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Environmental Performance Evaluation of Decentralized Wastewater Treatment Systems Using Life Cycle Analysis

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A

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Of

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DECLARATION

I, Nawraj Sapkota, hereby declare that this thesis entitled ***" Environmental Performance Evaluation of Decentralized Wastewater Treatment Systems using Life Cycle Analysis"*** is my original work and all other sources of information used are duly acknowledged. This research work has not been submitted to any other university for any academic award.

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ABSTRACT

Proper management of wastewater is a challenge for the cities in developing countries. The discharges of untreated wastewater into the urban rivers have huge impacts on public health as well as entire ecosystem of the earth. Therefore, treatment of wastewater is essential for the reduction of impacts on environment. Wastewater treatment plants remove the pollutant from the wastewater and thus reduce the pollutant load on the receiving water body. However the raw materials and energy required to build and operate the wastewater treatment systems also contribute to environmental burdens. Thereafter, the net environmental benefit of the wastewater treatment system can only be perceived by taking into account entire life cycle phases of the wastewater treatment system viz; construction, operation and demolition phases. In this study, Life Cycle Assessment (LCA) has been used as a tool for the sustainability assessment of small-scale decentralized wastewater treatment plants (WWTP) commonly used in developing countries. LCA is supportive to analyze the environmental burdens of WWTP that need to be a part of decision-making process towards sustainability. Life cycle assessment is known as cradle-to-grave analysis. LCA is a compilation and evaluation of the inputs, outputs and the potential environmental impact of a product system throughout its life cycle. The overall objective of the study is to analyze the environmental performance of the representative small-scale decentralized sanitation system.

In this study three-wastewater treatment scenario that consists of a combination of different small scale decentralized treatment methods are considered. The design capacities of the treatment modules used in the present study are 10 m^3/day and 50 m^3/day. The three Decentralized Wastewater Treatment (DEWATS) modules considered for the study are: 1) module 1 (DM1) consisting of Settler (S), Anaerobic Baffled Reactor (ABR), and Planted Gravel Filter (PGF), 2) module 2 (DM2) consisting of S, PGF and Collection Tank (CT) and 3) module 3 (DM3) consisting of S and PGF.

The Life Cycle Assessment was carried out as per ISO standards 14040-14044. In this study only the construction and operational phase was taken into account. The functional unit for this study is the treatment of wastewater generated by person equivalent over a period of 20 years.

In all modules, the greenhouse gas contribution (GWP) from the construction phase is 95% and 5% from operational stage. Acidification potential (AP) and Ozone layer depletion potential (ODP) are found to be 100% in construction periods. Among the treatment units, ABR has significant contribution to the eutrophication potential (EP). The other units like PGF, S and CT are responsible to the impact categories of AP, ODP and GWP. The study shows that configuration of the treatment units have an impact in the environmental performance. However, the more units the more environmental load is observed during the construction phase. On the other hand, increased in the units or treatment steps or modules increases the performance of system and hence decreases the environmental impacts of the whole system and vice versa. The production process of cement clinker, electricity, natural gas, brick, bituminous coal and transportation are responsible for the main impact during the construction phase. Based on the evaluation of three DEWATS modules, it cannot be said, which module is best, but the findings herein can support the decision-making process towards more sustainable DEWATS system.

Key words: life cycle assessment, sustainability, wastewater, DEWATS, emission, inventory

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ACRONYMS AND ABBREVATIONS

ABR	:	Anaerobic Baffled Reactor
AF	:	Anaerobic Filter
AP	:	Acidification Potential
BD	:	Biogas Digester
BOD	:	Biological Oxygen Demand
BORDA	:	Bremen Overseas Research and Development Association
CFCs	:	Chlorofluorocarbons
COD	:	Chemical Oxygen Demand
CT	:	Collection Tank
DEWATS	:	Decentralized Wastewater Treatment System
EIA	:	Environmental Impact Assessment
EMP	:	Environmental Management Plan
EP	:	Eutrophication Potential
EPA	:	Environmental Protection Agency
GWP	:	Global Warming Potential
IPCC	:	Intergovernmental Panel on Climate Change
ISO	:	International Standard Organization
LCA	:	Life Cycle Assessment
LCI	:	Life cycle Inventory
LCIA	:	Life cycle impact assessment
ODP	:	ozone layer depletion potential
PGF	:	Planted Gravel Filter
S	:	Settler or Septic Tank
SETAC	:	Society of Environmental Toxicology and Chemistry
SIA	:	Social Impact Assessment
SSWM	:	Sustainable Sanitation and Water Management

