C/N of all treatments dropped. The ones high in fiber dropped to a range of 34:1 to 30:1. These will be suitable to be used as soil conditioner, which includes treatments L:D 5:1, B:D 5:1 and B:M 8:1. However, treatments containing filter mud which are L:M 1:6, B:M 1:1, B:M 1:2, M and M:A 9:1. had a C/N ration ranging from 23:1 to 11:1, which make them suitable to be used as organic fertilizer. Changes in the C/N are shown in Figure 3.36.

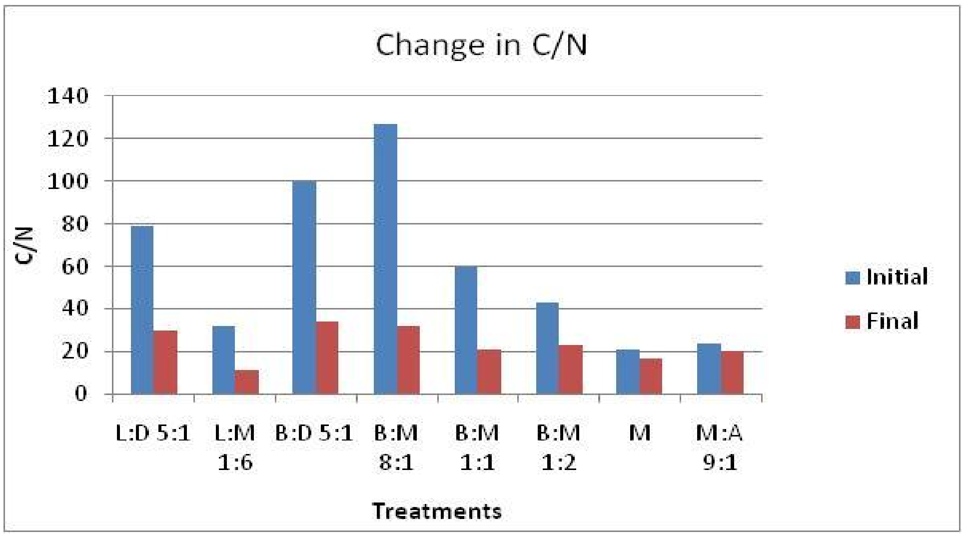


Figure 3.36. Change in C/N of different compost treatments

As for phosphorus, it increased with composting as a percentage for all treatments, but with decreasing rate as the amount of filter mud is increased, as shown in Figure 3.37. As for the change in phosphorus mass, it showed as increase for treatments numbers L:D 5:1,B:D 5:1, B:M 8:1 and small increase in B:M 1:2, but showed nearly no significant change in the remaining treatments L:M 1:6,B:M 1:1,M and M:A 9:1, as illustrated in Figure 3.38.

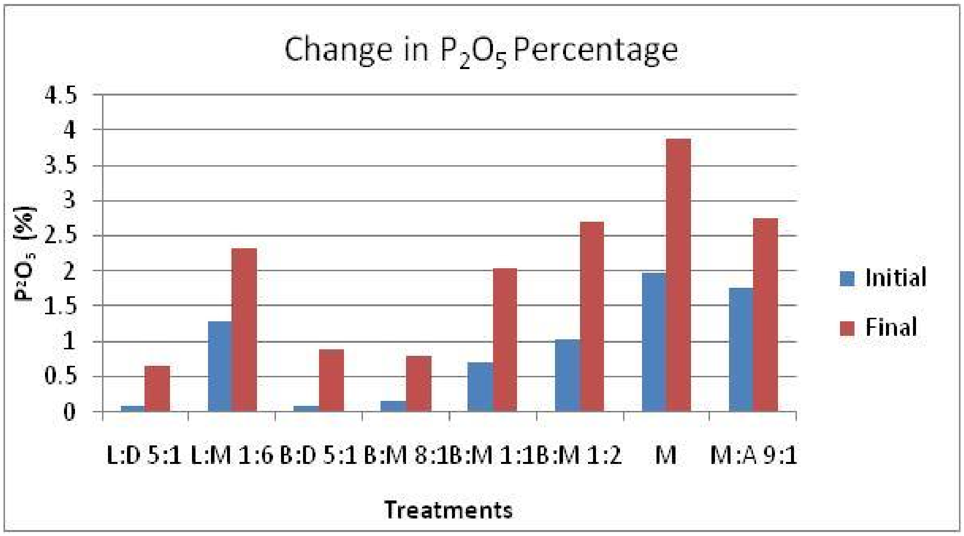


Figure 3.37. Change in percentage of phosphorus in different compost treatments

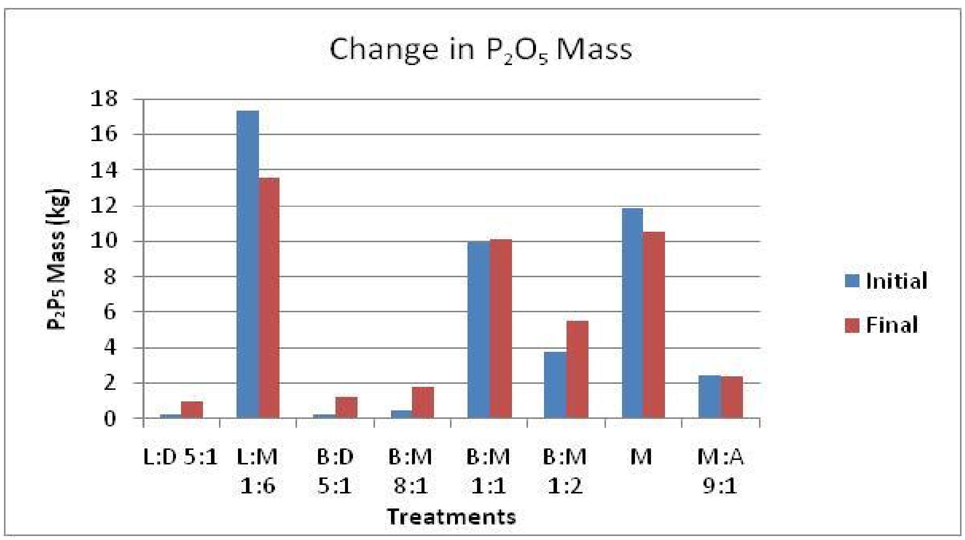


Figure 3.38. Change in mass of phosphorus in different compost treatments

As for potassium, treatments number L:D 5:1, B:D 5:1, B:M 8:1, B:M 1:2, M and M:A 9:1 witnessed an increase in the percentage of potassium with composting and a slight decrease for numbers L:M 1:6 and B:M 1:1. However, all treatments with the exception of treatment B:M 8:1, showed a decrease in the potassium mass content with composting. These relations are shown in Figures 3.39 and 3.40.

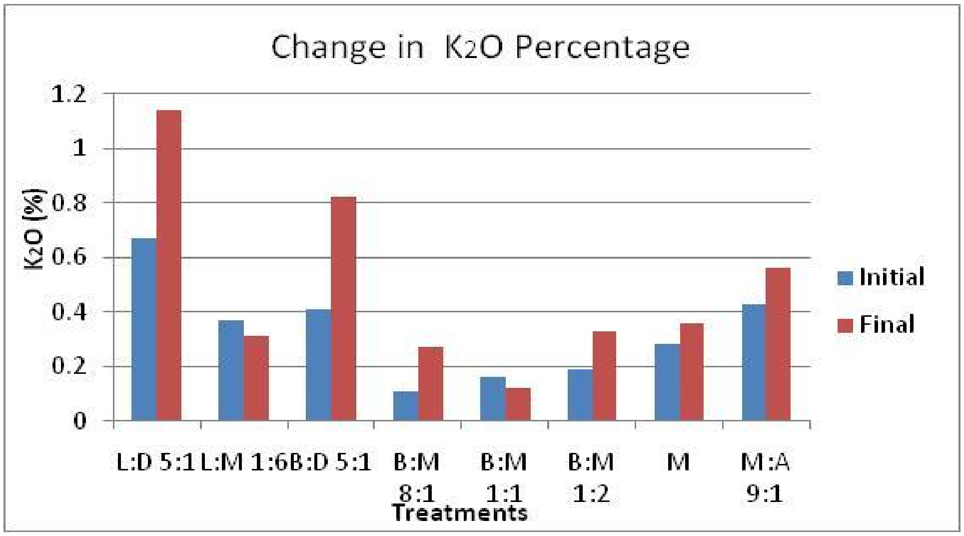


Figure 3.39. Change in percentage of potassium of different compost treatments

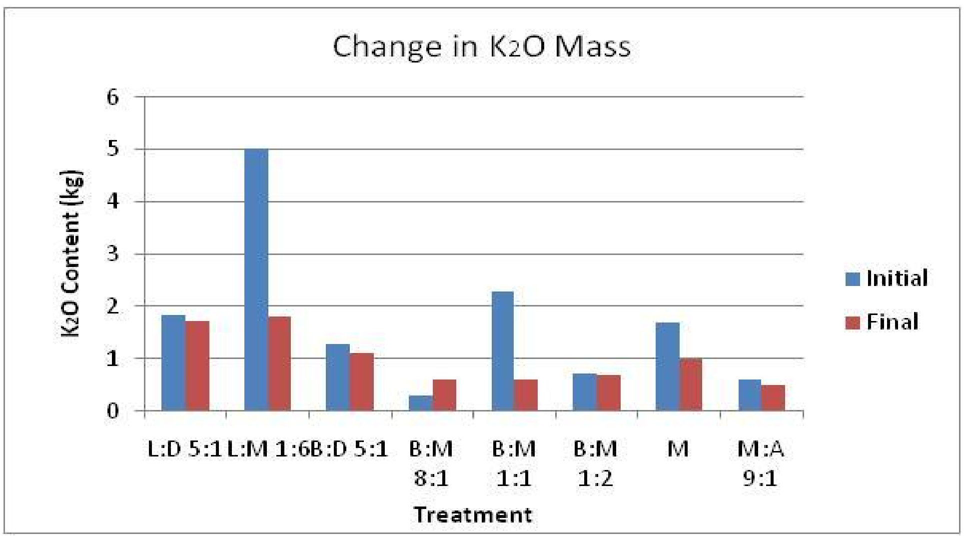


Figure 3.40. Change in mass of potassium of different compost treatments

Regarding the micro nutrients including calcium, magnesium, iron, manganese, copper and zinc, they all increased in concentration due to composting.

It can be also concluded from results of the analyses that at the start of the experiment, all treatments suffered from coliform bacteria (total and fecal) including salmonella and shigella bacteria and some had free nematode. However, all bacteria and nematode were destroyed during the composting process due to the high temperature reached during the thermophilic stages.

Moreover, all treatments after composting had a high water holding capacity (**WHC**) percentage as shown in Table 3.18. This is a favorable characteristic of composted material used as soil conditioner or organic fertilizer. Treatments with high fiber content had higher WHC.

Table 3.18. Measured water holding capacity of compost mixtures

Treatment	L: D 5:1	L: M 1:6	B:D 5:1	B:M 8:1	B:M 1:1	B:M 1:2	M	M:A 9:1
WHC (%)	434	212	448	771	492	689	303	331

3.4 Conclusion

Based on results of the pilot experiment, it can be recommended to the farmers of sugarcane to silage the green tops that resides from the harvesting process as it has a good nutritional value and silaging it would make use of the total amount produced and provide feed for their livestock for longer periods.

It is also recommended that the farmers shred the dry leaves and mix them with dung produced by their livestock and make compost out of the mixture to be used as a supplement to the synthetic fertilizers added to the soil.

The pilot experiment has also demonstrated that a variety of compost types and organic fertilizers can be produced from a combination of the residues generated from the sugar mills which are bagasse, filter mud and furnace ash. It depends on the amounts available in each sugar mill from each type residue. In all cases, the generated residues should undergo aerobic composting before being added to the soil as to improve its physical, chemical and biological properties as demonstrated in this research.

The compost or organic fertilizer produced in the sugar mills should be returned back to the sugarcane agricultural fields to replace a portion of the synthetic fertilizers currently used by the farmers.

Results of the pilot scale composting in terms of amount of nitrogen-phosphorus-potassium (NPK) associated with the production of each type of compost will be used in the life cycle assessment study as demonstrated in Chapter 5. The improvements to the environmental impacts associated with the sugarcane industry throughout its life cycle due to composting of the residues instead of their current disposal or reuse options will be identified and assessed.

Chapter 4
REVIEW OF LIFE CYCLE ASSESSMENT

4.1 Introduction

Life Cycle Assessment (LCA) is one of the tools of environmental management that include risk assessment, environmental performance evaluation, environmental auditing and environmental impact assessment. It is a useful tool to analyze interactions between human actions and the environment (Chauhan et al., 2011).

Life cycle assessment is defined by The International Organization for Standardization (ISO) as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040: 2006). Usually LCA considers the life stages of the product or activity starting from extraction and processing of raw material, manufacture, use (including maintenance), reuse and recycling, final disposal as well as transportation and distribution. It is also referred to as the “cradle-to-grave” approach.

Life cycle assessment is a well established tool that can be applied in industry, research and public policy (Azapagic and Perdan, 2011). It could be used in measuring environmental sustainability, comparison of alternatives to identify environmentally more suitable options, identification of “hot spots” to improve on processes, as well as product design and process optimization (Azapagic and Perdan, 2011).

LCA is an excellent tool in assessing the environmental sustainability of different industrial options, as it considers all impacts on the ecosystem and social system that could pose a threat for current and future generations (Contreras et.al. 2009).

4.2 LCA Phases

According to the ISO 14040 standards, LCA consists of four phases (Azapagic and Perdan, 2011) as shown in figure 4.1:

- Goal and scope definition which define the framework that all other LCA phases must comply with. It includes the statement of purpose of the study and its intended use as well as description of the system, its boundaries, its functional unit (or unit of analysis), data requirements and quality, impact assessment methodology, allocation procedure, assumptions and limitations (.

- Inventory analysis of all the inputs and outputs related to the product system including material, energy and emissions. Life cycle inventory (LCI) includes detailed definition of the system, data collection and validation, allocation of "environmental burdens in multiple-function systems" and estimation of burdens across the system.

- Life cycle impact assessment (LCIA) of the potential impacts associated with these inputs and outputs. LCIA includes selection of impact categories, category indicators and LCIA models, classification and characterization. LCIA includes three other optional steps which are normalization, grouping and weighting of impacts.

- Life cycle interpretation of the inventory data and impact assessment results related to the goal and scope of the study. It includes identification of the major burdens or impacts, detection of the "hot spots" in the life cycle, sensitivity analysis and evaluation of LCA findings and final recommendations.

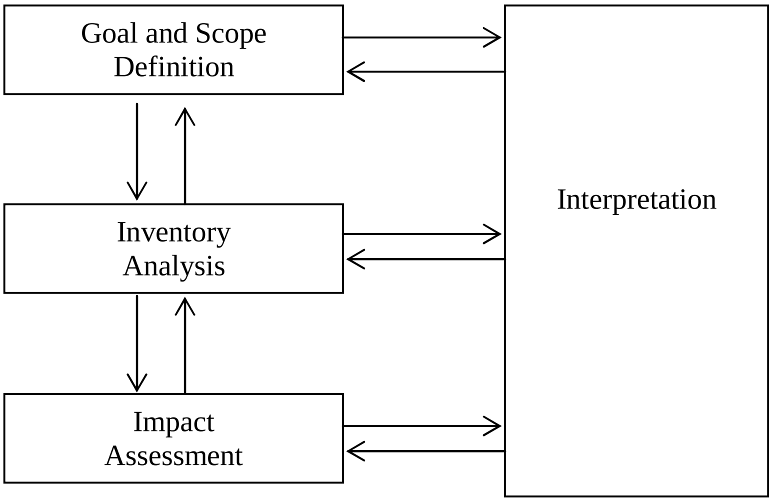


Figure 4.1. Life cycle assessment methodological framework (ISO 14040:2006 (E))

4.2.1 Goal and Scope Definition

The main purpose or goal of the LCA has to define whether the aim is to analyze the environmental performance of the product or process or to compare different products or processes.

The functional unit has to be identified as it will be the basis of calculation and comparison of the different systems fulfilling the same function. The functional unit must be measurable and when two products with different life spans are compared, it is important that the period of use must be considered (Sonnemann et al. 2004).

The system boundary specifies the range of the system under study and determines the processes and operations it comprises. The inputs and outputs to be considered must be recognized. The boundaries could be life cycle boundaries, geographical boundaries and/or environmental load boundaries. Life cycle boundaries will determine if the study is “cradle-to-grave” including the entire life cycle from prime material extraction until final disposal, or “cradle-to-gate” if the destination of the product is not known after manufacture or “gate-to-gate” if the assessment is restricted to the manufacturing process only. Geographical boundaries consider geographical limits to create confines of product system. As for environmental load boundaries, it could include one or a number of the following; air emissions, liquid emissions, solid waste, energy losses, noise, raw material.

The scope also defines the allocation procedures impact categories selected and methodology of impact assessment and subsequent interpretation to be used. It highlights data requirements, assumption, limitations, and type and format of the report required for the study.

4.2.2 Life Cycle Inventory Analysis

The life cycle inventory analysis (LCI) aims at identifying and quantifying the environmental burdens in the life cycle of the activity under study (Azapagic and Perdan, 2011). LCI is carried out for a unit process, which is considered as a "black box", and its inputs and outputs as shown in figure 4.2. Inputs to the unit process include products (components, materials, and services), natural resources (water, land, fossils etc.) and wastes for treatment. Outputs comprise of also products, waste and residuals to the environment such as air, water and soil pollutants as well as heat and noise (Curran, 2012).

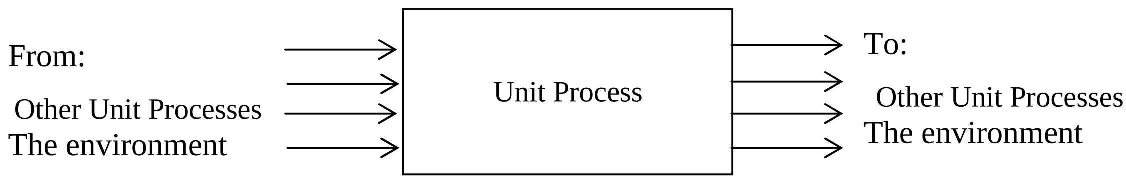


Figure 4.2. LCI of unit process (Curran, 2012)

Unit processes are the core or the central element of LCA, which are connected to form a system. For each unit process, quantitative data should be compiled in a clear manner, while synchronizing nomenclature and units. Following data collection, data should be validated, related to unit processes and related to the reference flow of the functional unit.

As industrial processes could yield more than one product, allocation of impacts to products should be done. Allocation in LCA means that the impacts are split between the multiple products generated from a process based on physical or economic ratios. System expansion (SE) is one method that avoids allocation and impact of production are related to marginal changes associated with increased demand of the product. Other more appropriate methods include economic allocation (EA) and mass allocation (MA). Economic allocation factors are based on the contribution of each product to the total economic value of all products using average values while mass allocation factors are based on relative mass of products as related to the total mass of products (Renouf et al., 2011).

4.2.3 Life Cycle Impact Assessment

The impact assessment phase uses the LCI results to evaluate the significance of potential environmental impacts. It involves correlating the inventory data with specific environmental impact categories and category indicators. The four steps of life cycle impact assessment (LCIA) (Graedel and Allenby, 2009), as presented in figure 4.3, are:

- Classification
- Characterization
- Normalization
- Valuation

Classification starts with compilation of the raw data on flows of material and energy or the inventory analysis. It consists of identification of environmental concerns recommended by the inventory analysis flow such as depletion of abiotic resources, climate change, human toxicity, terrestrial ecotoxicity, acidification and eutrophication.

Characterization quantifies the impacts resulting from the stress identified by the inventory values (Graedel and Allenby, 2009).

$$Sj = \sum_i Ci, j * Ej \qquad (4.1)$$

Where Ci,j is the "characterization factor" for species i and category j, Ej is the mass flow identified for species i in the inventory assessment and Sj is the category stress indicator for category j. Characterization does not show which impacts are more important. For example, the characterization factor for CO_2 in the impact category Climate change can be equal to 1, while the characterization factor of methane is 25. Hence, the release of 1 kg methane causes the same amount of climate change as 25 kg CO_2. The total result is expressed as impact category indicators.

Normalization relates the Sj values of characterization to a reference value Rj to arrive at a normalization indicator Nj.

$$Nj = Sj/Rj \tag{4.2}$$

The reference value is usually chosen by the organization conducting the LCIA. Nj being dimensionless, allows LCIA characterization to be comparable to each other. A generally used reference is "the average yearly environmental load in a country or continent, divided by the number of inhabitants" (Pre Consultants, 2010).

Valuation assigns weight factors (Wj) to the different impact categories based on their relative importance. Relative importance of impact categories is more of a political or social decision.

$$Wj = \Omega j \, Nj \tag{4.3}$$

where $\boldsymbol{\Omega}$j values are the weighing factors.

The overall life cycle impact assessment factor (I) is the summation of all impacts taking into consideration there relative importance and can be calculated as follows:

$$I = \sum_j Wj \tag{4.4}$$

The classification and characterization stages of the assessment are considered mandatory elements of the LCA to generate results as shown in figure 3.3. Normalization and weighting are extra optional elements that would enhance the analysis provided that the reference value for normalization has been determined by the country or organization conduction the LCA and the relative importance of impact categories are identified.

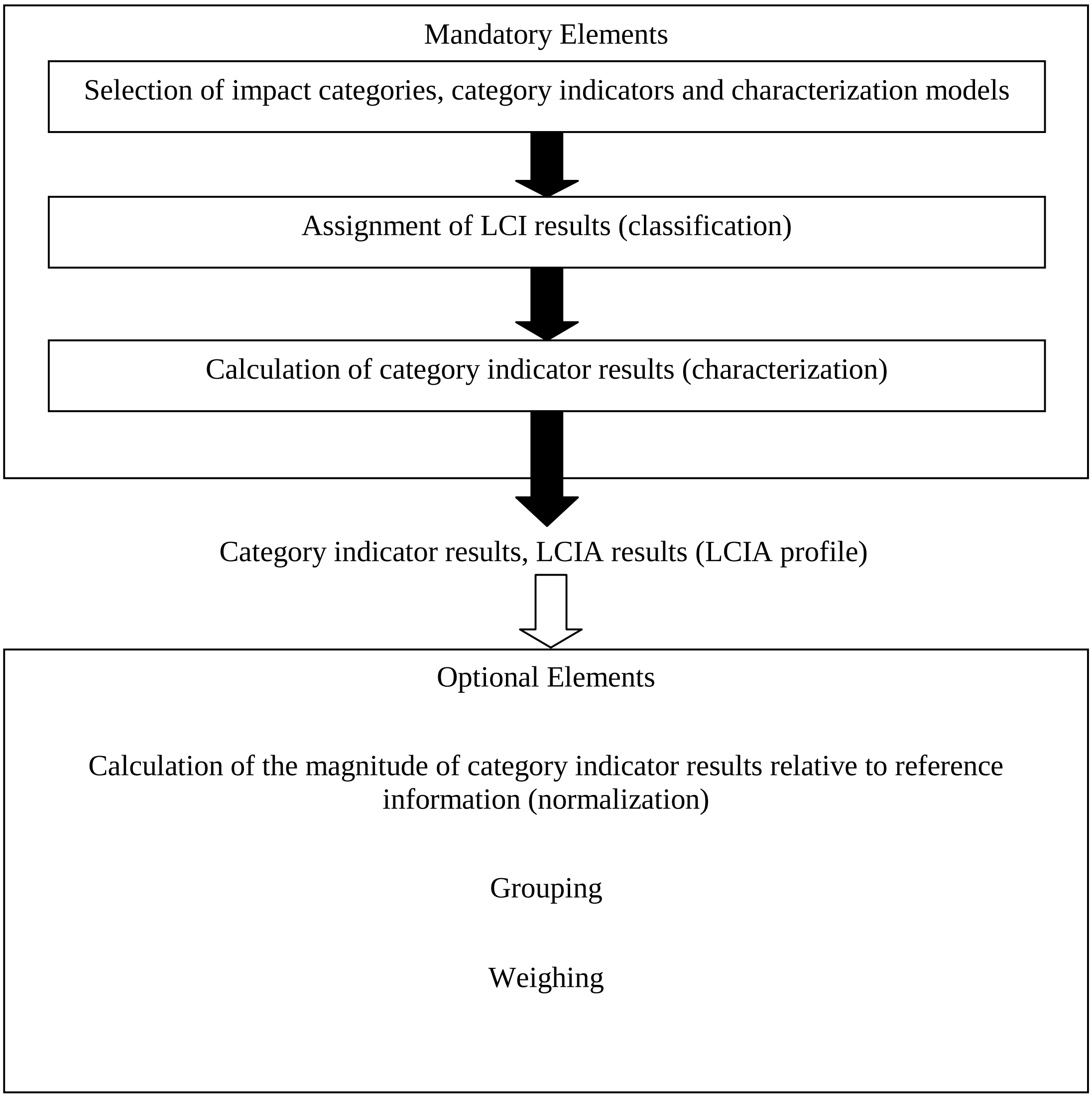


Figure 4.3. Mandatory and optional elements of LCIA phase (ISO 14040:2006)

4.2.4 Interpretation

Interpretation of the LCA results is the final step to identify major burdens and impacts, highlight "hot spots" in the life cycle, conduct sensitivity analysis and evaluation of LCA findings and final recommendations (Azapagic and Perdan, 2011).

4.3 Overview of LCIA Methodologies

There are a number of life cycle impact assessment (LCIA) methods that have developed over the years by several organizations in different countries. Each method uses different characterization models, normalization factors and weighting factors and hence yield different results. The selection of the impact methods to use depends on the goal and scope set for the LCA study.

LCIA methods can generally be divided into "midpoint approach" or "end point approach". The midpoint approach, also called the problem-oriented approach", aggregates the environmental burdens according to its relative contribution to the environmental impacts that they cause (Azapagic and Perdan, 2011). For example, carbon dioxide emissions are linked to the cause of global warming potential. As for the endpoint approach, also called damage-oriented method, relate the environmental burdens and impacts to 'areas of protection' such as human health, biotic and abiotic environments and human health. A number of multi issue as well as single issue methods are described below.

4.3.1 Eco-indicator 99

Eco-indicator 99, developed by Pre Consultants in Netherlands, is a damage oriented method linking midpoint and endpoint impact categories based on European environmental conditions (Curran, 2012). The types of damage considered in this method include damage to human health expressed as disability adjusted life years (DALYs), percentage damage to ecosystem quality represented as potentially disappeared fraction (PDF) of species in a certain area and time and finally damage to mineral and fossil resources expressed as additional energy in mega joules required to extract future lower grade ores (Azapagic and Perdan, 2011).

Damage to health category comprises indicators of carcinogenesis, respiratory effects, ionizing radiation, ozone layer depletion, and climate change. It is calculated by carrying out fate analysis to link emissions to temporary change in concentration, exposure analysis to link temporary concentration change to dose, effect analysis to link dose to health effects which are finally linked to DALYs by damage analysis using estimates of number of years lived disabled and years of life lost (Azapagic and Perdan, 2011).

Damage to ecosystem quality includes the indicators toxicity, acidification and eutrophication as well as land use and land transformation. It can be calculated by fate, effect and damage analysis or related to type of land use and land area. As for damage to resources, it involves depletion of mineral and fossil fuels. It is modeled in two steps; resources analysis and damage analysis (Azapagic and Perdan, 2011).

4.3.2 IMPACT 2002+

IMPACT 2002+, originally developed at the Swiss Federal Institute of Technology - Lausanne (EPFL), is a combined midpoint/damage approach as it links fourteen midpoint categories to four damage categories as shown in figure 4.4 (Pre Consultants, 2010).

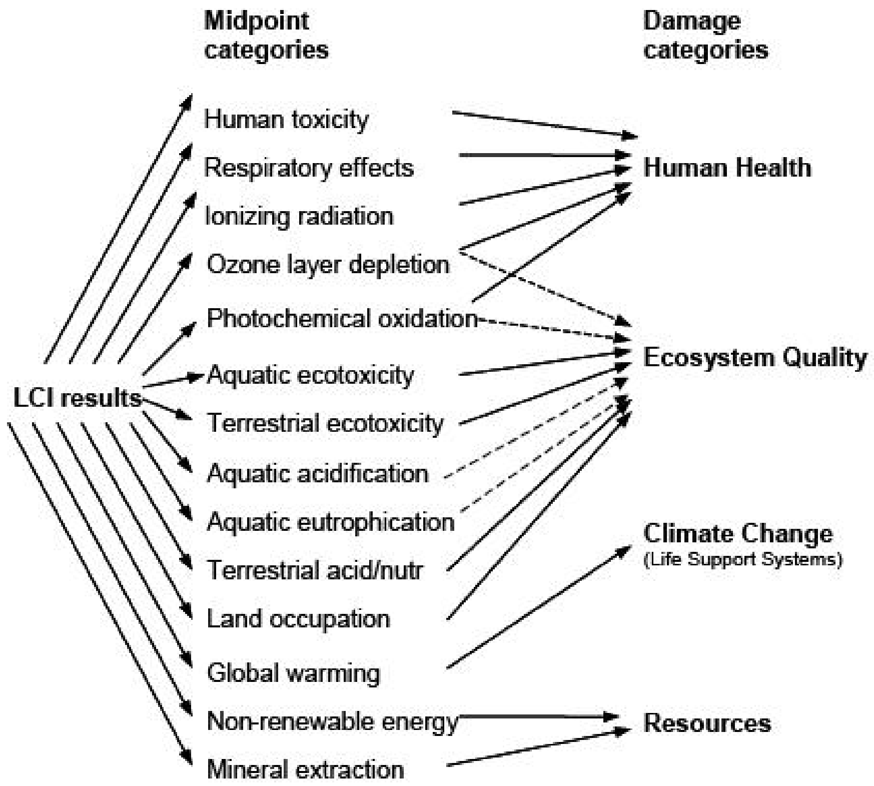


Figure 4.4. IMPACT 2000+ Framework (Pre Consultants, 2010)

4.3.3 CML 2 Method

In this method, which is considered a problem oriented method, environmental burdens are grouped according to their relative contribution to the environmental impact that they can cause including abiotic resource depletion, global warming, ozone depletion, acidification, eutrophocation, photochemical oxidant formation, human toxicity and eco-toxicity (Azapagic and Perdan, 2011). These impacts are considered “potential” rather than “actual” as they are quantified at intermediate position between environmental intervention and damage caused rather than endpoint. CLM 2002 was developed by Leiden University’s Institute of Environmental Sciences (CML) in the Netherlands with the aim of operationalizing the ISO14040 standards (Curran, 2012).

4.3.4 ReCiPe

ReCiPe 2008 is a method that integrates the ‘problem oriented approach’ of CML-IA and the ‘damage oriented approach’ of Ecoindicator 99. The ‘problem oriented approach’ defines the impact categories at a midpoint level which provides results of low uncertainty but leads to many different impact categories making it hard to draw conclusions. Ecoindicator 99, on the other hand, results in only three impact categories, making easier to draw conclusion but with higher uncertainty. ReCiPe, therefore, takes the advantage of both by implementing both strategies and having both midpoint and endpoint impact categories as shown in figure 4.5. The midpoint characterization factors are multiplied with a damage factor to obtain the endpoint characterization values (Pre Consultants, 2010).

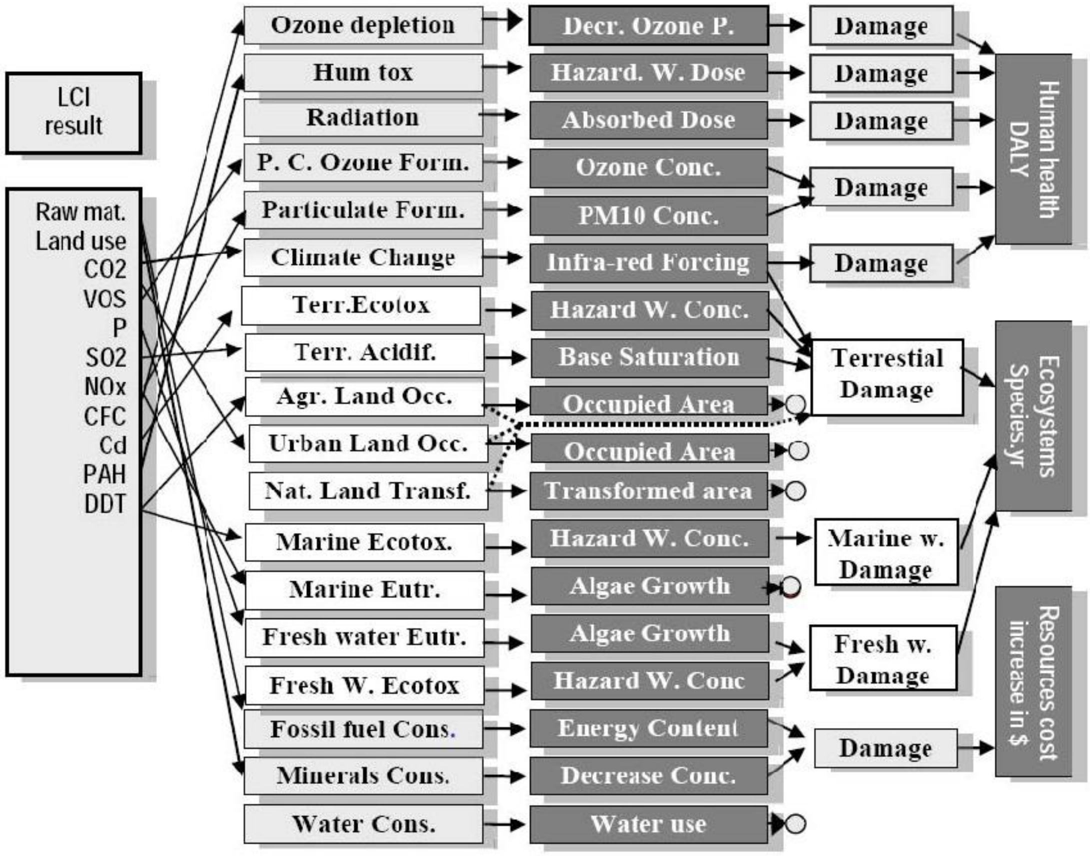


Figure 4.5. RECIPE relation between midpoint categories and endpoint categories (Pre Consultant, 2010)

ReCiPe 2008 and Eco-indicator 99 methods have three different versions: individualist (I), heirarchist (H) and egalitarian (E). The simplified characteristics of these methods are shown in table 4.1.

Table 4.1 Simplified characteristics of different perspectives (Goedkoop et al., 2000)

Perspective	Time Perspective	Manageability	Required Level of Evidence
Egalitarian (E)	Very long term	Problems can lead to catastrophy	All possible effects
Individualist (I)	Short term	Technology can avoid problems	Only proven effects
Hierarchist (H)	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus

4.3.5 Ecological Footprint

The ecological footprint (EF), which is a single issue method, is defined as "the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption" (Pre Consultants, 2010). The ecological footprint of a product is the sum of that related to direct and indirect land occupation (EF_{direct}), nuclear energy use ($EF_{nuclear}$) and to CO_2 emissions from fossil energy use (EF_{CO2}). This method does not include normalization and each impact is given a weighing factor of 1.

$$EF = EF_{direct} + EF_{nuclear} + EF_{CO2} \quad (4.5)$$

4.3.6 Greenhouse Gas Protocol

The Greenhouse Gas Protocol (GHG Protocol) is developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). GHG Protocol calculates carbon dioxide equivalents (CO_2e) of all non-CO_2 gases (CH_4, N_2O, SF_6, HFCs, CFCs) used and reports on the most recent 100-year Intergovernmental Panel on Climate Change (IPCC) global warming potentials (GWP) which is "a metric used to describe the time-integrated radiative characteristics of well mixed greenhouse gases over a 100-year time horizon" (Pre Consultants, 2010).

The total GHG emissions for a product inventory shall be calculated as the sum of GHG emissions, in CO_2e, of all foreground processes and significant background processes within the system boundary. A distinction is made between:

• GHG emissions from fossil sources
• Biogenic carbon emissions
• Carbon storage
• Emissions from land transformation

According to the standard on product accounting, GHGs from fossil and biogenic emissions must be reported independently. The reporting of the emissions from carbon storage and land transformation is optional.

4.3.7 IPCC 2007

IPCC 2007, an update of the method IPCC 2001, was developed by the International Panel on Climate Change. It registers the climate change factors of the Intergovernmental Panel on Climate Change (IPCC) with a timeframe of 20, 100 and 500 years.

IPCC characterization factors does not include indirect formation of dinitrogen monoxide (N_2O) from nitrogen emissions, CO_2 formation from CO emissions and does not consider biogenic CO_2 uptake and emission, but only considers the biogenic methane release. There is no normalization of weighting for this method.

4.4 LCA Studies Related to Sugarcane Industry in Sugarcane Producing Countries

Life cycle assessment was carried out for the sugarcane industry in a number of sugar producing countries such as Brazil, Thailand, Australia, Cuba, South Africa and Mauritius. The LCA was conducted to sugar cane planting, harvesting, milling and for the reuse options of its important by-product; bagasse.

A LCA study was carried out for the combustion of bagasse to generate electricity in Mauritius as compared to other forms of electricity production. The LCA showed that net avoided emissions of CO_2 due to the use of bagasse are equivalent to 15% of all fossil fuel emissions on the island. Moreover, the environmental impact of the cane cultivation, including fertilizer and herbicide manufacture, is five times that of the electricity generation in the power plant. Sensitivity analysis showed that measures that would reduce impacts are effective control of fly ash emissions from the boiler, optimization of fertilizer and herbicide use and effective irrigation to reduce water consumption. Bagasse-derived electricity, as compare to fossil fuel-derived electricity, has benefits in terms of greenhouse emissions, acidification, human toxicity, summer smog and non-renewable energy output but have drawbacks as related to freshwater consumption and eutrophication (Ramjeowon, 2008).

Contreras et al. (2009) used LCA to perform a comparison of four different alternatives for the use of by-products and wastes of sugar production in Cuba. The environmental advantages of producing alcohol, biogas, animal food and fertilizers from cane sugar by-products were investigated. Environmental impacts of the four different alternatives were assessed by using Eco-indicator 99 methodology to identify and quantify the aspects which have the largest environmental impact in each alternative and propose improvements in the systems. In the four alternatives the inputs to the agricultural stages were the same, except for fertilizer consumption, which varied according to by-product usage. The first alternative represented the conventional sugar production where synthetic fertilizers and pesticides are used in agriculture and bagasse produced from the milling process was combusted and molasses and agricultural wastes were used as animal fodder. Other wastes such a filter cake, furnace ash and wastewater were disposed to the environment. The other three alternatives tended to more use of by-products and waste streams as second alternative considered the use of wastewater, filter cake and ash to substitute synthetic fertilizers. Alternative three investigated biogas production from filter cake and wastewater and alternative four integrated alcohol and biogas production in the overall process. The cane sugar was considered as main product contributing to the total environmental load while the by-products were considered to substitute other products in the market (avoided products). The system boundaries included the production of the avoided products and their environmental load was subtracted from the total environmental load of the process. The fourth alternative showed the best results from the environmental perspective due to improved resource consumption pattern (Contreras et al., 2009).

Kiatkittipong et al. (2009) carried out a life cycle assessment of a four bagasse waste management options in Thailand; (1) landfilling with utilization of the landfill gas, (2) incineration for power generation, (3) anaerobic digestion for biogas production and (4) pulp production. The environmental aspects that were compared were global warming potential, acidification potential, eutrophication potential and photochemical oxidant reaction. The bagasse reuse options were compared to conventional systems for supply of electricity from grid power plant and production of pulp from eucalyptus. In this study, using bagasse for pulp production had the smallest overall impact significantly lower than the production of pulp from eucalyptus. Landfilling was the least preferred as it consumes land space and generated considerable quantities of CH_4 and NH_3 that could affect the global warming potential and photochemical smog if not properly controlled. As for bagasse incineration for power, it had lower environmental impacts than power generation from fossil fuel except in terms of photochemical oxidant potential. Among the three energy recovery systems, anaerobic decomposition gave the best environmental performance (Kiatkittipong et al., 2009).

A life cycle assessment study was conducted for the products resulting from Australian sugarcane including raw sugar, molasses, electricity (from bagasse combustion) and ethanol (from molasses) (Renouf et al., 2011). The LCA compared three models of sugar mills; (1) a conventional mill producing raw sugar and molasses (used in animal feed) and burning bagasse for produce steam and electricity for the mill, (2) upgraded sugar mill similar to the conventional but with upgraded boiler to increase efficiency of bagasse combustion and export excess electricity to the grid, (3) upgraded sugar mill with cogeneration but also producing ethanol from molasses fermentation and stillage as a co-product. Impact assessment method used was based on Impact 2002+ model including global warming potential (GWP), terrestrial and aquatic acidification potential (AP(ter)) and AP(eq)), eutrophication potential (EP), respiratory in-organics (RI), respiratory organics (RO), water use and land use. The LCA concluded that assessment results for Australian sugarcane products depended on the nature of the cane processing system and the range of products produced, variability in sugarcane growing and the allocation methodology. Using mass allocation factors in Renouf et al. LCA (2011), raw sugar was assigned 94.9% of the impacts and molasses 5.1%, while they were assigned 96 % and 4% respectively using economic allocation. Bagasse, was totally consumed in the mill to produce steam and electricity and so was not included in the allocation. The filter mud/cake and ash were also considered of no economical value and hence not considered as a co-product. Renouf et al. (2011) concluded that system expansion (SE) is suitable for sugar cane as a product but not for the other by-products. Mass allocation (MA) was found to be the most suited to sugarcane products as it is straightforward and provides a suitable representation of the physical relationship between the different products. Economic allocation (EA) could be troublesome as it is prone to fluctuation in prices.

Another LCA was conducted to identify and quantify the main environmental impact potentials of the sugar cane bagasse energy generation, transmission and distribution in Brazil to identify improvement opportunities (Lopes Silva et al., 2012). The study reached the conclusion that straw burning practice implemented prior to harvesting should be stopped to improve the photochemical ozone and human toxicity indicators. This will also benefit the global warming potential as emissions of hydrocarbons, methane and carbon monoxide will be eliminated. If the straw is used instead to improve soil conditions, it will improve nutrient enrichment potential.

Mashoko et al. (2013) tried to verify the environmental benefits of power production from bagasse through the development of life cycle inventories for the South African sugar industry. The model was based on a power output of 150 kWh per ton of bagasse. The study proved that bagasse electricity results in higher energy gain than coal and shows significant environmental benefits especially at higher efficiencies. When coal was burnt instead of bagasse, generation of electricity in mills accounted for most GHG emissions and sulfur dioxide emissions. Transportation of cane to the mills also contributed to non carbon dioxide emissions. The agriculture phase contributed to emissions, non renewable energy consumption and water use. Reduction of impacts during agriculture phase can be achieved by reducing the use of inorganic fertilizer and instead use sugar industry organic products such as filter cake as well as optimizing the amount of irrigation water used.

Poopak and Reza (2012) carried out a LCA for the production of paper from non-virgin material (bagasse) in Iran to evaluate the environmental performance of the process and identify inputs that have environmental potential from the paper making. In this study, CMLBaseline2000 method was used for LCIA. The study concluded that the fossil fuel used for power in the paper mill, fuel oil in this case, had the highest contribution to abiotic depletion and global warming potential. Kraft pulp contributed to acidification impact, eutrophication and toxicity impacts while chlorine used in bleaching was responsible for ozone layer depletion impact. The bagasse had a positive impact on global warming but highest impact on photochemical oxidation. It was therefore recommended to replace the fuel oil by another environmental friendly energy source, use another chemical for bleaching other than chlorine and recycle paper instead of using Kraft as raw material.

4.5 Conclusion

This Chapter introduced the concept of life cycle assessment that the researcher is going to use in Chapter 5 to assess the life cycle environmental impacts associated with the sugarcane industry in Egypt starting with the current practices of cane plantation, harvesting, milling and management of the wastes and residues generated from each stage. This will include use of chemical fertilizers, burning of the dry leaves, direct application of filter mud and ash as soil conditioners, as well as use of bagasse for steam and electricity generation within the mills as opposed to fossil fuels or use of bagasse to make fiberboard or paper.

The baseline scenarios will be compared to proposed environmental friendly practices that were experimented on a pilot scale and the results of which are included in Chapter 3. These include making compost and silage animal feed out of a combination of residues including dry leaves, bagasse, filter mud and ash. The impacts associated with replacing synthetic fertilizers with organic fertilizer will be investigated. The utilization of bagasse in compost of silage will be also compared to its use as fuel within the mill or as fiber in neighboring industries to make paper or fiberboard.

Chapter 5
LIFE CYCLE ASSESSMENT OF THE SUGARCANE INDUSTRY IN EGYPT

5.1 Introduction

The sugarcane industry in Egypt consumes water, energy and material and generates a number of products, by-products and waste streams, as well as emissions. The environmental impacts associated with the different phases of sugarcane production in Egypt have never been quantified. Cane cultivation involves the use of fertilizers, water and fuel for irrigation while harvesting results in green tops and dry leaves. Cane transportation consumes fuel to transport the cane to the mill either by train or lorry. Sugarcane milling involves the use of a number of chemicals for sugar extraction and purification and consumes fuel for generation of electricity and steam. The fuel used in milling is either bagasse generated from cane squeezing, or fuel oil or natural gas depending on their availability. Sugarcane milling also generates filter cake/mud from juice purification and furnace ash in case the bagasse is burnt for power. Bagasse, that is not burnt to produce steam and electricity, is used in Egypt in fiberboard making and pulp and paper production. Agricultural and milling residues could also be used to make animal fodder or compost and organic fertilizer. Each waste management or reuse option for these residues has its unique environmental impacts associated with it.

The aim of this research is to achieve environmental sustainability of the sugarcane industry in Egypt or to reach an “environmentally balanced” industry. To achieve this aim, life cycle assessment (LCA) was used to achieve the following goals: (1) assess the environmental performance of the sugarcane industry in Egypt starting from cane plantation, harvesting, transportation, and milling including environmental improvements that are associated with proposed residue management options, and (2) assess the environmental impacts associated with current bagasse reuse options. The scope, system boundaries and functional unit(s) for each goal were defined.

Life cycle assessment was performed according to the international standards ISO14040:2006 (Environmental management- life cycle assessment- principles and framework) and ISO 14044:2006 (Environmental management- life cycle assessment- requirements and guidelines), as described in Chapter 4. LCA was carried out using LCA software package SimaPro version 7.3.3. for Faculty developed by Pre Consultants, the Netherlands.

Collecting data to form the life cycle inventories (LCI) is the most important stage of the LCA application because it affects the remaining stages and final results of the analysis. As mentioned in Chapter 1, data was collected from primary and secondary sources including interviews, questionnaires, field visits as well as published reports and journal articles. The data was verified by cross checking it from a number of national and international sources. All data sources and assumptions used to form the LCI are included in the relevant sections of this chapter. Moreover, life cycle inventories published in journal articles, dissertation thesis and reports related to sugarcane cultivation, sugar production, fiberboard and paper manufacturing were used as a guide to establish the life cycle inventories for similar processes.

The impact assessment method used in this study is Recipe 2008 version 1.01, using midpoint indicators, hierarchist (H) and world normalization factors. It was used as it was set up in SimaPro 7.3.3. As mentioned in Section 4.3.4, Recipe 2008 provides results at both midpoint and endpoint levels. This study uses midpoint results. The hierarchist (H) version is used as it is based on the consensus building processes and as a balance between short and long term perspectives. The impact categories and their corresponding units reported in Recipe 2008 method are (Goedkoop et al., 2009):

- Climate change, kg CO_2 (carbon dioxide) to air
- Ozone depletion, kg CFC-11 (chlorofluorocarbon) to air
- Human toxicity, kg 1,4-DCB (dichlorobenzene) to urban air
- Photochemical oxidant formation, kg NMVOC (non methane volatile organic carbon) to air
- Particulate matter formation, kg PM_{10} (particulate matter less than 10 µm) to air
- Ionising radiation, kg U235 (Uranium) to air

- Terrestrial acidification, kg SO_2 (sulfur dioxide) to air
- Freshwater europhication, kg P (phosphorus) to freshwater
- Marine eutrophication, kg N (nitrogen) to freshwater
- Terrestrial ecotoxicity, kg 1,4-DCB (dichlorobenzene) to industrial soil
- Freshwater ecotoxocity, kg 1,4-DCB (dichlorobenzene) to freshwater
- Marine ecotoxicity, kg 1,4-DCB (dichlorobenzene) to marine water
- Agricultural land occupation, m^2x yr agricultural land
- Urban land occupation, m^2x yr urban land
- Natural land transformation m^2 natural land
- Mineral resource depletion, kg Fe (iron) equivalent
- Fossil fuel depletion, kg oil equivalent

Results of the assessment will be presented as normalize results. The weighted results are not presented as they are subject to the views of the particular group of panel (Recipe 2008 method) and may not apply to the Egyptian context specifically. Also, as it is difficult to define normalization factors for Egypt, the normalized factors used in this study are based on world population (as set up in Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3).

5.2 LCA of Sugarcane Plantation, Harvesting and Milling

5.2.1 Goal and Scope

The ***first goal*** of the study is to quantify the environmental impacts of a typical sugarcane production process in Egypt starting from cane plantation, harvesting, transport to the sugarcane mill and finally sugarcane milling to produce sugar and molasses. This includes the current practice of dry leaves burning post harvesting and the production the mill's steam and electricity by using bagasse as a source of fuel. This base model, shown in Figure 5.1, is compared to the following alternative models as per Figure 5.2:

1. Dry leaves are not burnt but instead shredded, mixed with cattle dung and made into compost in the field and added as soil conditioner having some nutrients decreasing the amount of synthetic fertilizers used in cane plantation.

2. In addition to dry leaves composting, filter mud and furnace ash composting in the mill is done to produce high quality organic fertilizer that is directly applied to the sugarcane fields also reducing considerably the amount of synthetic fertilizers currently used.
3. In addition to dry leaves composting, composting all the amount of bagasse resulting from milling operations and mixing it with filter mud to be used as soil conditioner instead of using it as a source of fuel to produce steam and electricity. In this case, either natural gas or heavy fuel is used as fuel in the mill.

The ***system boundary*** consists of the growing and harvesting of the sugarcane all the way to the production of sugar and molasses and co-generation of electricity from bagasse at the sugar mills. The following subsystems are considered:

- Agricultural stage including cane cultivation, harvesting and transport of **10 tons** of planted cane (***functional unit***). Cane cultivation includes irrigation and application of fertilizers. Harvesting is done manually and the dry leaves and green tops are separated from the cane. The current practice is burning of the dry leaves in the fields and transporting of the green tops to the farmers‘ barns to be consumed by the livestock as animal feed. The cane is transported to the sugar mill mainly by the mills‘ trains or trucks.
- The industrial stage which is based on a ***functional unit*** of **1 ton of sugar and 400 kg molasses** produced. The bagasse resulting from cane squeezing activities is usually used within the sugar mill for steam and electricity generation. Bottom and fly ash resulting from the bagasse burning in the furnace is sold to an external contractor along with the filter mud resulting from juice clarification process to be used as soil additive. The process of sugar production involves the use of chemicals, water and some fossil fuel to enhance the bagasse burning process.

The assessment is ***cradle-to-gate*** as all product or waste management activities happening outside the boundaries of the agriculture field or sugar mill is not considered in the LCA. The subsystems excluded, therefore, are:

- Sugar and molasses transport to other consumers
- Green tops, filter mud and ash transport to other consumers

- Production of cuttings or setts used for sugar cane plantations
- Road and rail transportation infrastructure
- Production, maintenance and decommissioning of capital goods such as buildings and machinery

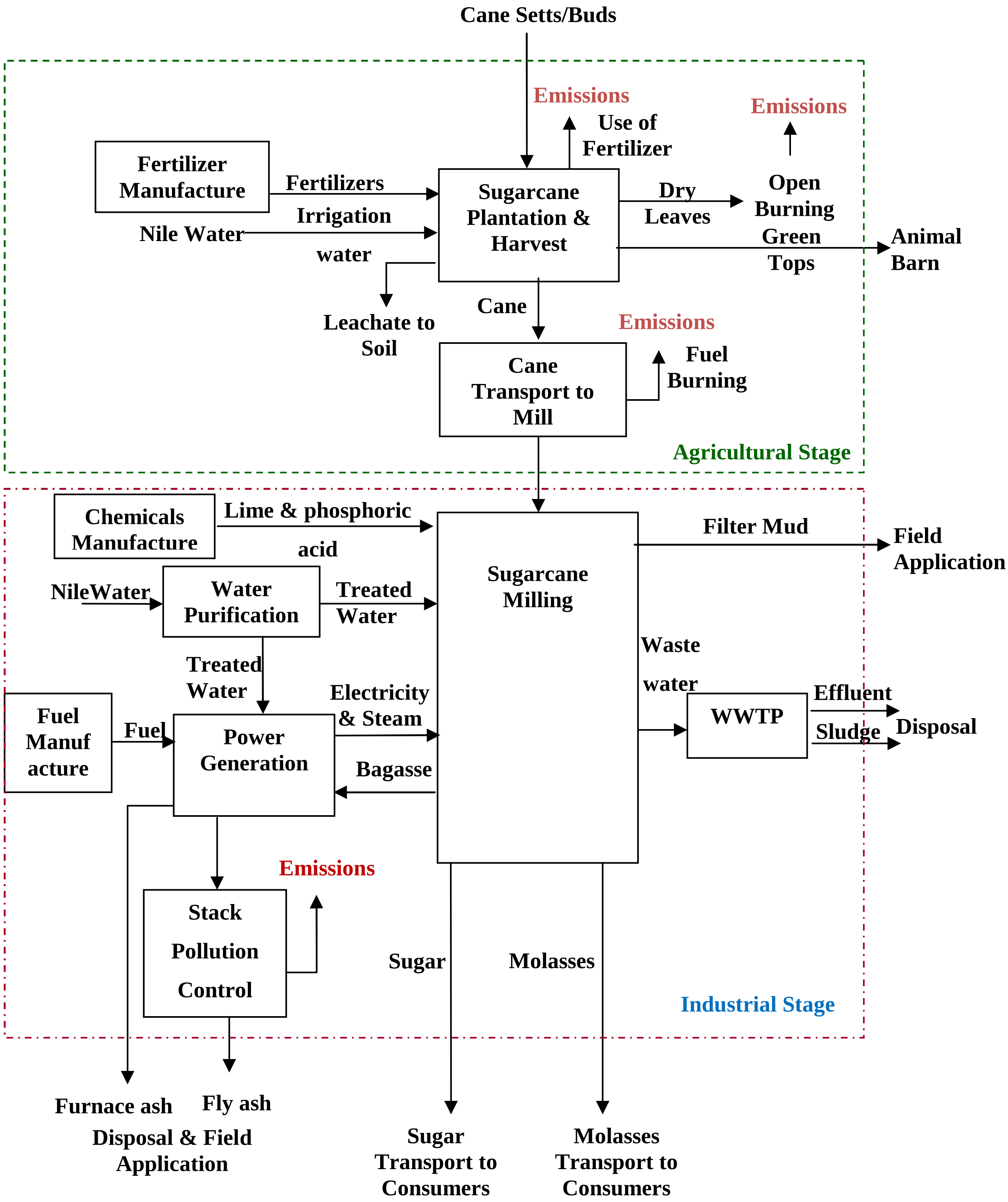
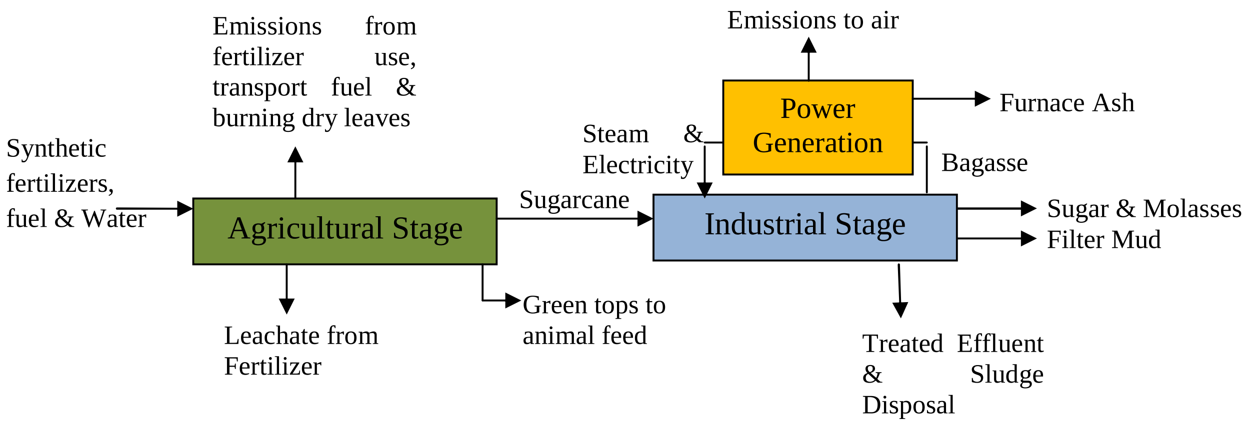
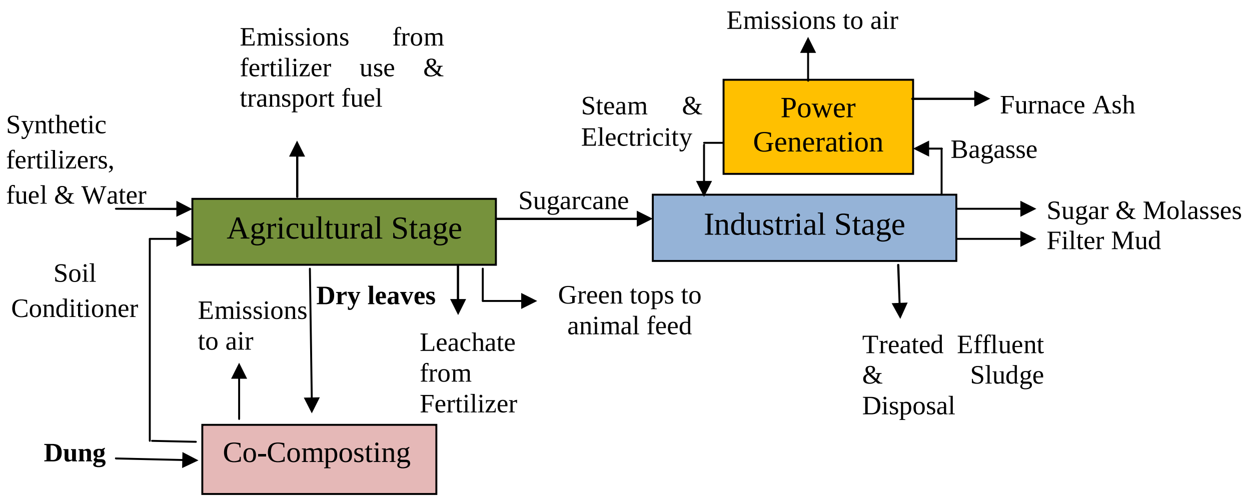


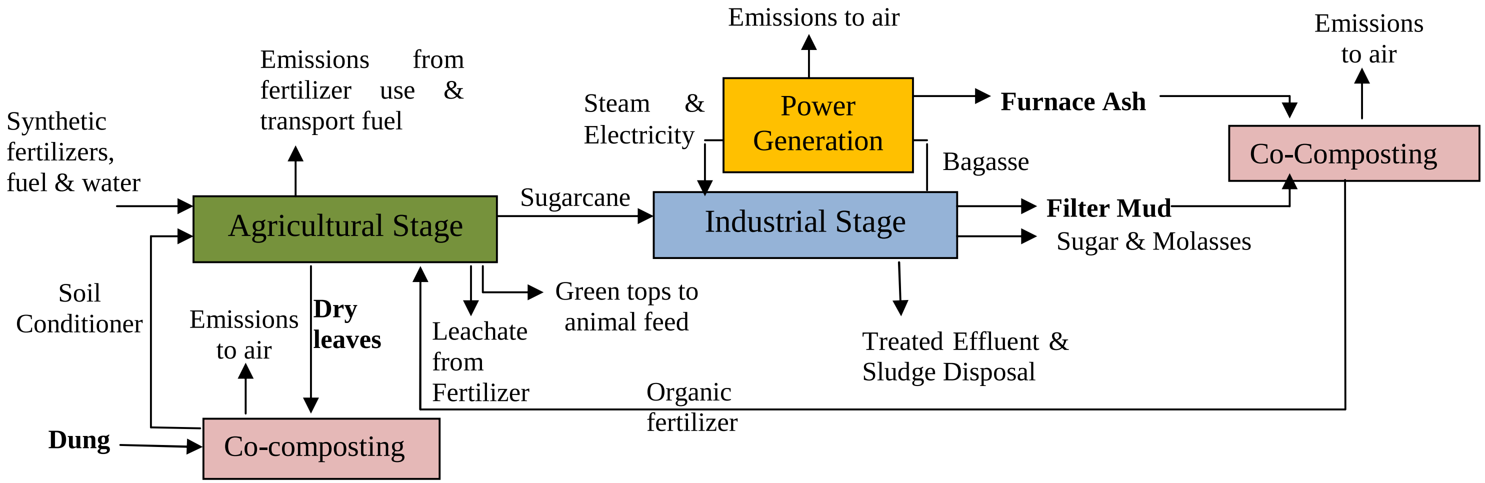
Figure 5.1. Scope of the sugarcane life cycle assessment (base model)



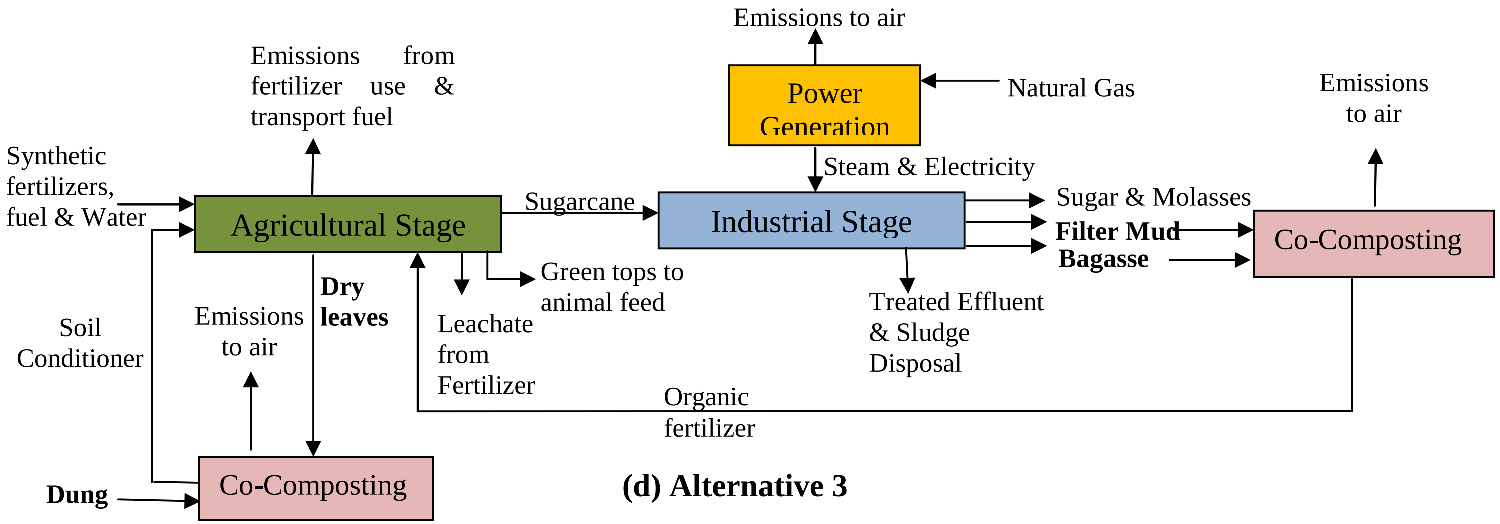
(a) Base model



(b) Alternative 1



(c) Alternative 2



(d) Alternative 3

Figure 5.2 Schemes of (a) base model, (b) alternative1, (c) alternative 2 and (d) alternative 3

5.2.2 *Life Cycle Inventory (LCI)*

Cane cultivation takes place from June to January and harvesting starts from December until May. Sugar cane milling takes place during the cane harvesting period as the harvested cane is immediately processed to produce sugar.

The main inputs to the sugar cultivation stage are the fertilizers supplying the soil with the NPK components (nitrogen, phosphorus and potassium). There are other trace components that could be added, such as iron and manganese, but are usually present through natural sources such as manure. According to the Ministry of Agriculture Land and Water Research Institute, nitrogen is added as 550 units/hectare/year in the form of urea or ammonium nitrate, phosphorus (P_2O_5) as 107 units/hectare/year in the form of triple phosphate or mono phosphate depending on availability and potassium (K_2O) is applied as 114 units/hectare/year as potassium sulfate. As for chemical pesticides, they are no longer used in Egypt as biological control is used to get rid of pests. According to the Intergovernmental Panel on Climate Change (IPCC, 2006), emissions to air the associated with fertilizer application are nitrous oxide (N_2O) and nitrogen oxides (NOx). Moreover, phosphorus and nitrates are expected to leach from the soil to groundwater and reach surface water.

Harvesting is done manually and results in two waste streams: cane tops, which are taken by the farmers to be used as animal feed, and dry leaves that are burned in the fields. These waste streams amount to about 25% of the harvest. Emissions associated with open burning of leaves include sulfur dioxides (SO_2), nitrogen oxides (NOx), particulate matter (PM), total organic carbons (TOC), as well as carbon monoxide (CO), which is considered biogenic as it is emitted from the burning of biomass.

When the dry leaves are used to make compost instead of burning, which is the case in alternatives models 1, 2 and 3, the emissions resulting from leaves burning will cease to exist and instead emissions associated with composting are added. These emissions include biogenic carbon dioxide and methane, as well as nitrous oxide. Carbon dioxide emissions resulting from biomass combustion or treatment are considered biogenic and are not calculated as part of the net greenhouse emissions.

Moreover, depending on the NPK (nitrogen-phosphorus-potassium) characteristics of the compost produced from dry leaves and dung as determined in the pilot scale composting experiment, the reduction in synthetic fertilizer amounts is calculated. For example, the compost will provide 15.5 kg of P_2O_5 per hectare and so the amount of single phosphate fertilizer applied to the field per feddan could reduced by the same amount.

Cane is loaded on the sugar mill's train which consists of 25 carts, each cart loads approximately 10 tons of cane and travels about 40 km from the field to the mill. The train works on diesel and consumes about 60-80 liters/trip. Fuel combustion emissions are associated with the transportation activities.

At the mill, inputs to the process includes a number of chemicals used for clarification, juice extraction and juice treatment such as calcium hydroxide, phosphoric acid, hydrochloric acid, sulfuric acid, sulfur and ammonium sulfate. Input water is treated to be used for equipment cleaning and as cooling water makeup.

The outputs of the sugar milling include the main product and co-product which are sugar and molasses, as well as by-products which are the bagasse, filter mud and the furnace ash. Bagasse in this system is assumed to be all combusted in the mill power house to produce steam and electricity. The filter mud and furnace ash are removed from the mill's premises to be used as soil conditioner in reclaimed lands. As for the wastewater, it is assumed that it is all directed to the wastewater treatment plant of the mill and treated to the regulatory requirements of the Ministerial Decree 402/2009 (MWRI, 2009) for disposal into water canals in Egypt.

Air emissions are mainly those resulting from combustion of bagasse, which is complemented with a small quantity to heavy oil (mazot) to boost the combustion process and start up the boilers. These include particulate matter (PM), volatile organic compounds (VOC), nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and sulfur oxides (SOx) (EPA, 1997). In case the bagasse is used as a source of fuel, carbon dioxide emissions associated with its combustion are not accounted for as greenhouse emissions. In other countries such as

South Africa, coal is used instead of heavy oil for start up of the combustion process (Mashoko, 2010).

When filter mud and ash or bagasse and filter mud are composted and returned to the agriculture stage, as shown in alternatives 2 and 3, emissions associated with the composting process are added to the industrial phase, as the composting process will take place in the sugar mill and not the field. However, reductions in the amount of synthetic fertilizers used for each alternative will impact the agricultural stage depending on the amount of nutrients (NPK) associated with each type of compost. Transportation of compost back to the field from the mill is calculated depending on the amount of compost.

The data for cane cultivation, harvesting, transportation and milling were obtained through field visits, interviews and questionnaires with the stakeholders directly involved in the sugarcane industry including land owners and farmers, mills' operators, health, safety and environment officers and based on data provided by the Egyptian Sugar and Integrated Industries Company (ESIIC). However, data related to the manufacture of chemicals, fertilizers and fuels are obtained from Eco-invent database in SimaPro.

Data and its sources that are used in formulating the inventory for the sugarcane agricultural and industrial stages are included in Table 5.1. Data and information provided by the Egyptian Sugar and Integrated Industries Company (ESIIC) were compiled mainly through interviews and questionnaires. The data were verified and compared to national and international published reports and journal articles. In Mauritius, for example, 0.013 ha of land is required to produce a ton of cane as compared to 0.016 ha for South Africa and 0.0093 ha for Egypt, which means that the cane fields in Egypt have more dense plantations. Also, Mashotoko et al. (2010) explain that in South Africa only 20% of the cane is irrigated and the rest is rain fed. Therefore, water requirement in Egypt for the irrigation of one hectare is about 25,000m^3/year, as compared to 17,000 m^3 in South Africa. Irrigation requirements are also related to the soil type. Moreover, in Brazil, 35% of the cane is harvested by machinery (Mashoko et al., 2010) whereas in South Africa, as in Egypt, harvesting is done manually. This affects the amount of fuel used in the agricultural stage.

Table 5.1. Data and references related to sugarcane agricultural and industrial stages

Item	Value/Assumption	Reference
1. Sugarcane Agricultural Stage		
1.1 Inputs		
Average cane harvest per hectare	107 ton/hectare	ESIIC questionnaire
Irrigation water requirements	25000 m^3/hectare/year	ESIIC questionnaire
CO_2 from air	449.4 kg/ ton cane	Jungbluth et al., 2007 (Eco invent report No.17)
Energy, gross calorific value in biomass	4947.8 MJ/ton cane	Jungbluth et al., 2007 (Eco invent report No.17)
Sugarcane fertilization requirements	Nitrogen 547 kg/hectare Phosphorus 107 kg/hectare Potassium 114 kg/hectare	Soil, Water and Environment Research Institute, Ministry of Agriculture, 2014
Fertilizers NPK content	Urea = 46.6 % N, Ammonium nitrate 33% N, Mono phosphate 15% P_2O_5, Potassium sulphate 48% K_2O	ESIIC questionnaire
Fuel Use for irrigation (gas oil)	107 liter/hectare/year	
Diesel Use for transportation	70 liters/(25 carts*10 tons/cart)	
Rail Transport	25 carts/train*10 ton/cart travel for 40km	
1.2 Outputs		
Emissions to air (fertilizers and burning of leaves)		
N_2O	1.25% of nitrogen input and 2.5% as N that as nitrate & 0.07 g/kg dry leaves	IPCC, 2006
NO_2	0.21*N_2O from soil and 2.5 g/kg dry leaves	Jungbluth et al., 2007 (Eco invent report No.17)
CH_4 TOC	2.7 g/kg dry leaves	IPCC, 2006
Non-methane TOC	2-6 kg/ton cane (leaves burning)	EPA, 1995
CO	30-41 kg/ton cane (leaves burning)	EPA, 1995 & Eco invent report No. 17
SO_2	0.4 g/kg dry leaves 1 kg/1 Gwh diesel for irrigation and 1 kg/1 Gwh diesel for transportation	Wang et al. 2008
PM_{10}	2.3-3.5 kg/ton cane (leaves burning)	EPA, 1995 & Jungbluth et al., 2007 (Eco invent report No.17)
Emissions to water (fertilizers)		
Phosphorus to river	0.003 kg/ton cane for every 10 kg of P_2O_5	Jungbluth et al., 2007 (Eco invent report No.17)
Phosphorus to groundwater	0.001 kg/ton cane for every 10 kg of P_2O_5	
Nitrates to groundwater	2.5% of N in fertilizer	

Item	Value/Assumption	Reference
2. Sugarcane Industrial Stage (season=150 day/year)		
2.1 Inputs		
Hydrated lime $Ca(OH)_2$	18000 ton/season	ESIIC questionnaire
NaOH- 50% in H_2O	2000 ton/season	
HCl- 30% in H_2O	250 ton/season	
Sulfuric acid	50 ton/season	
Ammonium sulphate	80 ton/season	
Sulfur	3000 ton/season	
Phosphoric Acid	3000 ton/season	
Chlorine	35 ton/season	
Washing Water	250 m3/hr	
2.2 Outputs		
Emissions to air from bagasse combustion kg/ton bagasse		
PM	8.4*0.5	EPA, 1997
NOx	1.2*0.5	
CO_2 Biogenic	1560*0.5	
Polycyclic organic matter	0.001*0.5	
CH_4 biogenic	30 g/1000 MJ bagasse	Wang et al., 2008
Emissions to air from diesel combustion		
CO_2	3.14 kg/kg diesel	IPCC, 2006
CH_4	0.0001 kg/kg diesel	
N_2O	0.00003 kg/kg diesel	
CO	0.0157 kg /kg diesel	Jungbluth et al., 2007 (Eco invent report No.17)
S_2O	100 mg/kg diesel	
Emissions to water and soil		
Sludge from WWTP	4000 ton/year	ESIIC questionnaire
Filter cake	350 kg/ton sugar	
Furnace ash	40 kg/ton sugar	
Wastewater to WWTP	50 m^3/hr	
Wastewater disposal characteristics		
TSS	30 mg/l	MWRI Ministerial Decree 402/2009, Article 61.
COD	40 mg/l	
BOD	30 mg/l	

Sugar and molasses are the main products, and life cycle impacts during sugar milling are economically allocated between them according to their market price and produced quantity as 90.6% to sugar and 9.4% to molasses, as demonstrated in Table 5.2. This is comparable to allocation factors used by Renouf et al. (2011), when raw sugar was assigned 94.9% of the impacts and molasses 5.1% using mass allocation, while they were assigned 96 % and 4% respectively using economic allocation. Bagasse, was totally consumed in the mill to produce steam and electricity and so was not included in the allocation (Renouf et al., 2011).

Table 5.2. Economic allocation of mill products in case bagasse is combusted in the mill

	Price (L.E./ton)	Amount produced as percentage of cane	Revenue (L.E.)	Allocation (%)
Sugar	3900	11%	429	90.6
Molasses	890	5%	44.5	9.4
			473.5	100

The inventory of inputs and outputs for the cultivation and harvesting of 10 ton of sugarcane and for sugar milling process to produce 1 ton of sugar and 400 kg of molasses for the base model and the three alternatives are included in Table 5.3.

Table 5.3. Inventory of inputs and outputs for sugarcane industry in Egypt

Item	Unit	Quantity			
		Base Model	Alternative		
			1	2	3
1. AGRICULTURAL STAGE (Functional Unit = 10 ton of cane)					
1.1 Inputs					
Inputs from Nature					
Land use	m^2	935	935	935	935
CO_2 from air	kg	4490	4490	4490	4490
Energy, gross calorific value in biomass	MJ	49470	49470	49470	49470
Water, river for irrigation	m^3	2220	2220	2220	2220
Inputs from Technosphere					
Urea as N	kg	31.1	28.9	27.3	23.7
Ammonium Nitrates as N	kg	22	20.5	19.5	16.5
Single phosphate as P_2O_5	kg	10	8.6	7	1.1
Potassium sulfate as K_2O	kg	10.7	8.1	7.8	5.4
Diesel Use for irrigation	kg	8	8	8	8
Operation Freight Rail, Diesel	tkm	280	280	290	320
Cattle Dung	kg	0	100	100	100
1.2 Outputs					
Emissions to Technosphere					
Cane tops consumed in farms	kg	1500	1500	1500	1500
Dry leaves burnt	kg	500	0	0	0
Compost to agriculture	kg	0	487.5	487.5	487.5

Item	Unit	Quantity			
		Base Model	Alternative		
			1	2	3
Emissions to air (fertilizer emissions, dry leaves burning (base model) and compost emissions (alternative models))					
N_2O	kg	1	1.055	1.009	0.889
NO_2	kg	1	0.18	0.174	0.149
TOC (methane and non-methane)	kg	21.35	0	0	0
CO biogenic	kg	300	0	0	0
SO_2	kg	0.2	0	0	0
PM_{10}	kg	30	0	0	0
$CO_{2,}$ biogenic	kg	780	214	214	214
$CH_{4,}$ biogenic	kg	0	2.4	2.4	2.4
Emissions to water					
Phosphorus to river	kg	0.03	0.026	0.021	0.0033
Phosphorus to groundwater	kg	0.01	0.0086	0.007	0.0011
Nitrates to groundwater	kg	1.27	1.23	1.17	1.05
2. INDUSTRIAL STAGE (Functional Unit = 1 ton of sugar and 400 kg molasses)					
2.1 Inputs					
Inputs from Nature					
Water, river for washing	m^3	4.00	4.00	4.00	4.00
Water, river for cooling water make up	m^3	14.00	14.00	14.00	14.00
Water, river for compost watering	m^3	0	0	0.18	1.35
Inputs from Technosphere					
Sugarcane from farm	kg	10000	10000	10000	10000
Hydrated lime $Ca(OH)_2$	kg	20.00	20.00	20.00	20.00
NaOH- 50% in H_2O	kg	2.22	2.22	2.22	2.22
HCl- 30% in H_2O	kg	0.28	0.28	0.28	0.28
Sulfuric acid	kg	0.06	0.06	0.06	0.06
Sulfur	kg	3.33	3.33	3.33	3.33
Phosphoric Acid	kg	3.33	3.33	3.33	3.33
Chlorine	kg	0.04	0.04	0.04	0.04
Fuel oil as fuel supplement	kg	72	72	72	0
Natural Gas as fuel	m^3	0	0	0	857
Diesel use for transport of compost back to field	kg			0.08	
2.2 Outputs					
Emissions to air (from fuel burning)					

Item	Unit	Quantity			
		Base Model	Alternative		
			1	2	3
PM	kg	13.30	13.30	13.30	0.10
PM10	kg	0.05	0.05	0.05	0
PM2.5	kg	0.01	0.01	0.01	0
NO_2	kg	2.10	2.10	2.10	1.92
SO_2	kg	4.30	4.30	4.30	0.01
SO_3	kg	0.16	0.16	0.16	0
CO	kg	0.045	0.045	0.045	1.1518
CO_2, Biogenic	kg	2418	2418	2465	666
CO_2	kg	228.43	228.43	228.43	1645.44
N_2O	kg	0.0048	0.0048	0.117	1.02
CH_4	kg	0.009	0.009	0.009	0.032
CH_4 biogenic		0.0670	0.0670	1.627	13.6
Polycyclic organic matter (POM)	kg	0.00156	0.00156	0.00156	0
Formaldehyde (HCOH)	kg	0.0004	0.0004	0.0004	0
Total organic compounds (TOC)	kg	0.012	0.012	0.012	0.152
Non-methane TOC	kg	0.0026	0.0026	0.0026	0
Volatile organic compounds	kg	0	0	0	0.075
Emission to land					
Sludge/wastewater/cake (K_2O equivalent)	kg	24.7	24.7	24.7	24.7
Filter cake	kg	350	350	0	0
Furnace ash	kg	40	40	0	0
Compost to agricultural stage	kg	0	0	107	1530
Emissions to water					
Wastewater	m^3	4	4	4	4
TSS	kg	0.12	0.12	0.12	0.12
COD	kg	0.16	0.16	0.16	0.16
BOD	kg	0.12	0.12	0.12	0.12

5.2.3 Impact Assessment

SimaPro uses networks to show the input processes to the product and the impact associated with these input processes. However, networks do not show the outputs and emissions and their related impacts. Therefore, the impact scoring of the product equals the total impacts of the inputs that are shown and the outputs that are not showing on the network. The width of the arrow gives an indication of the magnitude of the contribution of the impact of the input to the total impact.

Assessment of the base model as presented by the process network in Figure 5.3., shows that the main contributors to the impact of production of 1 ton of sugar in the mill are:

- Cultivation and harvesting of 9 tons of sugarcane at the farm, contributing by 66.78% (score of 0.0748 out of 0.112).
- Generation of electricity and steam in the mill from bagasse and some heavy oil acting as fuel supplement, contributing by 30.35% (score of 0.034 out of 0.112).
- Other minor impacts from emissions and discharges of the industrial process accounting for 2.87% (the remaining 0.0032 out of 0.112).

It is worth noting that due to the economic allocation of 90.6% of the impacts to sugar and the rest to molasses, as mentioned earlier, 90.6% of all activities, inputs and outputs in the datasheet are assigned to the 1 ton of sugar produced. Molasses will bear only 9.4% of the impacts as shown in Figure 5.4.

Figure 5.3 also indicates that the activities contributing to the impacts of cultivation and harvesting of 9 tons of sugar cane are:

- Manufacture of urea contributing by 16.8% (score of 0.0126 out of 0.0748)
- Manufacture of ammonium nitrate contributing by 18.1% (0.0136 out of 0.0748)
- Fuel consumption in irrigation contributing by 4.9% (0.00372 out of 0.0748)
- Emissions from the burning of the dry leaves which account for 60.2% (the remaining 0.045 out of the 0.0748).

-

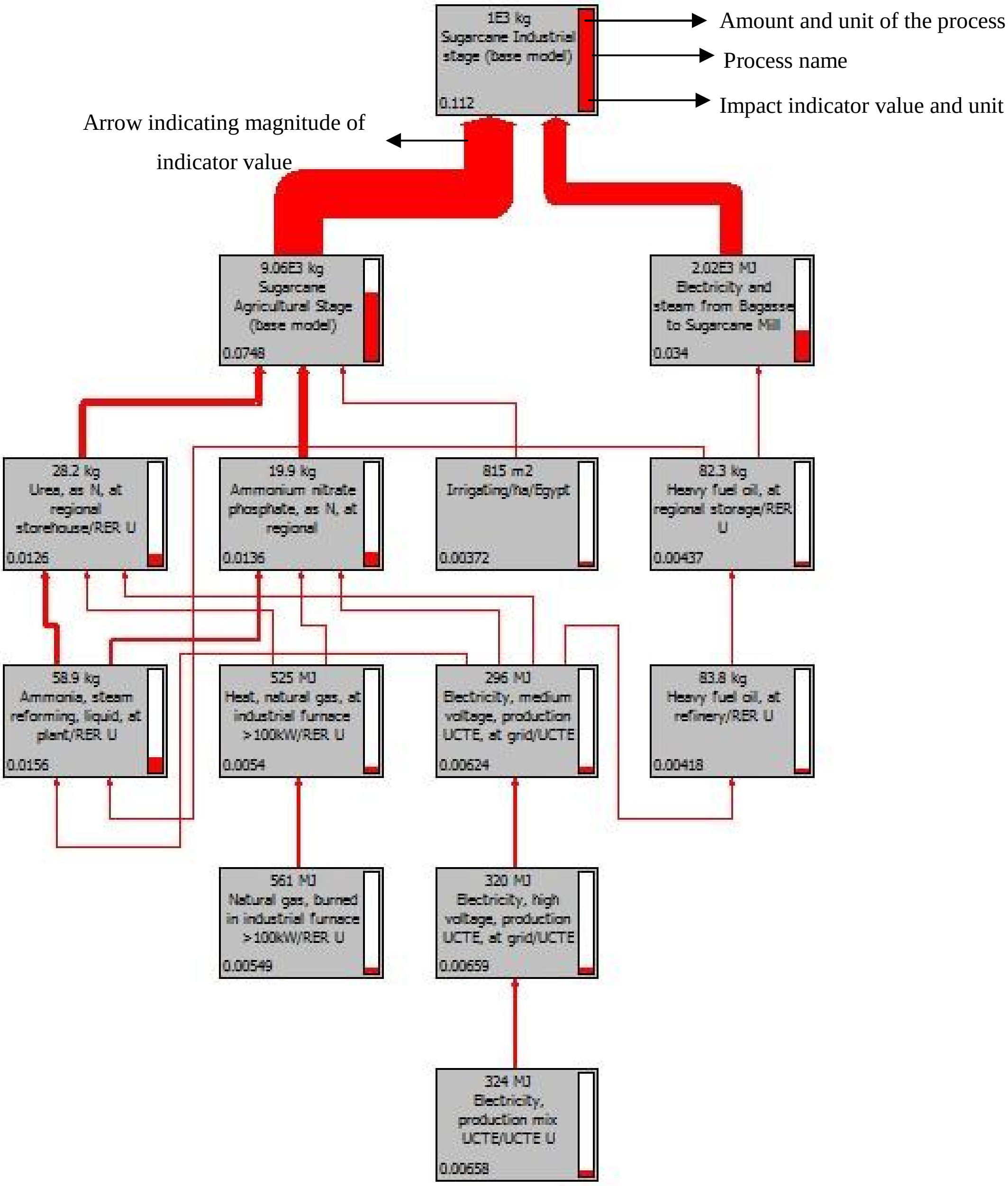


Figure 5.3. Process network for the production of 1 ton of sugar including agricultural and industrial stages (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

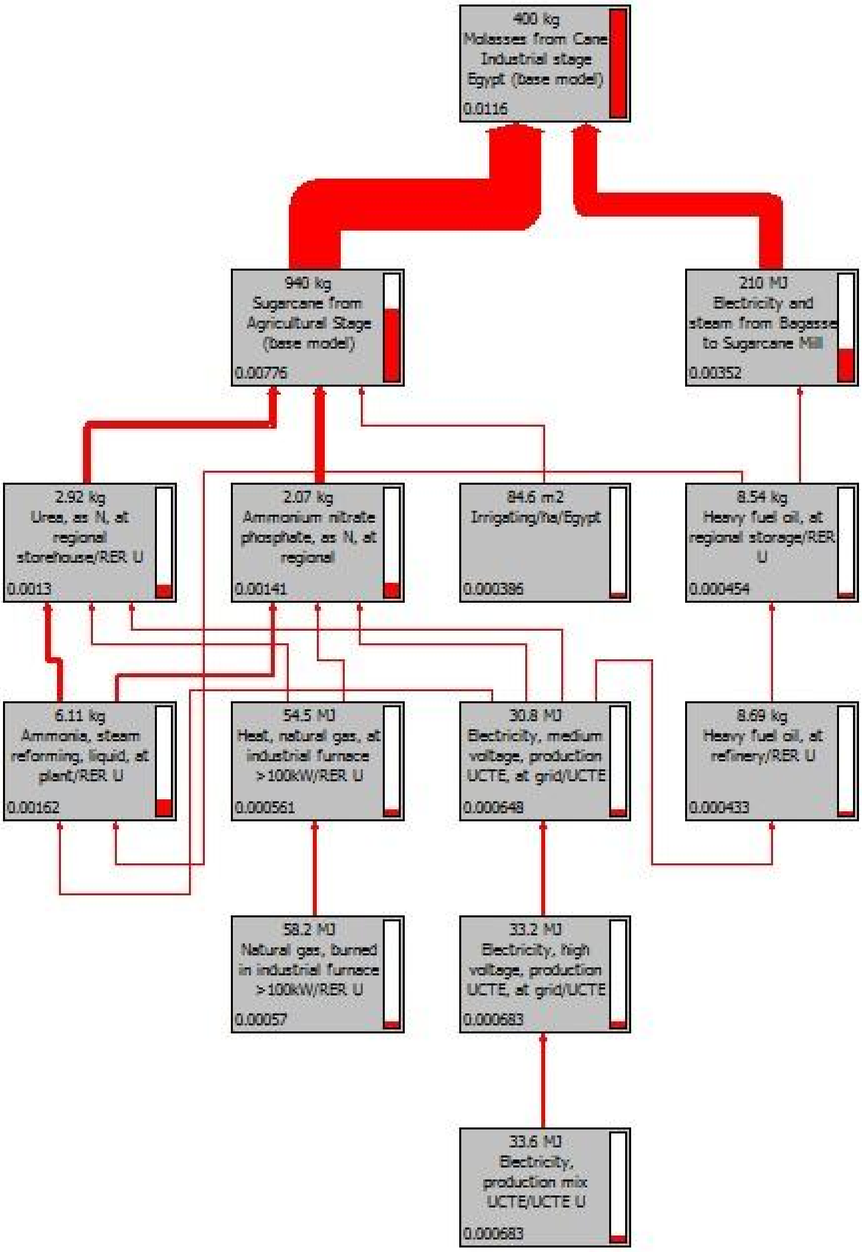


Figure 5.4. Process network for the production of 400 kg of molasses including agricultural and industrial stages (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

When carrying out the environmental assessment of the agricultural stage for 9 tons of cane, it becomes clear from the normalized output illustrated in Figure 5.5. that the most significant impacts categories are:

1. Particulate matter mainly from the PM_{10} emissions resulting from the open burning of the dry leaves.
2. Freshwater ecotoxicity mainly from phosphorus, from fertilizer application, being washed into water resources.

Other impacts that are less significant, but still exist, are:

1. Photochemical Oxidation (PO) due to emissions of organic compounds to the air from the burning of dry leaves.
2. Marine ecotoxicity and freshwater eutrophication as a result of nitrates and phosphorus, from fertilizer application, being washed into water resources.
3. Agricultural land occupation because of the occupation of 900 m^2 of land for every ton of cane planted.
4. Human toxicity as it is related to freshwater and marine toxicity.
5. Climate change due to emissions dinitrogen monoxide (N_2O) burning of dry leaves.
6. Fossil depletion due to use of diesel as fuel irrigation and cane transportation and for the fossil fuel used in fertilizer manufacturing.
7. Terrestrial acidification from the use of fuels in manufacture of fertilizers and in irrigation and transportation.

If the base model is compared to the three alternatives for the agricultural stage as is illustrated in Figure 5.6, it can be noticed that the following impact categories are greatly reduced:

- A significant improvement in the particulate matter formation and in the photochemical oxidation is shown in case the dry leaves are not burnt in the fields, as in the case of alternatives 1, 2 and 3.
- Freshwater toxicity, marine ecotoxicity and freshwater eutropication decreases with alternatives 1, 2 and 3 from base model as the amount of phosphorus and nitrate emission to groundwater and surface water decreases, due to the savings in the amount N and P fertilizers as it is replaced by nutrients from the organic

fertilizer. It is assumed in the calculation that there will be no washout of nutrients when it is provided in the form of compost or organic fertilizer.

- Human toxicity also decreases with the decrease in freshwater and marine toxicity
- Marine eutrophication decreases as the nitrate emissions to groundwater decreases with the reduction in the use of synthetic fertilizers containing nitrogen including urea and ammonium nitrate.
- Climate change impacts are associated with fossil fuel use during manufacturing of fertilizers, irrigation of cane fields and transportation of cane to the sugarcane mills which involves emissions of carbon dioxide, methane and nitrous oxides, as well as nitrous oxide (N_2O) emissions due to losses from denitrification of applied nitrogen fertilizers. This impact category slightly increases as the N_2O emissions also slightly increase due to composting emissions in alternatives 1 and 2. However, it decreases in alternative 3 due to the reduction in synthetic fertilizer amounts used and N_2O emissions related to them.
- Fossil fuel is also reduced as the amount of synthetic fertilizer is decreased, as it is replaced by compost and organic fertilizer and hence the amount of fossil fuel required for their production is decreased.

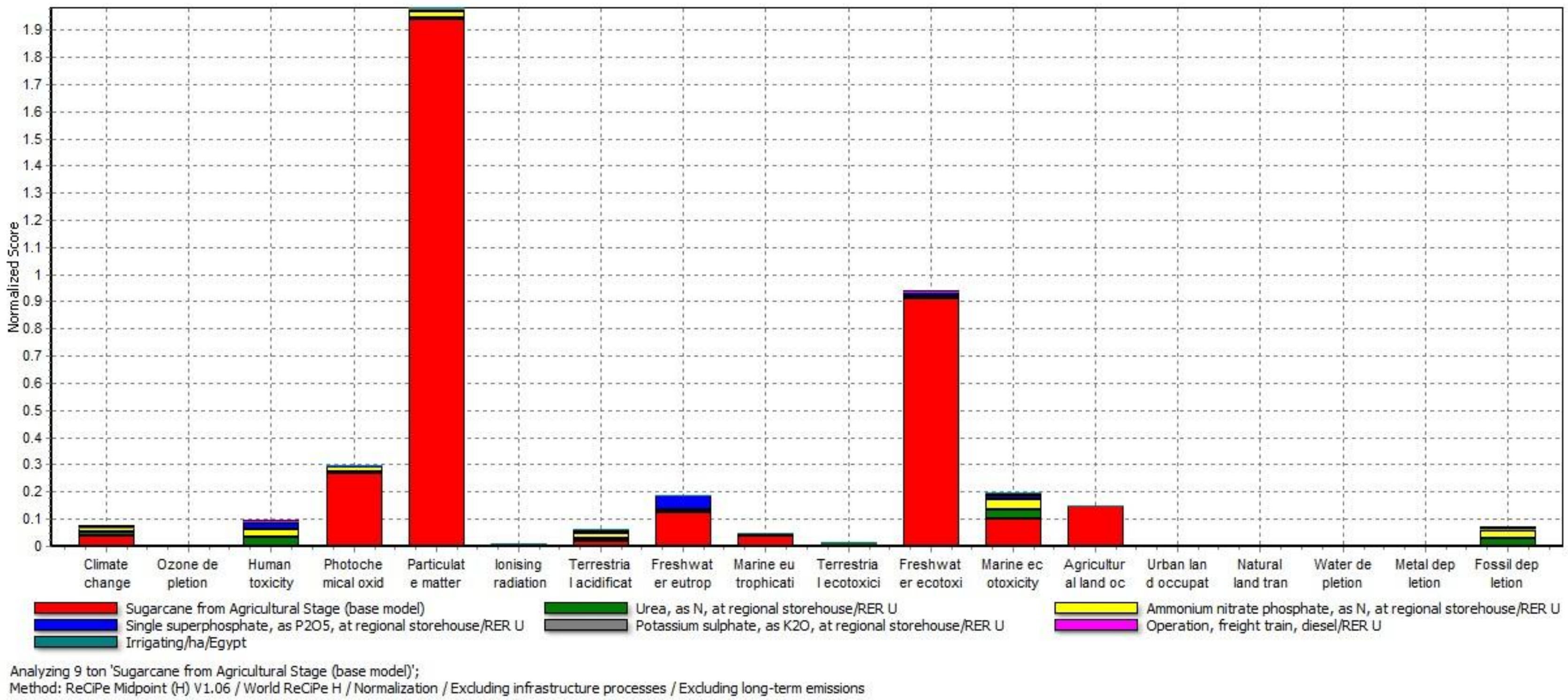


Figure 5.5. Normalized impacts of sugarcane agricultural stage for 9 tons of cane - base model (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

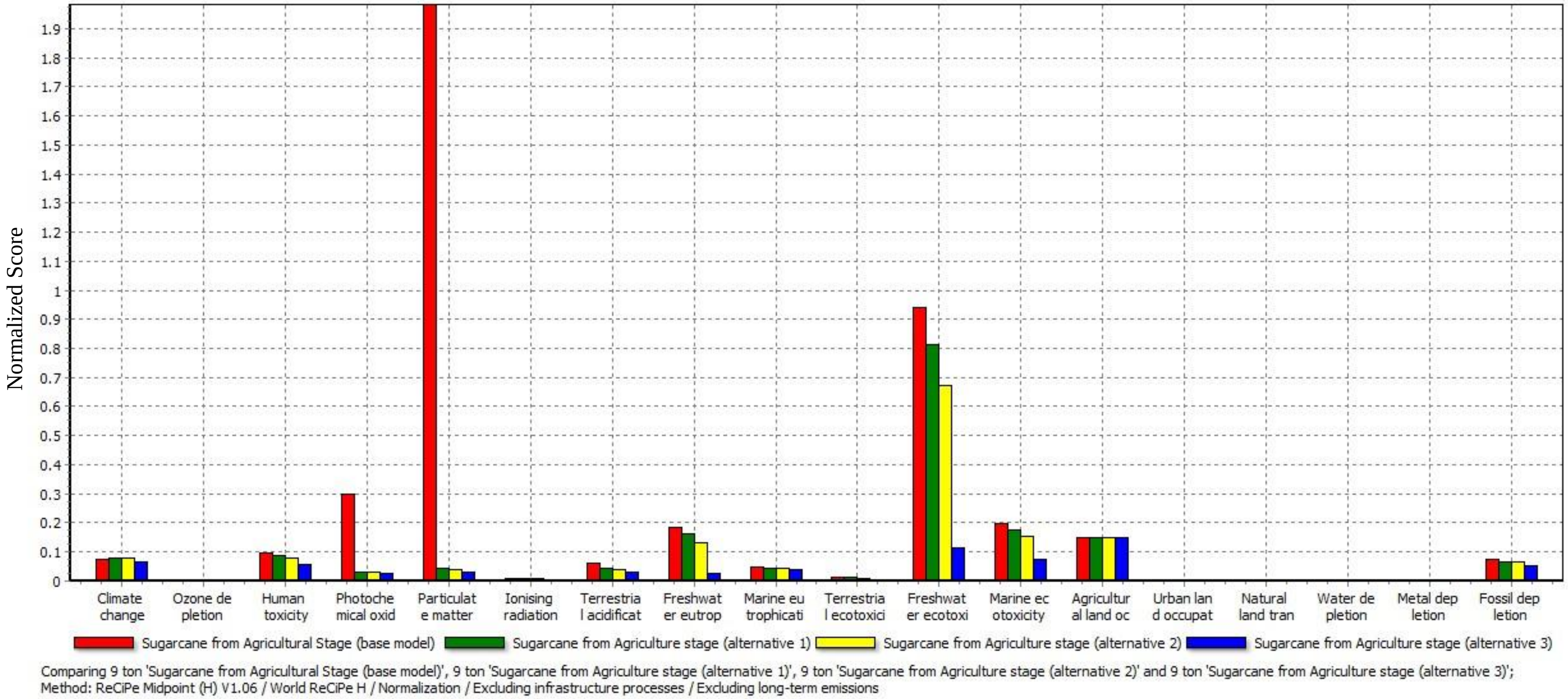


Figure 5.6. Normalized impacts of agricultural stage of 9 ton cane base model as compared to alternatives 1, 2 and 3 (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

When life cycle assessment comparison was carried out for the whole system, including the agricultural and industrial stages for the base model and the three alternatives, the following conclusions can be made based on the normalization graphs presented in Figures 5.7 and 5.8:

- The magnitude of the impact category particulate matter formation has increased above that of the agricultural stage due to particulate emissions (including PM_{10} and $PM_{2.5}$) associated with the combustion of bagasse and heavy oil (acting as fuel supplement) in the sugar mill. However, there was also a significant decrease from the base model for the three alternatives as the activity of dry leaves burning was ceased. Particulate matter decreased more with regards to alternative 3 as bagasse and heavy oil combustion did not take place since natural gas was used as fuel.
- Photochemical oxidation decreased significantly in alternatives 1, 2 and 3 from the base model when the burning of the dry leaves was ceased. However, it was higher in magnitude in the sugar production than cane plantation due to the incomplete combustion of wet bagasse with water content of about 50% moisture content, which increased CO emissions and the CO emissions associated with combustion of natural gas.
- Climate change increased in alternative 3 due to the use of natural gas, which emits higher amounts of greenhouse emissions than biomass fuel or bagasse.
- Fossil depletion was found to give higher value in case of alternative 3 due to the use of natural gas for producing steam and electricity in the sugar mill rather than bagasse and a small amount of heavy oil in case of the base model and alternatives 1 and 2.
- Terrestrial acidification gave higher magnitude of the impact than the agricultural stage due to sulphur dioxide emissions associated with combustion of heavy oil in the power house of the mill as a supplement to bagasse. It decreased in case of use of natural gas as fuel in alternative 3, due to the decrease in sulfur oxide emissions.

As for the impact categories that followed the same pattern as that of the agriculture stage because they are directly related to that stage are the freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, marine eutrophication and agricultural land occupation.

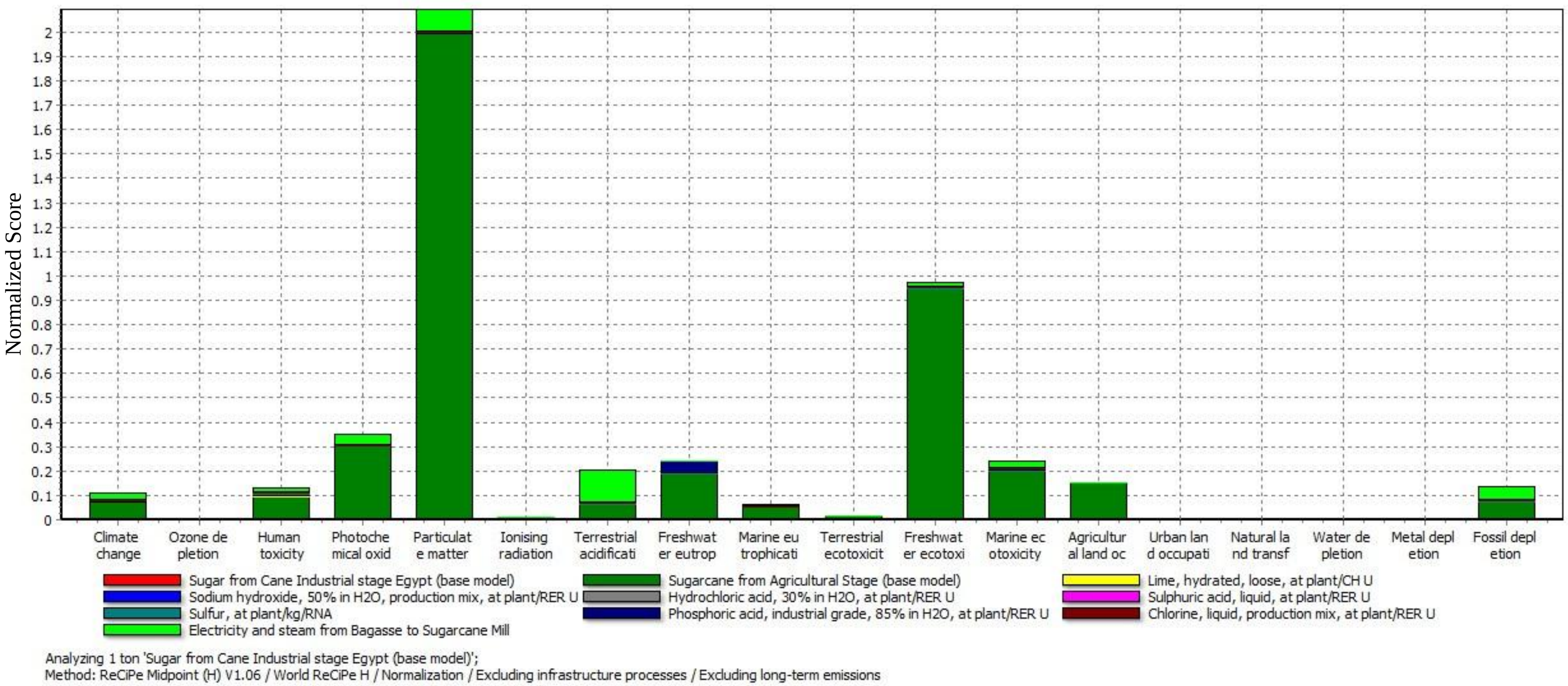


Figure 5.7. Normalized impacts of production of 1 ton of sugar from 9 tons of cane- base model (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

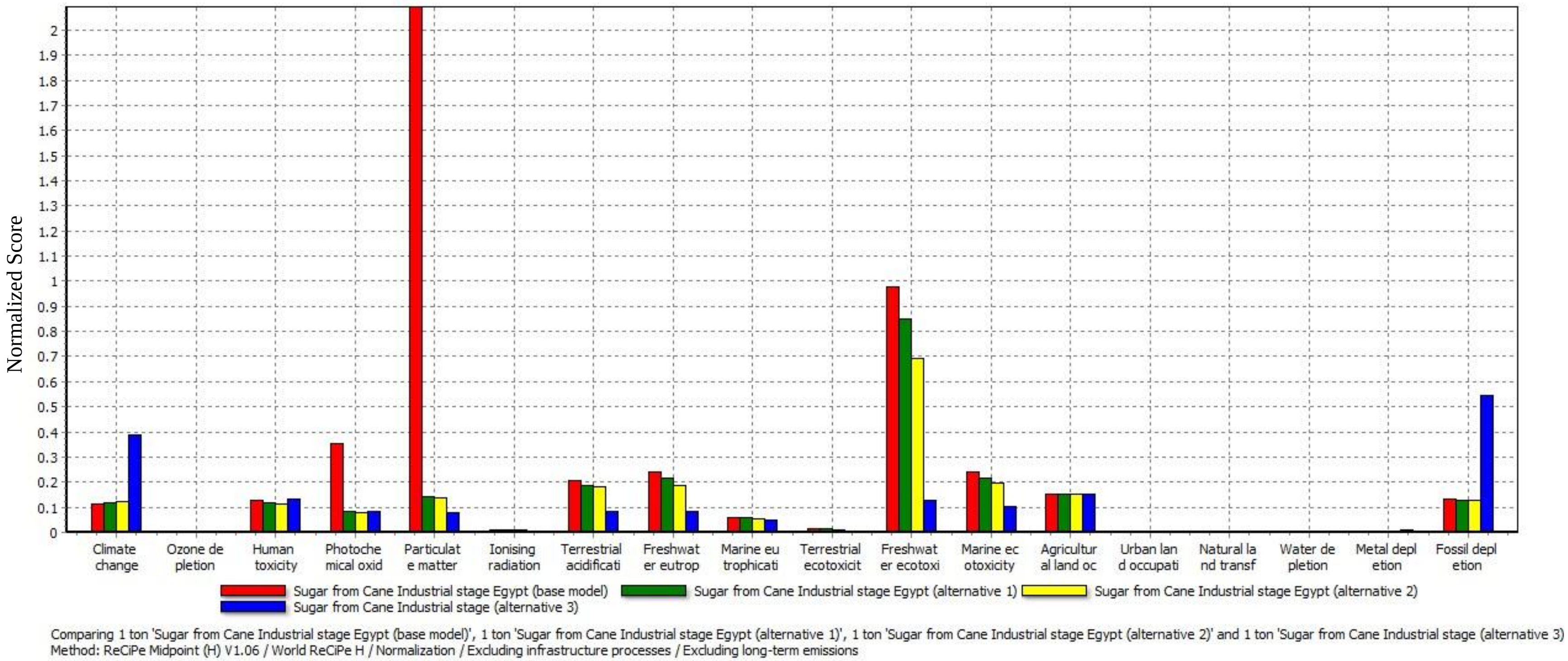


Figure 5.8: Normalized impacts associated with the production of 1 ton of sugar for the base model as compared to alternatives 1,2 and 3
(Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

5.3 LCA of Bagasse Reuse Options

5.3.1 Goal and Scope

The ***second goal*** is to define the most environmental friendly use of the main by-product of sugarcane milling which is bagasse. The bagasse use option that shows the highest reduction of environmental impacts can be identified by comparing the environmental impacts of the selected bagasse use pathways with that of the alternative production systems. Hence, it is important to define the raw material that bassage is used as a substitute for and assess the environmental impacts associated with these production processes. Table 5.4 presents the bagasse use systems chosen to be investigated and the corresponding alternative systems.

Table 5.4. Bagasse use pathways and alternative systems

Bagasse Use Systems	Alternative Systems
Use in sugarcane mill power house to produce steam and electricity	Use of natural gas or fuel oil in sugarcane mill power house to produce steam and electricity
Fiberboard making from bagasse	Fiberboard making from wood
Paper production from bagasse	Paper production from wood
Compost production from bagasse	Synthetic fertilizer from chemicals

The evaluation of each of the bagasse options was based on the utilization of 1 ton of bagasse. The options were compared based on the same functional units of 0.2 MWh of electricity being generated and 1.6 ton of steam, 0.238 ton of paper production, 0.322 m^3 of fiberboard and 0.493 ton of compost. The same amounts of electricity, paper, fiberboard and fertilizer can be obtained from other conventional processes which are (1) steam and power production using natural gas or heavy fuel oil, (2) fiberboard from wood, (3) paper from wood and (4) synthetic fertilizer from chemicals. The conventional fiberboard and paper manufacture process is chosen to be very similar to the ones used with the bagasse and give a similar product as shown in Figure 5.9.

The ***system boundary*** of all scenarios start after sugar is extracted from cane generating bagasse as a waste residue. This approach was used by Kiatkittipong et.al.

(2009), as bagasse was considered as waste having no financial value and so the environmental impacts associated with cane cultivation, transportation and sugar production were associated with sugar and molasses and not the bagasse, and hence were not included in this analysis. Moreover, impacts associated with construction, commissioning and maintenance of the fiberboard and paper factories are also not included in the scope of this study. The LCA can be considered as ***gate-to-gate*** for these systems as they start with the bagasse or other substitute material, entering the production process and ending with the production of the product. It does not also include assessment of the use or disposal of the products generated.

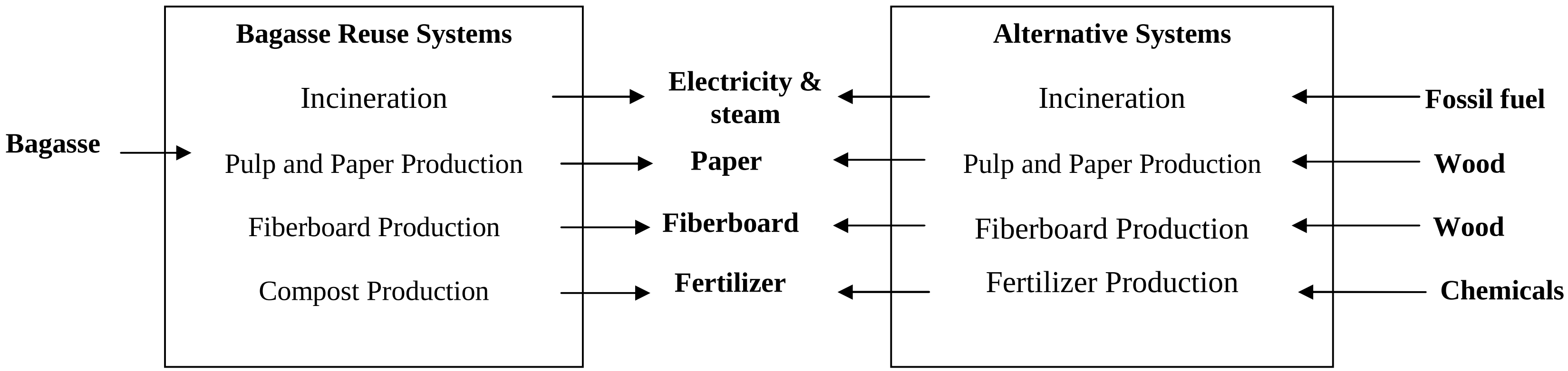


Figure 5.9. System boundary of LCA of bagasse reuse options

5.3.2 Life Cycle Inventory (LCI)

a. Bagasse to Paper

As mentioned in Chapter 2, bagasse generated from the sugar mill is transferred to the neighboring paper factory, as the case of Qena Paper Mill which complements Kous Sugar Mill.

The bagasse is depithed and the pith is returned to the sugar mill to be used as fuel in its power house, generating emissions of particulate matter (PM), nitrogen oxides (NOx), biogenic carbon dioxide (CO_2) and polycyclic organic matter (POM). The bagasse is stored in wet form and so is constantly watered. The wet bagasse is then conveyed to the pulp mill to undergo cooking, pulp washing, pulp screening, cleaning, thickening and bleaching. Pith further removed is stored and sold to contractors. This process requires steam and chemicals such as sodium hydroxide, sodium sulphite and chlorine dioxide for cooking and bleaching the pulp. The chemicals are recovered from the black liquor, resulting from the pulping activities, through burning in a recovery boiler and mixing with calcium oxide. This process is called the “kraft process” and accordingly involves the emission of particulate matter, sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO) and non-methane volatile organic carbons (NMVOC). The process also results in calcium carbonate (lime mud powder), which is considered solid waste and is disposed in a designated landfill.

Pulp and paper mill energy generation is provided in part from the burning of liquor waste solids in the recovery boiler and from the power house run on fossil fuel. Power boilers at pulp and paper mills and chemical recovery units are sources of a variety of emissions including particulate emissions, fuel combustion emissions (SOx, NOx, CO, CO_2), nitrous oxides (N_2O), methane (CH_4), total organic carbons (TOC) and volatile organic carbons (VOC).

Large quantities of wastewater are generated from the pulp and paper mill and is it assumed that all wastewater produced by the paper mill is directed to the wastewater treatment plant and treated to reduce the BOD, COD and suspended solids content to the limits set by Ministerial Decree 402/2009 amending Law 48/1982 for discharge to the River Nile canals (MWRI, 2009).

The data for the pulp and paper production from bagasse was provided by the manager of Qena Paper Company, Eng. Mohamed El Shazly, and was verified through national reports such as the "Pulp and Paper Self Monitoring Manual" prepared by Egyptian Pollution Abatement Project (EEAA, 2003). The air pollutant emission factors were based on EPA guidelines (1985). The data and sources are presented in Table 5.5. The paper mill operates for 315 days per year.

Table 5.5. Data and references related to paper production from bagasse in Egypt

Item	Value/Assumption	Reference
1. Inputs		
Bagasse	1 ton bagasse produces 0.24 ton paper	Qena Paper Company questionnaire and EEAA, 2003
Sodium Hydroxide	50 kg/ton pulp	
Sodium Sulfite	2.5-4 kg/ton pulp	
Chlorine dioxide	15-17 kg/ton pulp	
Calcium oxide	180-200 kg/ton pulp	
Long fiber Pulp	24000 ton annually	
Calcium carbonate	12000 ton annually of filler	
Natural gas	700-750 m^3/ton paper	
Process Water	65-70 m^3/ton paper	
Demineralized boiler water	7.5 m^3/ton paper	
2. Outputs		
Sludge from Bio WWTP	30 ton/day	Qena Paper Company questionnaire
Lime Mud (Calcium Carbonate)	85-100 dry ton/day	
Wastewater to WWTP	18500 m^3/day	
Emissions to air (Kraft Process) (kg/10^3 kg)		
NOx	1	EPA, 1985
CO	5.5	
NMVOC	2	
SOx	2	
TSP	1	
PM10	0.8	
PM2.5	0.6	
Wastewater disposal characteristics (mg/l)		
TSS	30	MWRI Ministerial Decree 402/2009
COD	40	

Item	Value/Assumption	Reference
BOD	30	
TDS	1200	

The LCA inventory for paper making from bagasse was based on the utilization of 1 ton of bagasse to produce 0.238 ton of paper, as presented in Table 5.6.

Table 5.6. LCI for production of 0.238 ton paper from 1 ton bagasse

Item	Unit	Quantity
1. Inputs		
Inputs from Nature		
Water, river treated used as process and boiler water	m^3	18.45
Raw water for bagasse washing	m^3	0.45
Inputs from Technosphere		
Bagasse	kg	1000
Sodium Hydroxide	kg	7.74
Sodium Sulfite	kg	0.46
Chlorine dioxide	kg	2.48
Calcium oxide	kg	29.39
Calcium carbonate	kg	23.8
Long fiber Pulp	kg	47.60
Natural gas	m3	167
2. Outputs		
Emissions to air (natural gas combustion)		
PM	kg	0.020
NO_2	kg	0.085
SO_2	kg	0.0016
CO	kg	0.224
CO_2	kg	319.87
N_2O	kg	0.0017
CH_4	kg	0.006
TOC	kg	0.029
VOC	kg	0.0146
Emissions to air (kraft process)		
PM	kg	0.154
PM_{10}	kg	0.123
$PM_{2.5}$	kg	0.093
NOx	kg	0.155

Item	Unit	Quantity
CO	kg	0.851
NMVOC	kg	0.309
SOx	kg	0.309
Emissions to air (pith burning)		
PM	kg	0.624
NO_2	kg	0.089
CO_2 Biogenic	kg	116.02
Polycyclic organic matter (POM)	kg	0.000074
Emissions to Land		
Pith sold to contactors	kg	4.76
Sludge from Bio WWTP	kg	18.7
Lime Mud	kg	58
Emissions to Water		
Wastewater	m^3	11.55
COD	kg	0.46
BOD	kg	0.34
TDS	kg	13.86
TSS	kg	0.34

b. Bagasse to Fiberboard

Fiberboard making from bagasse is based on the fact that utilization of 1 ton of bagasse produces 0.322 m^3 of fiberboard. The process also starts with depithing and burning the pith in the power house of the sugar mill. The bagasse is also stored wet until it is used in the fiberboard plant where it is washed, cleaned and dewatered. The fibers are cooked with steam and paraffin wax is added. Urea formaldehyde (UF) is used as an adhesive in the gluing process. The glued fibers are dried and pressed and the boards are then finished.

Natural gas is used for steam and heat generation. Electricity is also obtained from the local grid, as well as a diesel generator. Emissions to air resulting from the fiberboard making process, including particulate matter, formaldehyde, methanol, phenol, propionaldehyde, total hydrocarbons (THC), volatile organic carbons (VOC), acetaldehyde, acetone, acrolein and alpha-pinene were estimated based on EPA (2002) emission factors for hardboard and fiberboard manufacturing. As for fuel and pith combustion emissions, they include particulate matter, carbon dioxide, carbon monoxide, sulfur and nitrogen oxides as well as methane, organic carbons and polycyclic organic matter (POM).

The fiberboard mill also has a wastewater treatment plant for treating wastewater to the limits set by Ministerial Decree 402/2009 amending Law 48/1982 for discharge to River Nile canals (EEAA, 2009).

The data related to fiberboard manufacture was taken from the production manager, Eng. Nagi Naguib, of Nagaa Hammadi Fiberboard Factory which is located in Deshna. The data was also verified and cross referenced to international experience in the same sector through published scientific journal articles. As for the air pollutants emission factors, they were based on EPA guidelines (2002). Table 5.7 includes the data and sources for fiberboard production in Egypt. It is assumed that the fiberboard factory works for 315 days per year.

Table 5.7. Data and references related to fiberboard production from bagasse in Egypt

Item	**Value/Assumption**	**Reference**
1. Inputs		
Bagasse	3.125 ton of bagasse produces 1 m^3 of fiberboard	Nagaa Hammadi Fiberboard Factory questionnaire
UF Resin	90-98 kg/m^3 for thick board & 130 for thin	
Urea solution	2 kg/m^3	
Paraffin	1.5-2 kg/m^3	
Electricity from Grid	350-400 kWh/m^3 fiberboard from Industry	
Fuel (natural gas) for heating	125-140 m^3/m^3 fiberboard	
Raw water for bagasse washing	15 m^3/hr	
Water for cooling & mechanical sealing & dilution of UF	15 m^3/hr	
Boiler feed water (softened)	12 m^3/hr	
2. Outputs		
Emissions to air (fiberboard production)		
PM	0.95 kg/10^3 kg	EPA, 2002
Condensed matter	0.285 kg/10^3 kg	
Carbon monoxide	0.03496 kg/m^3	

Item	Value/Assumption	Reference
Formaldehyde	0.003534 kg/m^3	EPA, 2002
Methanol	0.00646 kg/m^3	
Phenol	0.000456 kg/m^3	
Propionaldehyde	0.0002622 kg/m^3	
THC as carbon	0.02394 kg/m^3	
VOC as propane	0.03116 kg/m^3	
Acetaldehyde	0.0003686 kg/m^3	
Acetone	0.001444 kg/m^3	
Acrolein	0.0002166 kg/m^3	
Alpha-pinene	0.00494 kg/m^3	
Outputs		
Pith burnt in boiler	37,500 ton/year	Nagaa Hammadi Fiberboard Factory questionnaire
Rest pith from bagasse washing sold out	1200 ton/year	
Sludge to compost	3000 ton/year	
Wastewater to WWTP	200 m^3/hr	

The life cycle inventory for the production of 0.322 m^3 of fiberboard from 1 ton of bagasse is presented in Table 5.8.

Table 5.8. LCI for production of 0.322 m^3 of fiberboard from 1 ton of bagasse

Item	Unit	Quantity
1. Inputs		
Inputs from Nature		
Water, river treated for use for process, cooling and boiler feed	m^3	0.8211
Water, river for bagasse washing	m^3	0.4564
Inputs from Technosphere		
Bagasse	kg	1000
UF Resin	kg	33.4
Urea solution	kg	0.644
Paraffin	kg	0.644
Electricity from Grid	kWh	128.8
Natural gas for heating	m^3	41.86
2. Outputs		
Emissions to air (fiberboard making)		
PM	kg	0.956

Item	Unit	Quantity
Condensed matter	kg	0.287
CO	kg	0.011
Formaldehyde	kg	0.001
Methanol	kg	0.002
Phenol	kg	0.00015
Propionaldehyde	kg	0.00008
THC as carbon	kg	0.00771
VOC as propane	kg	0.01003
Acetaldehyde	kg	0.00012
Acetone	kg	0.00046
Acrolein	kg	0.00007
Alpha-pinene	kg	0.00159
Emissions to air (fuel combustion- natural gas)		
PM	kg	0.00509
SO_2	kg	0.00040
NO_2	kg	0.02143
CO	kg	0.05626
CO_2	kg	80.3712
N_2O	kg	0.00043
CH_4	kg	0.00154
TOC	kg	0.00737
VOC	kg	0.00368
Emissions to air (pith burning)		
PM	kg	0.634
NOx	kg	0.091
CO_2 Biogenic	kg	117.73
Polycyclic organic matter (POM)	kg	0.00008
Emissions to Land		
Sludge to compost	kg	12
Pith sold to contractors	kg	4.7
Emissions to Water		
Wastewater	m^3/ton	5.89
COD	kg	0.235
BOD	kg	0.176
TDS	kg	7.07
Suspended Solids	kg	0.176

c. Bagasse to Steam and Electricity

According to the data provided by the Egyptian Sugar and Integrated Industries Company, one kWh of electricity can be produced by 1.3 m^3 of natural gas, 1.2 kg of mazot or 5 kg of bagasse. These inputs will be the basis of comparison of impacts associated with electricity generation using bagasse as compared to conventional fossil fuels. The emission factors for the air pollutants from the combustion of heavy oil and natural gas are based on the EPA guidelines 1995) as shown in Table 5.9. The bagasse combustion emissions were already included in Table 5.1.

Table 5.9. Data and references related to fossil fuel combustion emissions

Item	**Value/Assumption**	**Reference**
Emissions to air from heavy oil combustion (kg/10^3 liter)		
PM	3.6948	EPA, 1995
PM_{10}	0.707	
$PM_{2.5}$	0.1477	
NOx	3.09	
SO_2	56.52	
SO_3	2.05	
CO	0.6	
CO_2	3000	
N_2O	0.0636	
CH_4	0.12	
Polycyclic organic matter (POM)	0.000132	
Formaldehyde (HCOH)	0.0051	
Total organic compounds (TOC)	0.1536	
Nonmethane TOC	0.0336	
Emissions to air from natural gas combustion (kg/10^6 m^3)		
PM (total)	121.6	EPA, 1995
CO_2	1920000	
Lead	0.008	
N_2O	22.72	
SO2	9.6	
TOC	176	
Methane	36.8	
VOC	88	

Item	Value/Assumption	Reference
NO_2	2240	
CO	1344	

To make the outputs comparable to those of paper or fiberboard produced from 1 ton of bagasse, it is calculated that 240 kg of mazot (heavy oil) or 260 m^3 of natural gas will give the same amount of steam and electricity as illustrated in Table 5.10.

Table 5.10. LCI for Producing 0.2 MWh of Electricity and 1.6 ton Steam

	Unit	Quantity		
		Baggase	**Fuel Oil**	**Natural Gas**
1. Inputs				
Inputs from Technosphere				
Bagasse	kg	1000	0	0
Fuel oil as fuel supplement	kg	23.23	240	0
Natural Gas as fuel	m^3	0	0	260
2. Outputs				
Emissions to air (from fuel burning)				
PM	kg	4.290	0.938	0.0303
PM10	kg	0.016	0.179	0
PM2.5	kg	0.003	0.037	0
NO_2	kg	0.677	0.785	0.5818
SO_2	kg	1.387	14.344	0.0025
SO_3	kg	0.052	0.521	0
CO	kg	0.015	0.153	0.3490
CO_2, Biogenic	kg	780	0	0
CO_2	kg	73.687	761.42	498.618
N_2O	kg	0.0015	0.0162	0.0062
CH_4	kg	0.0029	0.0304	0.0095
CH_4 biogenic		0.0216	0	0
Polycyclic organic matter (POM)	kg	0.00050	0	0
Formaldehyde (HCOH)	kg	0.00013	0.0013	0
Total organic compounds (TOC)	kg	0.00387	0.0391	0.0461
Non-methane TOC	kg	0.00084	0.0085	0
Volatile organic compounds	kg	0	0	0.0227
Emission to land				

	Unit	Quantity		
		Baggase	**Fuel Oil**	**Natural Gas**
Furnace ash	kg	12.90	0	0

d. Bagasse to Compost

It is proposed, based on the results obtained from Chapter 3, that bagasse, if not used to generate steam and electricity in the mill, to be mixed with filter mud and produce compost which should be returned to the cane fields. One ton of bagasse if mixed with 125 kg of filter mud (as per the actual amounts generated from the sugar mill) would result in 493 kg of compost. Inputs to this process are water and fuel consumed by the loader mixing the compost windrow every week. According to the IPCC (2006), composting will result in carbon dioxide and methane emissions which are considered biogenic, as well as nitrous oxide emissions, as presented in Table 5.11.

Table 5.11. Emission factors of composting of agricultural residues (IPCC, 2006)

Item	**Value/Assumption**
CO_2 biogenic	0.44 kg/kg dry solids treated
CH_4 Biogenic	0.004 kg/kg wet waste treated
N_2O	0.0003 kg/kg wet waste treated

The inventory associated with composting 1 ton of bagasse is presented in table 5.12.

Table 5.12. LCI for Production of 493 kg of Compost from 1 ton of Bagasse

	Unit	Quantity
1. Inputs		
Inputs from Technosphere		
Bagasse	kg	1000
Filter Mud	kg	125
Water from River	m^3	0.435
Diesel fuel	kg	5
2. Outputs		
Emissions to air (from composting)		
CO_2, Biogenic	kg	214.8
CH_4, Biogenic	kg	4.38
N_2O	kg	0.329

5.3.3 Impact Assessment

a. Bagasse to Paper

The main impacts associated with the production of 238 kg of paper from 1 ton of bagasse, as shown in the process network in Figure 5.10, are attributed to:

- Emissions from pulp and paper production from pulping, paper making and combustion of natural gas and pith by 72.64 % (0.04773 out of 0.0657).
- Natural gas production which is used in the power house of the paper mill for production of steam and electricity by 12% (0.00792 out of 0.0657).
- Quicklime production as 6.36% (0.00418 out of 0.0657).
- Other chemicals used in pulping such as chlorine dioxide and sodium hydroxide 5.22 % (0.00343 out of 0.0657).
- Virgin pulp used in the process, assumed here as sulphate pulp from Eco-invent database by 3.7 % (0.00244 out of 0.0657).

The impact categories most contributing to these sources of impacts, as presented in Figures 5.11, are:

- Fossil depletion from use of natural gas in the paper mill, for production of virgin pulp and production of chemicals used in the pulp and paper production.
- Climate change due to emissions associated with use of kraft pulping process, combustion of natural gas, pith generated from the depithing process as well as production of natural gas, quicklime and sulphate pulp.
- Agriculture land occupation due to wood cultivation for the production of virgin pulp (sulphate pulp).
- Human toxicity due to the production of sodium hydroxide, virgin sulphate pulp, chlorine dioxide and natural gas.
- Particulate matter formation due to emissions of PM_{10} and $PM_{2.5}$ from kraft pulping and from particulate emissions associated with pith burning as well as production of virgin sulphate pulp and natural gas.
- Marine ecotoxicity and freshwater eutrophication are mainly attributed to manufacture of virgin sulphate pulp as well as sodium hydroxide and chlorine dioxide.
- Photochemical oxidation is attributed to production of natural gas, virgin pulp and chlorine dioxide.

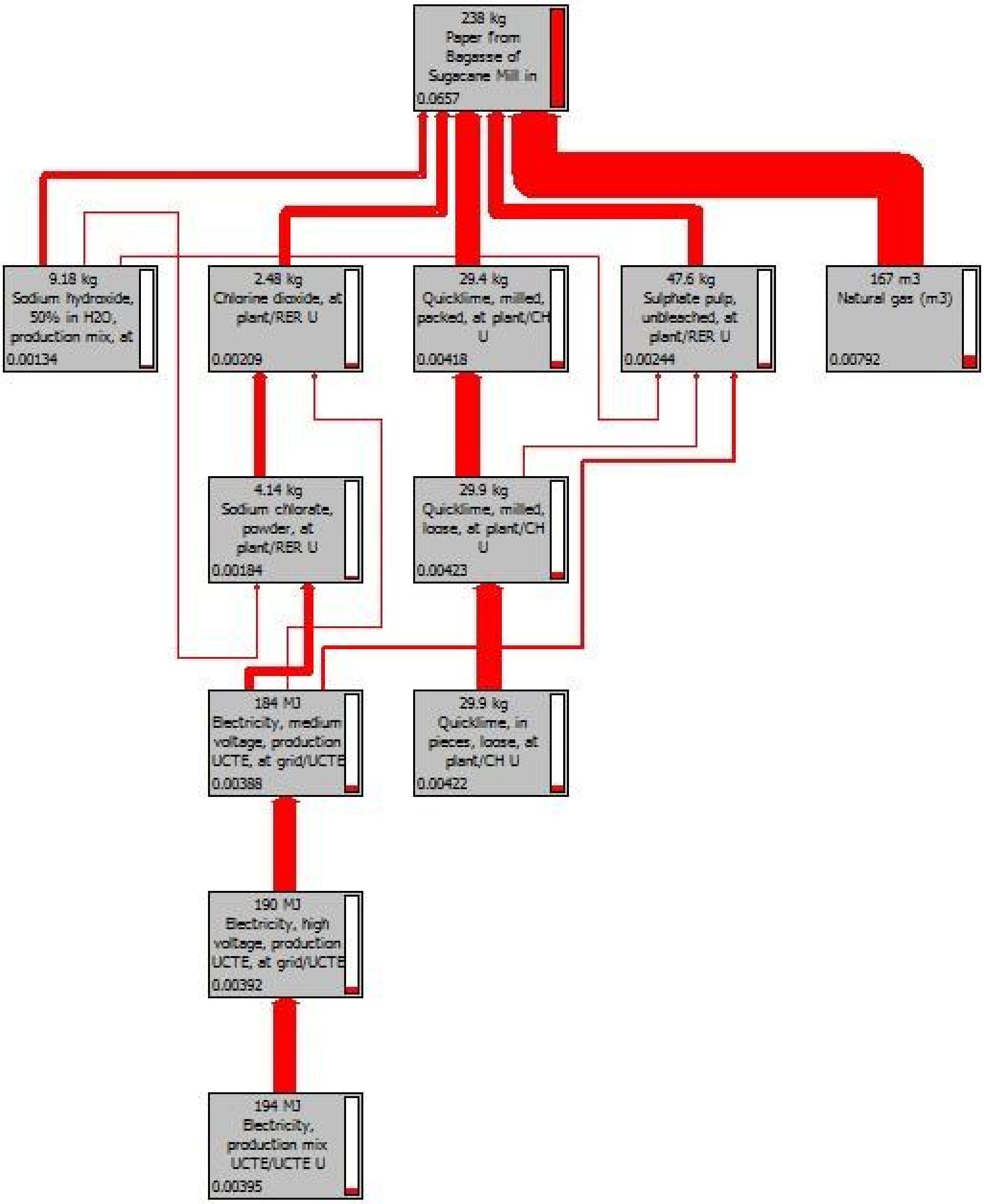


Figure 5.10. Process network for the production of 238 kg of paper from 1 ton bagasse (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

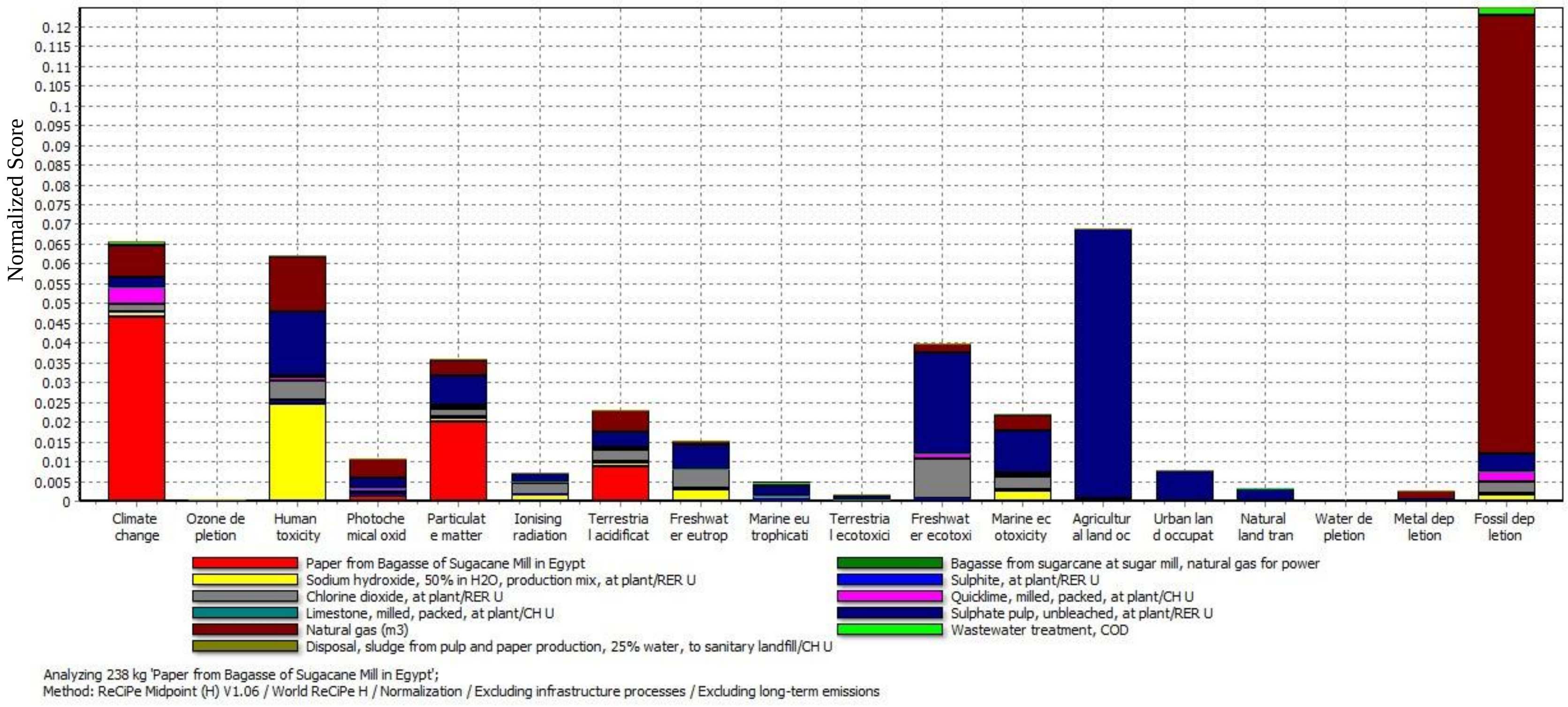


Figure 5.11. Normalized impacts of production of 238 kg of paper from 1 ton bagasse in Egypt (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

The life cycle impacts for paper production from bagasse in Egypt were compared to a newspaper (0% de-inking) produced from virgin wood in Europe with similar pulping process. As shown in Figures 5.12 and 5.13, it can be concluded that:

- Paper production from bagasse in Egypt consumes more fuel (natural gas) and so the fossil depletion is higher and hence climate change impacts are also higher due to greenhouse gas emissions associated with combustion of natural gas.
- Particulate matter formation is almost the same but slightly higher in case of paper produced from bagasse due to PM_{10} and $PM_{2.5}$ emissions.

However, paper produced from bagasse in Egypt showed better environmental performance in the following impact categories, in order of magnitude of impact:

- Human toxicity
- Agriculture land occupation
- Freshwater ecotoxicity and eutrophication
- Marine ecotoxicity
- Ionizing radiation
- Terrestrial acidification
- Photochemical oxidation

The above can be attributed to the fact that paper from wood requires agricultural land for production of virgin pulp. More chemicals and electricity are used in the production of paper from wood than that of bagasse.

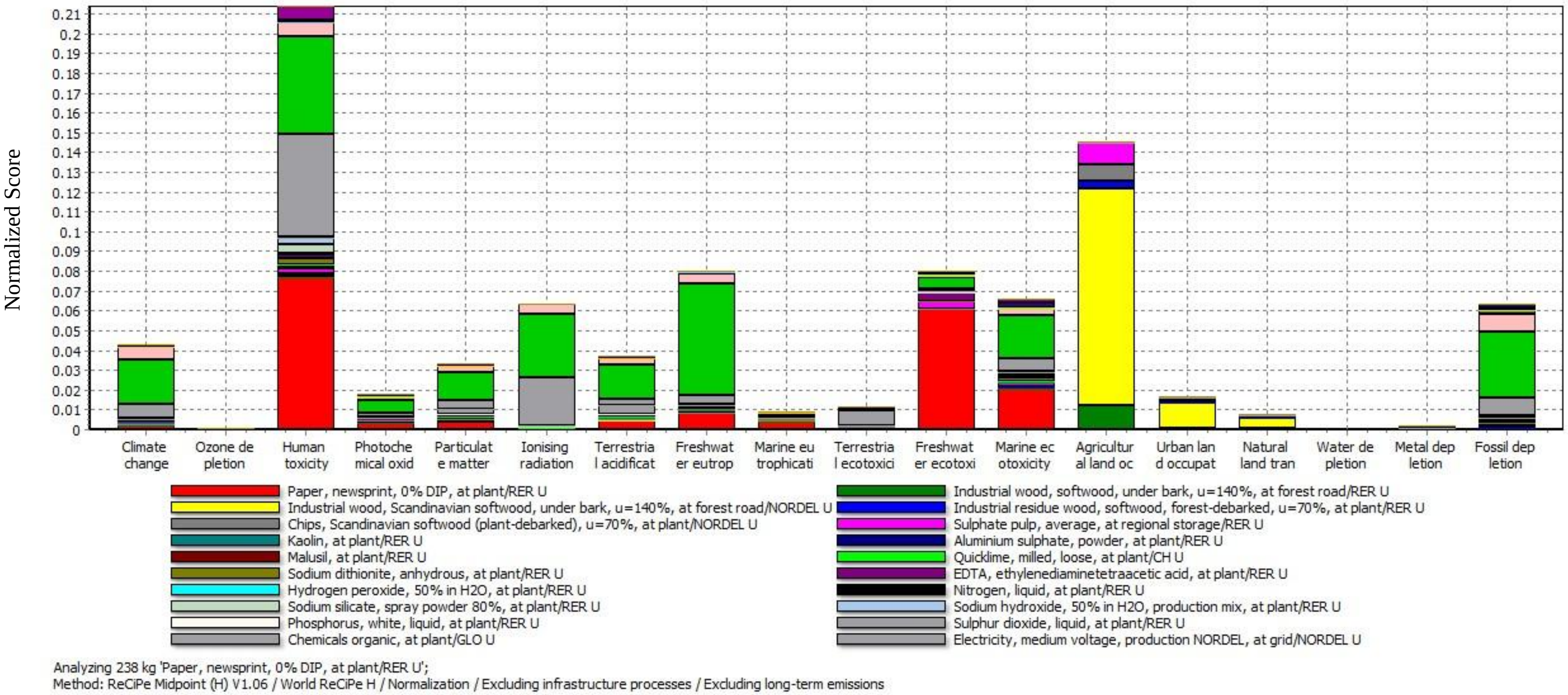


Figure 5.12. Normalized impacts of production of 238 kg of paper from wood in Europe (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

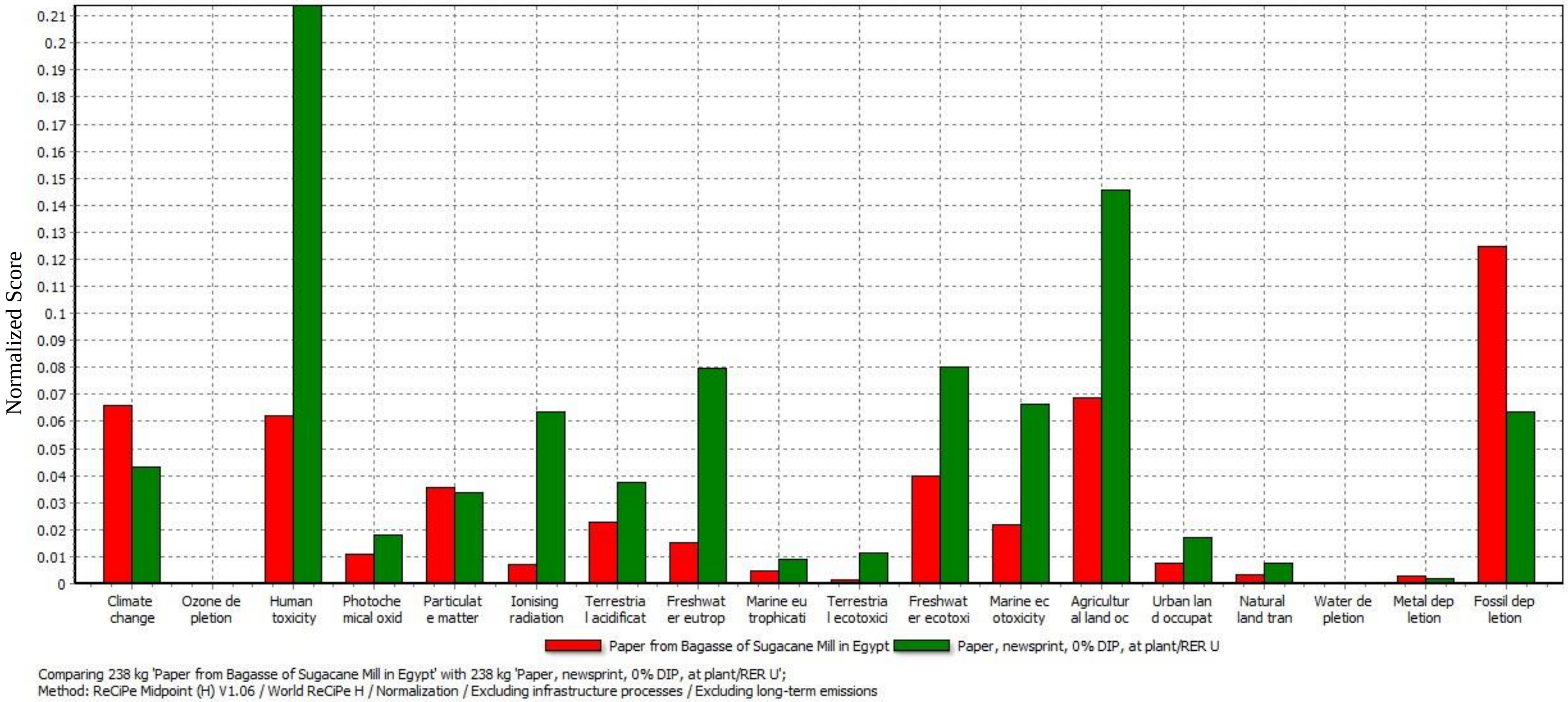


Figure 5.13. Normalized impacts comparing paper produced from bagasse in Egypt and paper produced from wood in Europe

(Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

b. Bagasse to Fiberboard

As for medium density fiberboard (MDF) that can be produced from 1 ton of bagasse, impacts associated with its production scored by Recipe midpoint method by 0.0361 points, are shown in Figure 5.14. These impacts are directly related to:

- Urea formaldehyde production which is the main chemical used in fiberboard making, and contributes by 35% (0.0126 out of 0.0361).
- Electricity supplied to the plant contributes by 30% (0.0108 out of 0.0361).
- Emissions from fiberboard manufacturing and combustion of natural gas used as fuel by 29.5% (0.0106 out of 0.0361).
- Natural gas fuel by 5.5% (0.00199 out of 0.0361).

Significant impact categories related to the attributes of production of fiberboard from bagasse, as presented in Figures 5.15:

- Human toxicity associated with the manufacture of urea formaldehyde resin and from the production of electricity that is used by the fiberboard factory, as well as from natural gas production.
- Fossil depletion due to the use of natural gas in manufacture of urea formaldehyde and in the production of heat in the fiberboard mill, as well as fuel mix used in the production of electricity supplied to the mill.
- Marine ecotoxicity and freshwater ecotoxicity due to the manufacture of urea formaldehyde and electricity.
- Climate change human health mainly from greenhouse emissions associated with production of urea formaldehyde and combustion emissions from natural gas in the fiberboard, in addition to fuel mix used to produce electricity supplied to the mill.
- Freshwater eutrophication and ionizing radiation from manufacture of urea formaldehyde
- Particulate matter formation and photochemical oxidation due to urea formaldehyde production and fuel mix combustion to produce electricity supplied to the fiberboard mill.

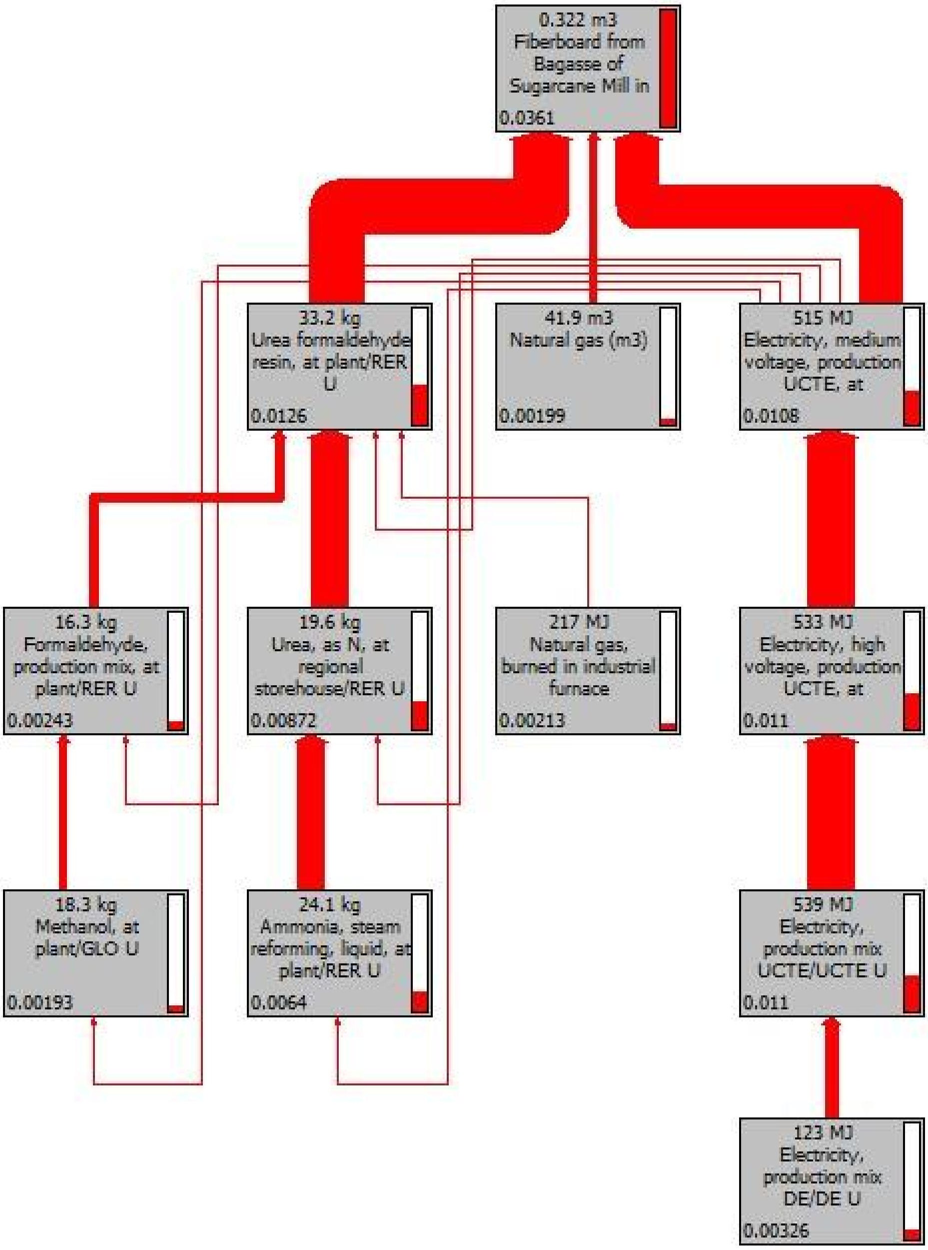


Figure 5.14. Process network for the production of 0.322 m^3 of fiberboard from 1 ton bagasse (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

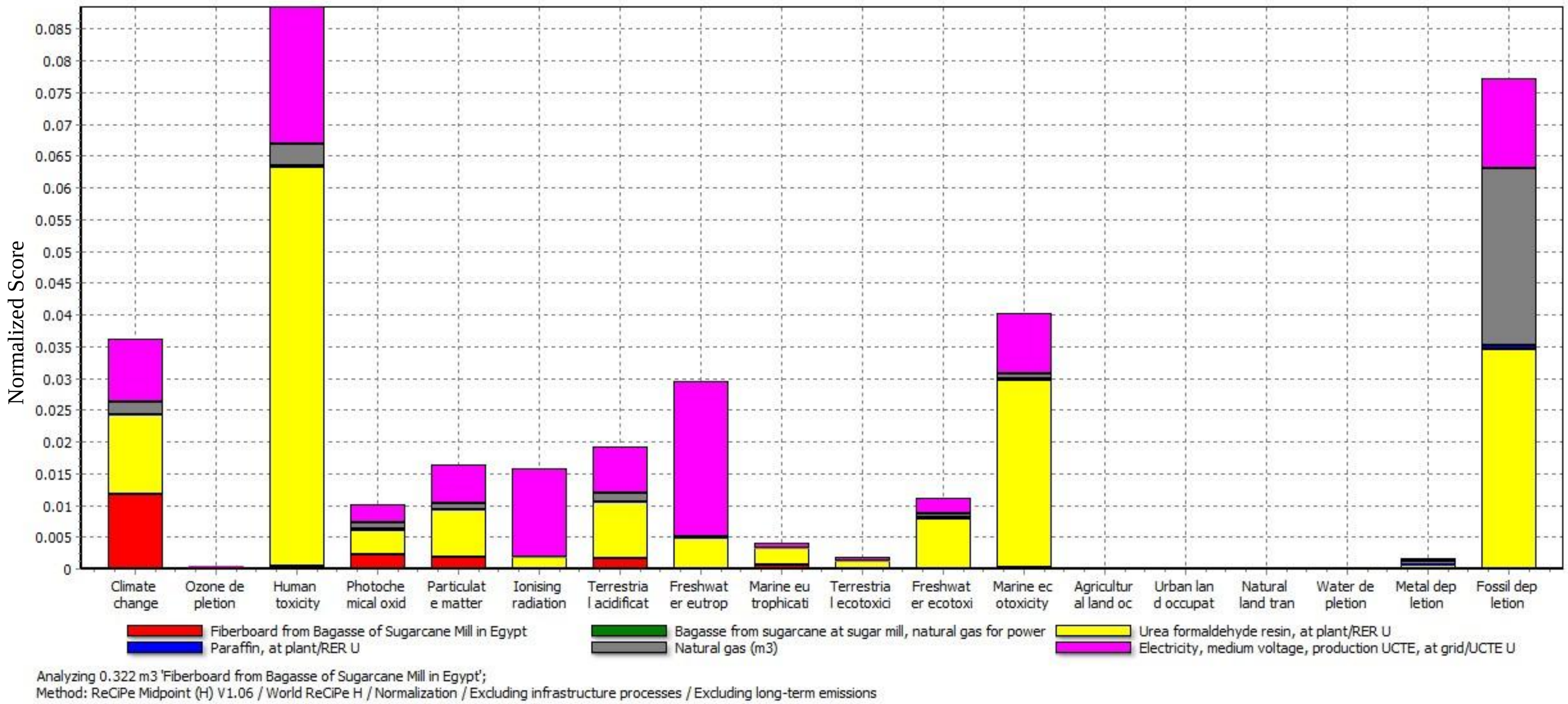


Figure 5.15. Normalized impacts of production of 0.322 m^3 of fiberboard from 1 ton bagasse in Egypt (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

MDF production from bagasse in Egypt is compared to a similar process of producing MDF from wood in Europe. It is concluded that the former has higher impacts than the latter due to the following, as illustrated in Figures 5.16 and 5.17:

- Fossil fuel depletion is higher in the fiberboard production from bagasse due to higher consumption of fuel both in the fiberboard factory, to produce electricity required by the factory or to make urea formaldehyde.
- Climate change is also higher as it is directly related to the fossil fuel consumption in the factory.
- Terrestrial acidification and marine ecotoxicity is higher in bagasse MDF due to the high consumption of urea formaldehyde than that used in the wood MDF factory in Europe.

However, MDF from bagasse show better environmental performance in terms of the following impact categories:

- Agricultural land occupation is higher for fiberboard produced from wood due to the land needed to cultivate wood trees.
- The human toxicity is higher incase MDF is manufactured from wood due to the burning of wood chips (soft wood) in the mill's furnace. This also contributes to the rise in terrestrial ecotoxicity.

Both processes show similar performance in terms of photochemical oxidation, particulate matter formation, ionizing radiation and freshwater eutrophication.

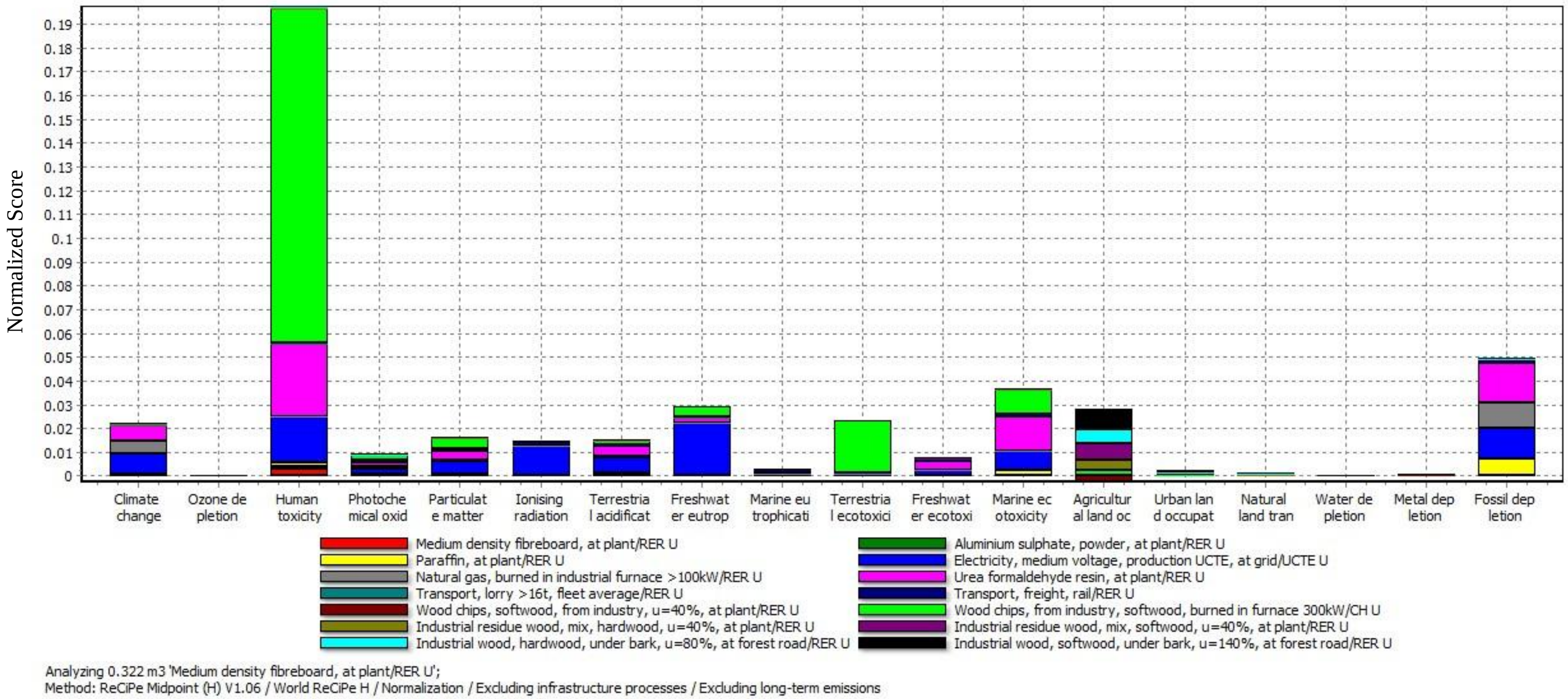


Figure 5.16. Normalized impacts of production of 0.322 m^3 of fiberboard from wood in Europe (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

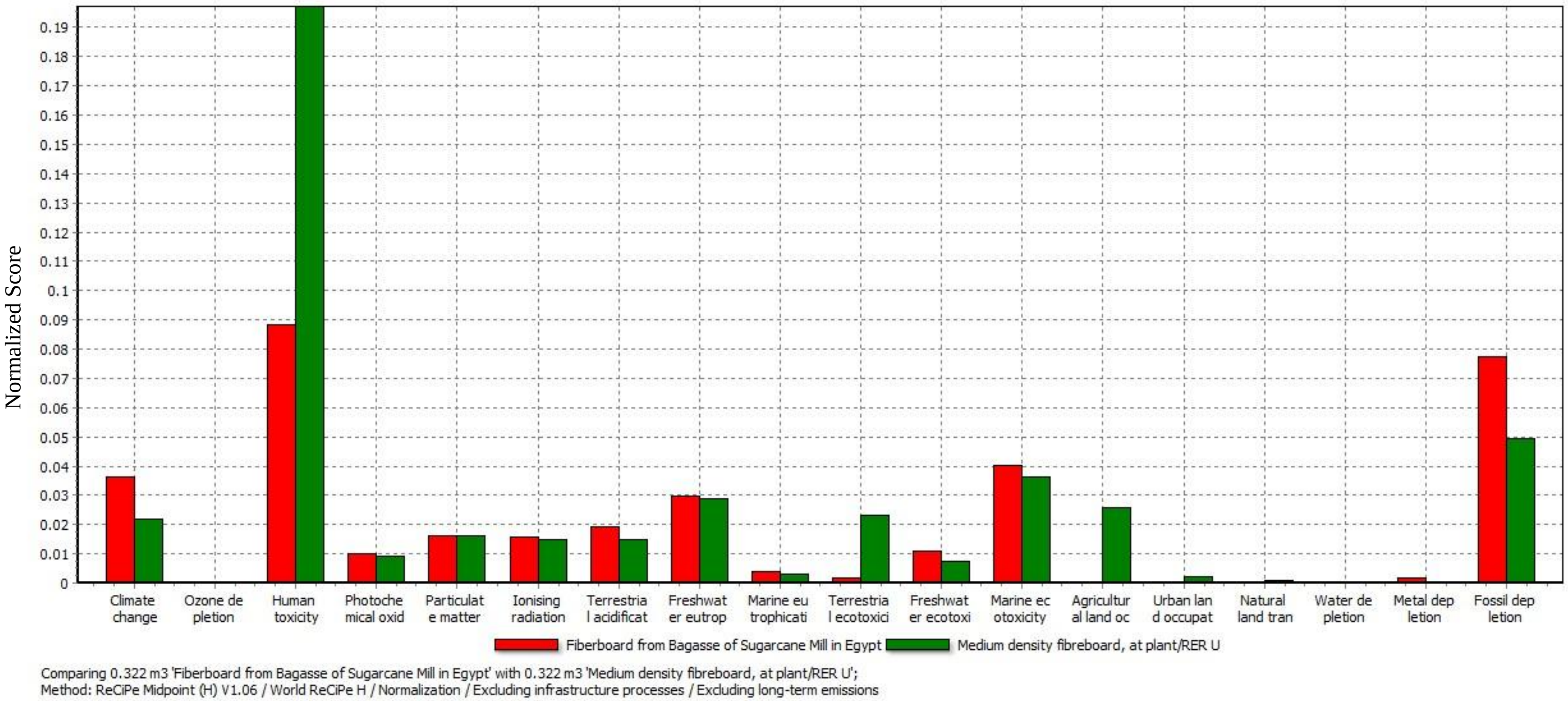


Figure 5.17: Normalized impacts comparing production of MDF from bagasse in Egypt and MDF from wood in Europe (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

c. Bagasse for Steam and Electricity Generation

A comparison was made for production of steam and electricity for the sugar mill from the three possible fuel sources:

1. Bagasse with a quantity of heavy oil to enhance the combustion process
2. Heavy fuel
3. Natural gas

It is concluded from LCA of the three options that steam and electricity generation using heavy oil as fuel is the least environmental friendly, because it has the highest impacts in terms of terrestrial acidification, particulate matter formation, fossil depletion, climate change, marine and freshwater ecotoxicity, human toxicity and photochemical oxidation, as illustrated in Figure 5.18.

Impacts associated with the use of natural gas are higher than those of bagasse for fossil depletion, climate change, human toxicity and photochemical oxidation.

However, steam and electricity generated from bagasse and heavy oil mix have higher impacts as compared to natural gas for particulate matter formation, terrestrial acidification, freshwater and marine toxicity. Particulate matter formation is attributed to the bagasse combustion, while the remaining impacts are more related to the combustion of heavy oil used for the combustion start up.

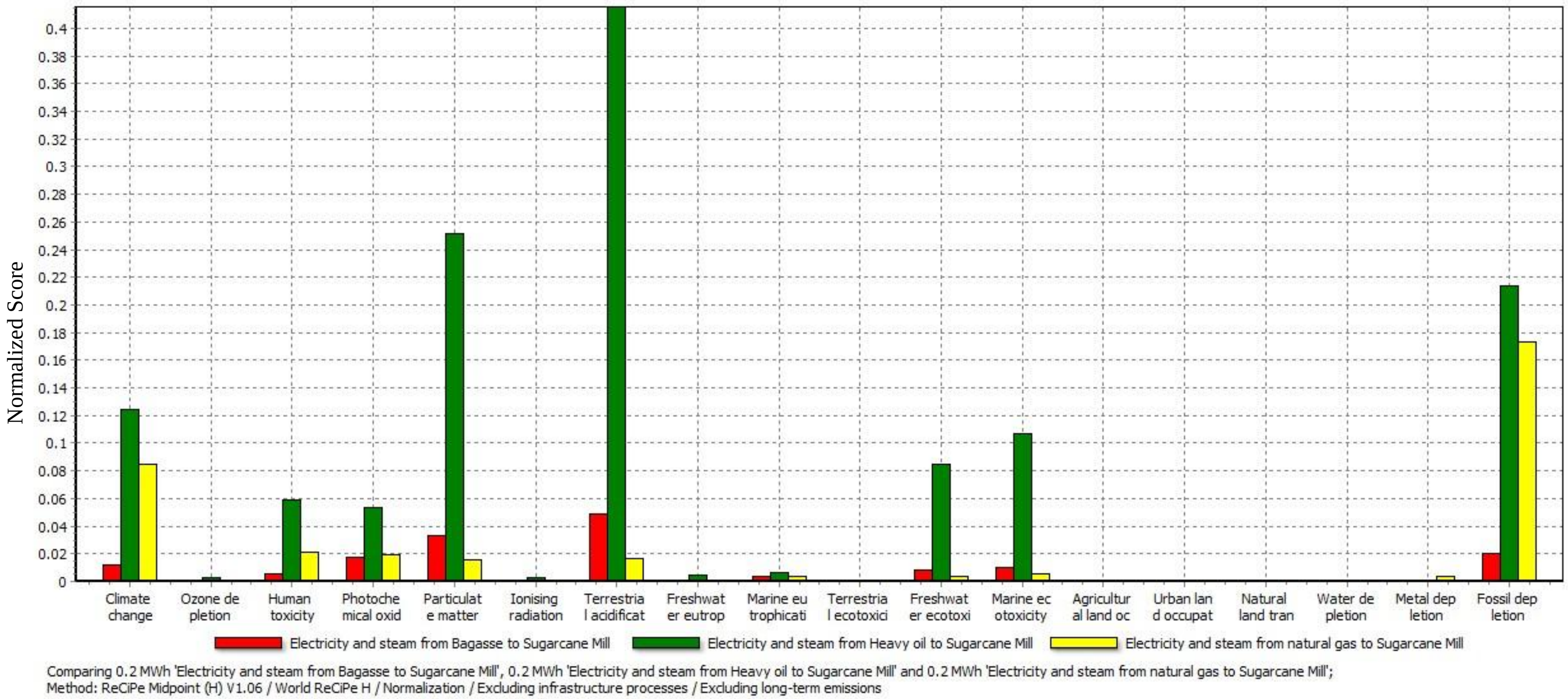


Figure 5.18. Normalized impacts of production of 0.2 MWh of electricity and 1.6 tons of steam from bagasse, heavy oil and natural gas (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

d. Bagasse as Compost

When 1 ton of bagasse generated from the sugar mill is mixed with 0.125 tons of filter mud (the ratio of 8:1 as produced from the mill), the mix will result in 493 kg of compost as per calculations of Table 3.9. If we consider only the impacts of composting, the main impact category will be the climate change and photochemical oxidation from greenhouse gas emissions resulting from composting, which are mainly the nitrous oxide as the carbon dioxide and methane emissions are considered biogenic as shown in Figure 5.19. There are also some minor impacts from the use of diesel as fuel for compost turning which are fossil depletion as well as freshwater, marine and human ecotoxicity and negligible impacts associated with terrestrial acidification and particulate matter formation.

However, the compost will have an NPK content of nutrients (as determined by the pilot experiment in Chapter 3) and so it can replace the following amounts of synthetic fertilizers:

- 1.74 kg urea as N
- 1.3 kg of ammonium nitrate as N
- 2.4 kg of single phosphate as P_2O_5
- 0.8 kg of potassium sulfate as K_2O

These amounts of synthetic fertilizers are entered in the compost data inventory sheet as avoided products and the LCA result shows environmental improvements, as illustrated in Figure 5.20 in terms of fossil depletion, freshwater eutrophication, human toxicity, marine ecotoxicity, freshwater ecotoxicity, terrestrial acidification and particulate matter formation.

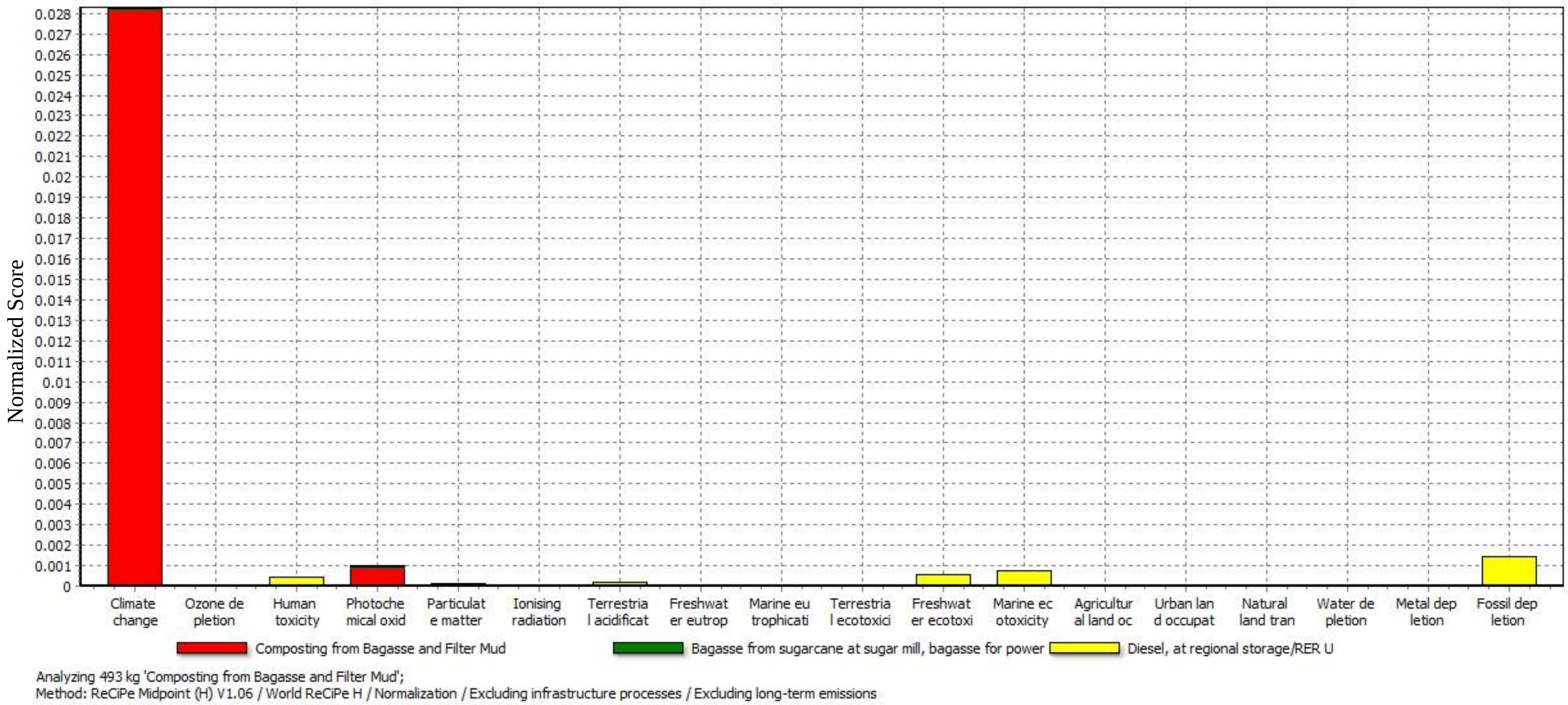


Figure 5.19. Normalized impacts of production of 493 kg of compost from 1 ton of bagasse mixed with 0.125 tons of filter mud (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

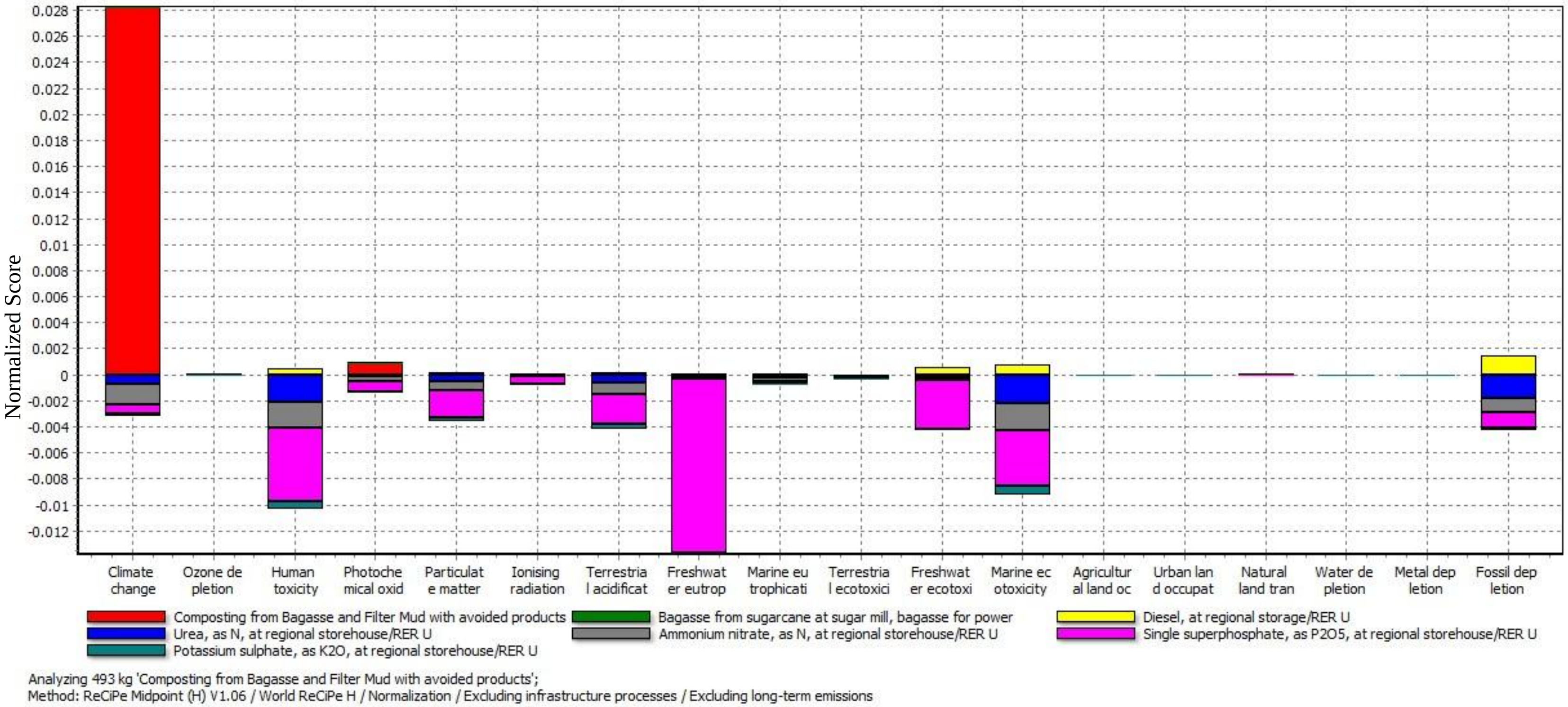


Figure 5.20. Normalized impacts of production of 493 kg of compost from 1 ton of bagasse and 0.125 tons of filter mud and avoided synthetic fertilizers
(Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

e. Comparing Bagasse Reuse Options

Comparing the life cycle impacts associated with fiberboard, paper, electricity and compost production, we can deduct that bagasse reuse in paper production is the least environmental friendly as it has the highest impact in terms of fossil depletion, climate change, particulate matter formation, agricultural land occupation, freshwater ecotoxicity, urban and natural land occupation, as presented in Figure 5.21. It also has high impact in terms of human toxicity. This is attributed to the highest consumption of fossil fuel for power generation, emissions due to fuel combustion and due to the kraft pulping process and finally due to the use of virgin pulp (consumption of land for trees).

The second least preferable option is fiberboard production from bagasse as it is also high in terms of human toxicity, fossil depletion, marine ecotoxicity, climate change and freshwater eutrophication. This is mainly due to high fossil fuel consumption, use of urea formaldehyde and fossil fuel mix used in the operation of electricity required for the production process.

This is followed by electricity production as it has impacts related to terrestrial acidification, particulate matter formation, photochemical oxidation, fossil depletion and freshwater and marine ecotoxicity, mainly from combustion of bagasse- heavy oil mix as fuel.

As for production of compost from bagasse, it has the lowest overall impact. However, it has higher impact in terms of climate change than the electricity generation alternative due to the nitrous oxide emissions released during composting.

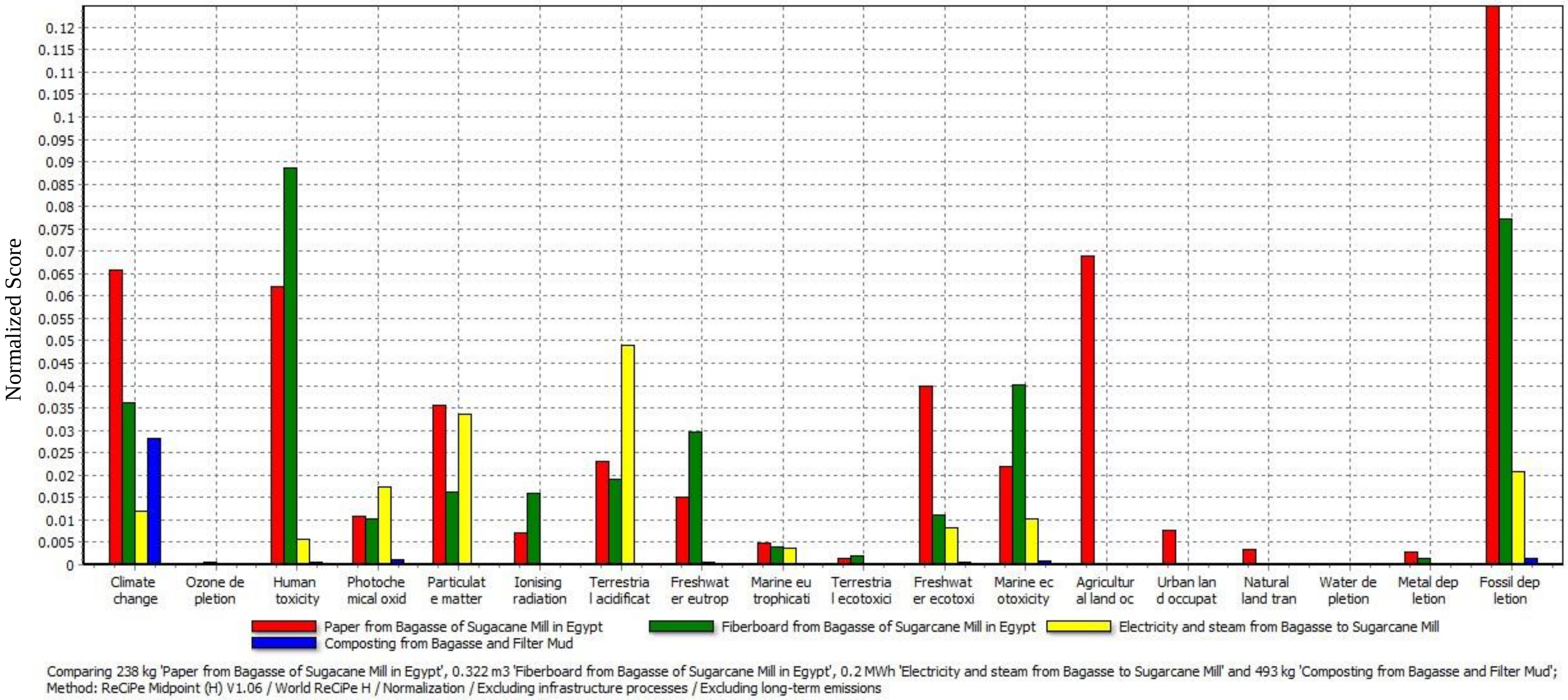


Figure 5.21. Comparison of normalized impacts for the four options of reuse of 1 ton of bagasse (Recipe Midpoint (H) V1.06/World Recipe H/normalization in SimaPro version 7.3.3)

5.4 Summary of Findings

It can be concluded that the agricultural stage contributes by more than 60% to the total environmental impacts of the sugar industry in Egypt, while the industrial stage impacts are responsible for about 40% of the impacts. The main contributor to the impacts of the agricultural stage is the current act of sugarcane burning in the fields post harvest which accounts to 60% of the impacts, followed by the manufacture of inorganic fertilizers and finally fuel consumption for irrigation and transportation. As for the industrial stage, the main contribution to environmental impacts is attributed to the steam and electricity generation using bagasse and start up heavy oil.

Stopping the dry leaves burning contributed positively to the environmental performance of the agricultural stage. Further improvement is achieved when the dry leaves are composted and used as soil additive replacing some of the NPK inorganic fertilizers. Reduction in the amount of fertilizer will decrease the impacts associated with its manufacture and impacts resulting from the washout of the nutrients from the inorganic fertilizers.

Composting filter mud and ash residues and returning the compost to the agricultural fields will further increase the environmental benefits of replacing the inorganic fertilizer by the organic ones.

A similar LCA study carried out in Mauritius (Ramjeowon, 2008), concluded that the environmental impact of the cane cultivation, including fertilizer and herbicide manufacture, is five times that of the electricity generation in the power plant. It proposed that measures that would reduce impacts are effective control of fly ash emissions from the boiler, optimization of fertilizer and herbicide use and effective irrigation to reduce water consumption. Bagasse-derived electricity, as compare to fossil fuel-derived electricity, has benefits in terms of greenhouse emissions, acidification, human toxicity, summer smog and non-renewable energy output but have drawbacks as related to freshwater consumption and eutrophication (Ramjeowon, 2008).

Another study carried out in Brazil explained that cane straw burning practice implemented prior to harvesting should be stopped to improve the photochemical ozone and human toxicity indicators and benefit the global warming potential as emissions of hydrocarbons, methane and carbon monoxide will be eliminated. If the straw is used instead to improve soil conditions, it will improve nutrient enrichment potential (Lopes Silva et al., 2012).

Moreover, impact assessment carried to the reuse options of bagasse concluded that paper produced from bagasse in Egypt as compared to that produced from wood in Europe consumes more fuel (natural gas) and so the fossil depletion is higher and hence climate change impacts are also higher due to greenhouse gas emissions associated with combustion of natural gas. However, paper from bagasse showed better environmental performance in terms of human toxicity, freshwater ecotoxicity and eutrophication, marine ecotoxicity, ionizing radiation, terrestrial acidification and photochemical oxidation due to the use of more electricity and chemicals in case of paper production from wood. Also agriculture land occupation is higher in wood paper due to the need to cultivate wood to produce the virgin pulp.

A similar LCA carried out in Iran for the production of paper from non-virgin material (bagasse) concluded that the environmental performance of production can be improved if the fuel oil used is substituted with more friendly energy source and the use of chlorine as a bleaching agent can be replaced and that recycled paper is added as raw material rather than ‘kraft pulp’ (Poopak and Reza, 2012).

When fiberboard (MDF) manufactured from bagasse was compared to that manufactured from wood, it was concluded that it had higher environmental impacts in terms of fossil fuel consumption in the fiberboard factory, to produce electricity required by the factory or to make urea formaldehyde. It was also higher in terms of climate change due to the fossil fuel combustion and terrestrial acidification and marine ecotoxicity due to the high consumption of urea formaldehyde. However, MDF from bagasse show better environmental performance in terms of agricultural land occupation as it has lower virgin pulp content, human toxicity as well as terrestrial ecotoxicity.

As for comparing the environmental performance of the alternative fuels used for production of steam and electricity in the sugar mill, it was concluded that heavy oil was the least environmental friendly in almost all impact categories. Impacts associated with the use of natural gas are higher than those of bagasse for fossil depletion, climate change, human toxicity and photochemical oxidation but lower in terms of particulate matter formation, terrestrial acidification, freshwater and marine toxicity. A similar conclusion was reached by Mashoko et al. (2013) when a study in South Africa proved that bagasse electricity results in higher energy gain than coal and shows significant environmental benefits associated with reduction in greenhouse emissions and sulfur dioxide emissions especially at higher efficiencies.

Composting of the bagasse had minimal impacts associated with emission of greenhouse emissions but had environmental benefits associated with the reduction of inorganic fertilizers in the agricultural fields due to its replacement with organic fertilizer generated from the composting activity. This would contribute to the reduction of environmental impacts of inorganic fertilizer manufacture.

Finally when comparing all alternatives of bagasse use, it was found that bagasse reuse in paper production is the worst environmental performance followed by fiberboard mainly because of the high fossil fuel consumption of both alternatives and due to the chemicals used in their manufacture. The use of bagasse for steam and power generation had better environmental performance except for some categories due to the use of heavy oil as a supplement to it during combustion. As for the production of compost from bagasse, it has the lowest overall impact. However, it has higher impact in terms of climate change than the electricity generation alternative due to the nitrous oxide emissions released during composting.

Kiatkittipong et al. (2009) also carried out a LCA of a four bagasse waste management options in Thailand including landfilling with utilization of the landfill gas, incineration for power generation, anaerobic digestion for biogas production and pulp production. It was concluded that using bagasse for pulp production had lower impacts than the production of pulp from eucalyptus. Landfilling was the least preferred as it consumes land space and generated considerable quantities of CH_4 and NH_3 that could affect the global warming potential and photochemical smog, if not properly controlled. Bagasse incineration for power had lower environmental impacts than power generation from fossil fuel except in terms of photochemical oxidant potential and among the three energy recovery systems, anaerobic decomposition gave the best environmental performance (Kiatkittipong et al., 2009).

5.5 Proposal for Environmentally Balanced Sugarcane Industry

The findings of the experimental silage and compost production as well as life cycle assessment have set scientific grounds for the transformation of the sugarcane industry in Egypt into an environmentally balanced industry. According to the concept of industrial ecology, as explained in Chapter 2, 'waste utilization' is encouraged and the industrial system will imitate the natural one by conserving and reusing resources entirely in production and consumption. The plan proposes to work on the two stages of the sugarcane production process separately, which are the agricultural stage and industrial stage. This approach will minimize transportation costs and environmental impacts.

In the agricultural stage the following measures, as illustrated in Figure 5.22, are proposed to minimize the impacts associated with the cane cultivation and harvesting activities and close the natural cycle generating zero waste:

1. The green tops resulting from the harvesting activities should be shredded and ensilaged as soon as they are cut, to preserve their nutritional value and provide the farmer with animal feed reserve for his livestock. This will minimize the losses that were encountered when the green tops were directly fed to the livestock during the harvest season and were not totally consumed.
2. The dry leaves should be collected, shredded and mixed with animal dung to form a compost mix, which the farmers should water and turn for about 16-20 weeks to get good compost suitable for spreading back in the sugar field.

Based on the quantities of dry leaves generated per one hectare (10,000 m^2) of land, the compost piles or windrows will only require less than 100 m^2 of the hectare (less that 1% of land area). Each hectare would generate about 5 tons of compost replacing about 10.4% of the amount of fertilizers used per hectare.

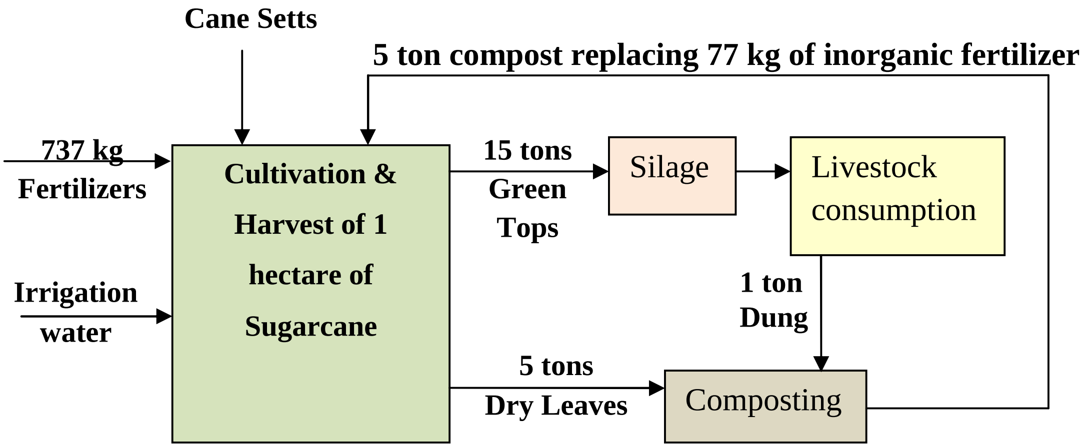


Figure 5.22: Proposal for zero waste sugarcane agricultural stage

As for the industrial stage, there are two proposed scenarios. The first scenario assumes that due to a deficiency or unavailability of natural gas, bagasse will be used to generated steam and electricity for the mill and hence the only residues generated from sugar mill are filter mud and furnace ash. In this case, every hectare of agriculture land will generate 3.5 tons of filter mud and 400 kg of furnace ash which is composted will give 1 ton of organic fertilizer. If this compost is returned to the sugarcane agricultural fields, it could replace 45 kg of the total amount of inorganic fertilizer currently used per hectare of land (about 6%).

The second scenario is that the bagasse is not used for steam and electricity generation in the sugar mill nor is it used for the production of paper or fiberboard. In that case, all the bagasse will be mixed with the filter mud to produce compost in the mill. One hectare of cane would generate 31 tons of bagasse and 3.5 tons of filter mud. If these are composted, they will result in 15.3 tons of compost with a NPK content that could replace 194 kg of the total amount of fertilizers used per hectare of cane (about 26%).

The two scenarios are illustrated in Figure 5.23 and 5.24. The percentage of land required in each sugar mill in Upper Egypt to produce compost for each scenario is shown in Tables 5.13 and 5.14.

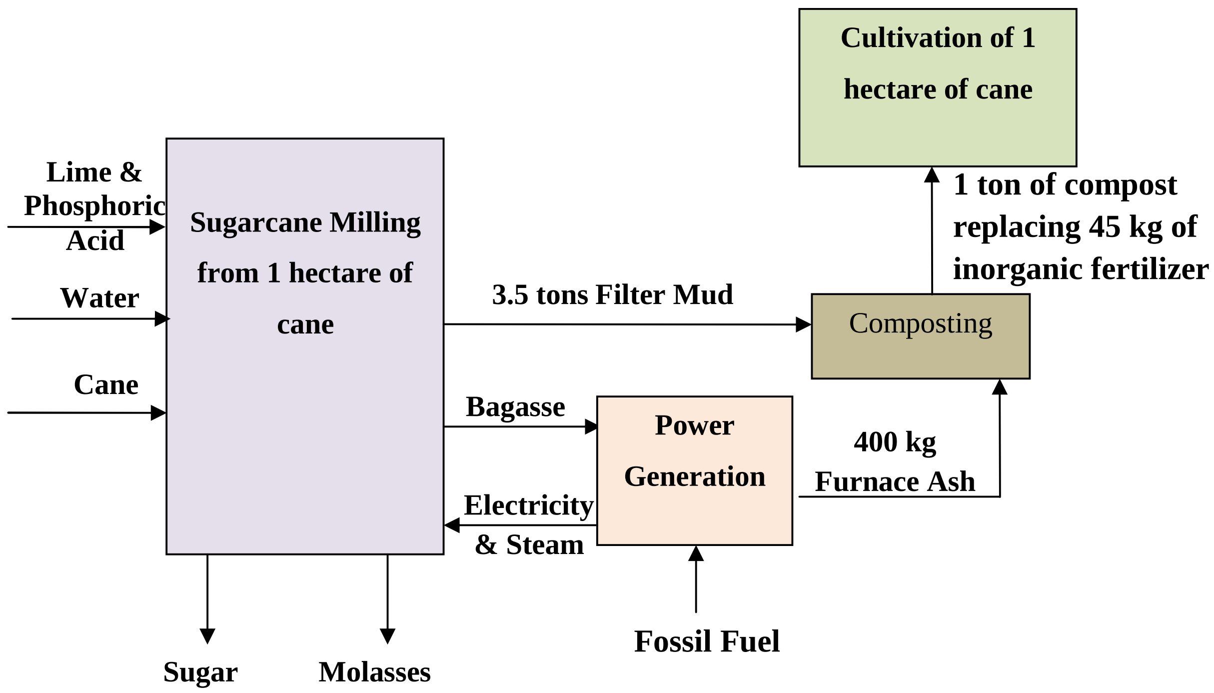


Figure 5.23: Proposal for zero waste industrial stage- scenario 1

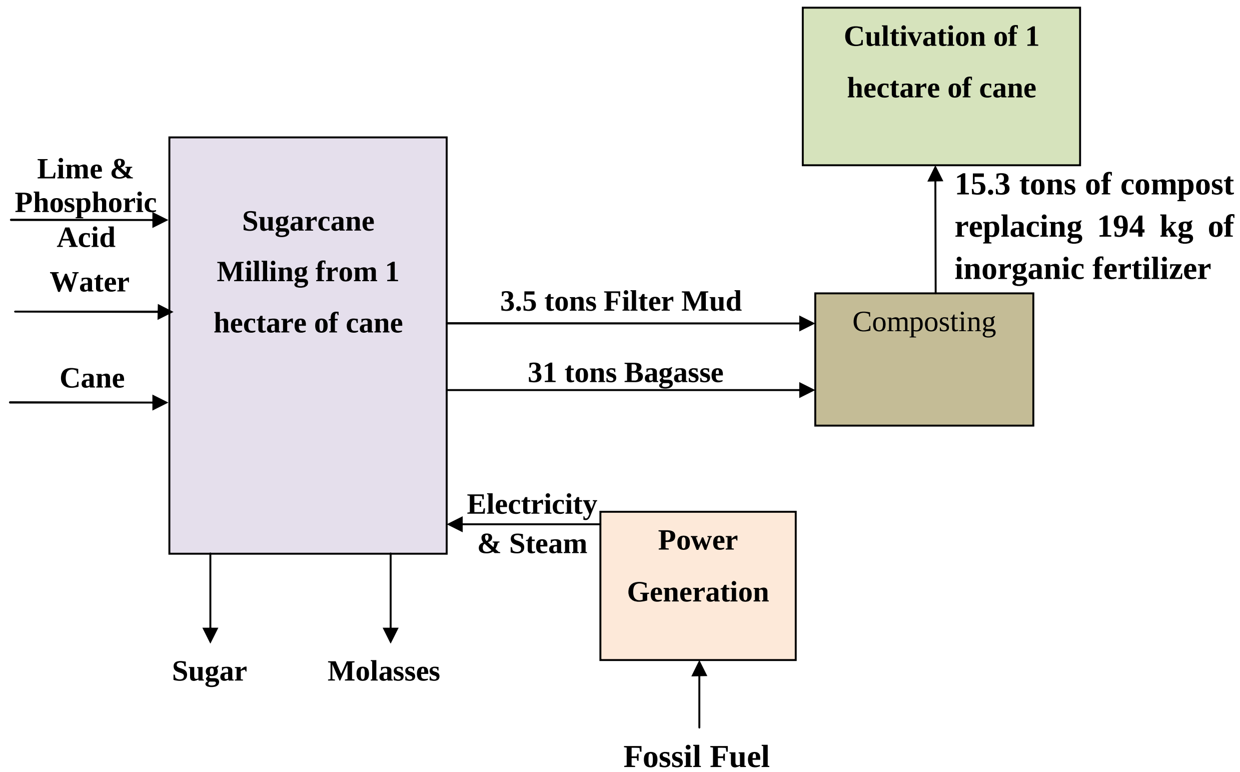


Figure 5.24: Proposal for zero waste industrial stage- scenario 2

Table 5.13: Land requirements in sugar mills for compost yards, compost produced and inorganic fertilizer replaced for scenario 1

Governorate	Mill	Mill Area (Hectare)	Filter Mud (tons)	Furnace Ash (tons)	Total Residues (tons)	Total Residues (m^3)	Compost Land Area (hectare)	Compost Land Area from Mill Area	Compost Produced (tons)	Inorganic Fertilizer Replaced (tons)
El Menia	Abou Korkas	4,163	14,283	1,632	15,915	27,067	4	0.09%	4,081	184
Sohag	Gerga	5,188	18,607	2,127	20,734	35,261	5	0.09%	5,316	239
Qena	Nagaa Hammadi	14,280	50,230	5,741	55,970	95,188	13	0.09%	14,351	646
	Deshna	8,132	28,402	3,246	31,648	53,824	7	0.09%	8,115	365
	Kous	16,003	52,389	5,987	58,377	99,280	13	0.08%	14,968	674
Luxor	Armant	13,288	46,221	5,282	51,503	87,591	12	0.09%	13,206	594
Aswan	Edfu	14,054	41,977	4,797	46,775	79,549	11	0.08%	11,994	540
	Komombo	19,048	63,744	7,285	71,029	120,797	16	0.08%	18,213	820

Table 5.14: Land requirements in sugar mills for compost yards, compost produced and inorganic fertilizer replaced for scenario 2

Governorate	Mill	Mill Area (Hectare)	Bagasse (tons)	Filter Mud (tons)	Total Residues (tons)	Total Residues (m^3)	Compost Land Area (hectare)	Compost Land Area from Mill Area	Compost Produced (tons)	Inorganic Fertilizer Replaced (tons)
El Menia	Abou Korkas	4,163	126,506	14,283	140,789	777,842	104	2.49%	62,437	792
Sohag	Gerga	5,188	164,806	18,607	183,413	1,013,334	135	2.60%	81,340	1,031
Qena	Nagaa Hammadi	14,280	444,892	50,230	495,122	2,735,482	365	2.55%	219,576	2,784
	Deshna	8,132	251,564	28,402	279,966	1,546,776	206	2.54%	124,159	1,574
	Kous	16,003	464,019	52,389	516,408	2,853,085	380	2.38%	229,016	2,904
Luxor	Armant	13,288	409,387	46,221	455,608	2,517,170	336	2.53%	202,052	2,562
Aswan	Edfu	14,054	371,799	41,977	413,776	2,286,056	305	2.17%	183,501	2,327
	Komombo	19,048	564,588	63,744	628,332	3,471,449	463	2.43%	278,652	3,533

Chapter 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions could be made as a result of the findings of Chapter 3 and 5 including pilot scale production of silage and compost from sugarcane residues, and life cycle assessment of current and proposed practices related to sugar cane industry:

1. Use of fertilizer in agricultural stage contributes to climate change and fossil fuel consumption and decreasing their use will have a positive impact.
2. Burning of dry leaves post cane harvest is one of the main sources of greenhouse gases and particulate matter formation and hence, stopping the practice of burning will reduce these impacts considerably.
3. Production of compost or organic fertilizer from residues of sugarcane agricultural and industrial stages, including dry leaves, filter mud, furnace ash and bagasse, has proven to be viable, as it gives high quality product that improves the soil's physical, chemical and biological properties.
4. Composting is an environmental friendly process as it has low impacts on the environment and replacement of inorganic fertilizers by the compost or organic fertilizer reduces its use, and thus its harmful impacts associated with their manufacture.
5. Production of silage from green tops is recommended as it provides a reserve of natural nutritional animal feed.
6. Use of bagasse inside sugar mills to produce its steam and electricity, instead of heavy oil or natural gas, has positive impacts in terms of reduction in global warming potential and fossil fuel consumption. However, its main drawbacks are in the particulate emissions which could be significantly reduced through installation of dust filters and increasing combustion efficiency.
7. Use of bagasse for paper production has the highest environmental impact due to the high consumption of fossil fuel, as well as emissions of greenhouse gases and particulate matter formation.

6.2 Recommendations

It is recommended to try to apply the LCA methodology to strategic national projects along with strategic impact assessment studies to identify the environmental performance of project alternatives during project planning phase. It is not sufficient for decision makers to rely on economic feasibility studies that neglect the environmental and social aspects of considered policies, plans or projects.

It is also recommended to promote the concept of green industries, eco-industrial parks and environmentally balanced industries in an attempt to close material and energy cycles, achieve zero waste and zero pollution and optimize on the use of energy.

This research has been conducted with the aim of providing supporting information about sugarcane residue reuse strategies in Egypt for decision makers. However, due to time constraints on data collection, this study only considers the environmental aspects of the current and potential uses of sugarcane residues. Therefore, to provide stronger supporting information for decision makers, further research to consider economic and social aspects is highly recommended.

It is proposed to apply results of this study combined with implementation of cost assessment for each alternative considering direct and indirect environmental costs due to substitution of synthetic fertilizers with organic fertilizers and fossil fuels with bagasse.

The life cycle inventory (LCI) for some processes used in this research, such as manufacture of fertilizers, electricity generation and transmission and chemical manufacture were based on the database from European countries. Due to lack of time, data and resources it was not possible at this stage to create a database for these processes in the Egyptian context but rather the Ecoinvent database provided by SimaPro 7.3.3 was utilized. It is thus recommended to formulate LCIs for these processes that are more representative for Egypt which would lead to more accuracy in the overall LCA results.

There is also an opportunity for improvement of the concept of environmentally balanced sugarcane industry in Egypt by including other waste streams that were not included in this study such as:

- Sludge generated from the wastewater treatment plants of the sugar mills, paper and fiberboard mills whether industrial or domestic wastewater
- Pith generated from the depithing of bagasse in the paper and fiberboard mills
- Lime mud generated from the chemical recovery unit of the paper mill

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APPENDIX A

Questionnaires

&

Letters to ESIIC CEO from AUC

Data for Sugarcane Milling

Energy

- Amount of electricity consumed in the process (kwh/ton cane)
- Amount of steam required for the process (kg/ton cane)
- Amount of fuel consumed in case of bagasse, heavy oil or bagasse

Production

- Material Balance (inputs & outputs)
- Type and amount of chemicals used in sugar milling

Type	Amount	Reason for use	Local/Imported
Limestone			
Hydrated lime			
Sodium hydroxide			
Hydrochloric acid			
Sulphuric acid			
Ammonium sulphate			
Others			

- Water Balance

Water use	Amount	Treatment Required

Environmental

Wastewater generated	Amount	Treatment/Disposal method

- Specification of treated effluent (TSS,COD, BOD_5, Total Nitrogen, Total Phosphorus) and final disposal method

- Amount of sludge generated and disposal method

- Physical and chemical composition of bagasse, filter mud and ash

- Air emissions

Parameter	Emission flow rate (m^3/hr)	Pollution load (ton/year)
CO		
SO_2		
NOx		
PM_{10}		
TSP		

- Air pollution control devices
- Solid waste type, amount and treatment/disposal method

Data for Fiberboard Production from Bagasse

Energy

- Amount of electricity consumed in the process (kwh/ton cane)
- Amount of steam required for the process (kg/ton cane)
- Amount of fuel consumed in case of natural gas, bagasse, heavy oil or pith

Production

- Material Balance (inputs & outputs)
- Type and amount of chemicals used

Type	Amount	Reason for use	Local/Imported
UF Resin			
Urea solution			
Free formalin			
Paraffin			
Parraffin emulsion			
Ammonium sulphate			
Others			

- Water Balance

Water use	Amount	Treatment Required

Environmental

Wastewater generated	Amount	Treatment/Disposal method

- Specification of treated effluent (TSS, COD, BOD_5, Total Nitrogen, Total Phosphorus) and final disposal method

- Amount of sludge generated and disposal method

- Air emissions

Parameter	Emission flow rate (m^3/hr)	Pollution load (ton/year)
Formaldehyde		
CO		
NOx		
SOx		
Filterable matter		

- Air pollution control devices
- Solid waste type, amount and treatment/disposal method

Data for Pulp and Paper Production from Bagasse

Energy

- Amount of electricity consumed in the process (kwh/ton cane)
- Amount of steam required for the process (kg/ton cane)
- Amount of fuel consumed in case of natural gas, bagasse, heavy oil or pith

Production

- Material Balance (inputs & outputs
- Type and amount of chemicals used

Type	Amount	Reason for use	Local/Imported
Sodium hydroxide			
Sodium sulfite			
Chlorine oxide			
Calcium hydroxide			
Calcium carbonate makeup			
Virgin pulp			

- Water Balance

Water use	Amount	Treatment Required

-

Environmental

Wastewater generated	Amount	Treatment/Disposal method

- Specification of treated effluent (TSS, COD, BOD_5, Total Nitrogen, Total Phosphorus) and final disposal method

- Amount of sludge generated and disposal method

- Air emissions

Parameter	Emission flow rate (m^3/hr)	Pollution load (ton/year)
PM10		
CO		
NOx		
SOx		
Suspended particles		
VOC		

- Air pollution control devices
- Solid waste type, amount and treatment/disposal method

THE AMERICAN UNIVERSITY IN CAIRO
Department of Mechanical Engineering

الجامعة الأمريكية بالقاهرة

السيد الاستاذ المحاسب المحترم/ محمد عبد الرحيم

رئيس مجلس الادارة والعضو المنتدب

شركة السكر والصناعات التكاملية

تحية طيبة وبعد،

نحيط سيادتكم علما بأن المهندسة/ داليا عادل حبيب الباحثة بكلية الهندسة بالجامعة الأمريكية بالقاهرة تقوم بإعداد رسالة دكتوراه عن موضوع بعنوان "تقييم دورة حياة صناعة السكر وبدائل إعادة إستخدام مخلفاتها" "Life Cycle Assessment of Sugar Industry and Its Waste Reuse Options" والخاص بشركتكم الموقرة، وفى هذا الصدد نأمل فى تعاون سيادتكم وشركتكم الموقرة لتسهيل مهمتها فى الحصول على البيانات الخاصة بهذا الموضوع. ولهذا نرفق لسيادتكم استبيان بالبيانات المطلوبة من الادارات المختلفة.

ونحن إذ نشكر سيادتكم على حسن تعاونكم،

تفضلوا بقبول فائق الاحترام والشكر،

Salah El Haggar

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د/ صلاح الحجا ر

الزميل / الفاضل د / سعد عبد اللطيف
٧ / ١١ / ٢٠١٣م

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السيد المهندس/ حسن كامل

رئيس مجلس الادارة والعضو المنتدب لشركة السكر والصناعات التكاملية المصرية

تحية طيبة وبعد،

نحيط سيادتكم علما بأن المهندسة/ داليا عادل نخلة تقوم بتحضير رسالة دكتوراة فى الهندسة لتعظيم الاستفادة من مخلفات صناعة قصب السكر فى مصر. ولهذا نرجو من سيادتكم تسهيل مهمتها والسماح لها بزيارة مصنع نجع حمادى للسكر وكذلك مصنع الورق بقوص ومصنع الفيبر بورد بدشنا وذلك للتعرف على مراحل تصنيع قصب السكر والمخلفات المتولدة وكيفية التعامل الحالى معها. كما نرجو السماح لها بالحصول على بعض البيانات الخاصة بطاقة الانتاج وكميات المخلفات والمنتجات المتولدة من الصناعة.

ونحن إذ نشكر سيادتكم على **حسن تعاونكم**،

تفضلوا بقبول فائق الإحترام والشكر،

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مع المصانع
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