TN	**:**	**Total Nitrogen**
TP	**:**	**Total Phosphorous**
UN	**:**	**United Nations**
UNCSD	**:**	**United Nations Commissions on Sustainable Development**
UNEP	**:**	**United Nation Environment Program**
UNICEF	**:**	**United Nation International Children's Emergency Fund**
UV	**:**	**Ultraviolet**
VOC	**:**	**Volatile Organic Carbon**
WHO	**:**	**World Health Organization**
WWT	**:**	**Wastewater Treatment**
WWTS	**:**	**Wastewater Treatment System**

1. Introduction

Ongoing urbanization, changing environment, global warming, industrialization, unmanaged urban settlement, and population growth are all the factors that have serious impact on water sources. Wastewater comprises pathogens, organic matter, nutrients, chemicals, heavy metal and natural organic matter that are either in soluble or particulate form (Corcoran et al. 2010). Therefor discharge of wastewater into the water bodies is hazardous. In the world 2.3 billion people don't have access to adequate sanitation and every year over 300 thousand people die due to the diarrheal diseases, lack of sanitation and dirty water cause the death of 900 children's everyday (WHO/UNICEF 2014).

In developing countries direct discharge of wastewater into the water bodies (lakes, river etc.) and scarcity of safe drinking water are the major challenges. Wastewater discharge can have major impacts on aquatic biodiversity, public health and eutrophication. Therefore, the treatment of wastewater is necessary before it is discharged into the water bodies. Reuse of wastewater supports to reduce the scarcity of water worldwide (Frances 2013). The public understanding of adequate sanitation, health and hygiene might help to minimize the effects of waterborne diseases.

In South Asia a very smaller population used improved sanitation. In India and Nepal community leader of both rural and urban communities are well aware about safe drinking water and adequate sanitation (Water Aid Nepal 2011). India represents more than 16% of world's population; with the rapid increase in population, the production of wastewater is also increasing. India has more than 234 sewage treatment plants, which are situated along the bank of the major rivers (Kaur et al. 2012). In Nepal, more than 43% of the populations still practice open defecation system (Bright-Davies et al., 2015). Here, all wastewater are connected into the water bodies without treatment. Still a large number of households do not have access to a safe drainage network and un-safe discharge into the surface water is the consequence. In India about 75% of all contamination of surface water is due to the unsafe discharge of wastewater (Seshadri 2015). Due to the poor sanitation condition of developing and underdeveloped countries, it is difficult to meet norms for millennium development goal of 50% access of improved sanitation by 2015 and 100% by 2025.

Centralized or conventional wastewater treatment is one of the methods for wastewater management. Centralized Wastewater treatment is defined as off-site treatment method of centrally collected wastewater (Hophmayer-Tokich 2006). Traditionally, Centralized systems have been the best option for the municipal wastewater management and the method is widely accepted (Braadbaart 2006). Decentralized wastewater treatment, whereas, can be defined as cluster or onsite treatment, disposal or reuse of wastewater in small scale.

The adequate management of water and sanitation depends on the country's economy (Hophmayer-Tokich 2006). In south Asia, decentralized wastewater treatment (DEWATS) is more common and is also accountable with regards to economy, socio-cultural and environmental factors. Centralized systems are generally not a feasible option for poor communities and low-density area due to the high cost and weak institutions (Hophmayer-Tokich 2006). Due to the high construction and operational cost of centralized wastewater treatment, small-scale decentralized wastewater treatment is gaining acceptance in the developing countries (Massoud et al. 2009). The sustainability of the system is important for decision makers when establishing the wastewater treatment system

In Nepal and India, biological/biogas digester (BD), settler, anaerobic baffled reactor (ABR), anaerobic filter (AF), planted gravel filter (PGF), septic tank, constructed wetland (horizontal & vertical), collection tank, etc. are the DEWATS systems most commonly used (Gutterer 2009).

Sustainability is evaluated from three aspects: environment, economic and social. The term sustainability or sustainable development must be guided by ecological and political perspectives, which are interrelated with environmental conservation/protection, economical safeguarding and social welfare (Glavič, and Lukman 2007).

Technically, sustainability means avoiding a large footprint by using resources to produce and reproduce. The UN sponsored Brundtland Commission 1987 (World Commission on Environment and Development); defined sustainable development as *"….development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*.

1.1 Objectives of the Study

The overall objective of the study is to analyze the environmental performance of representative small scale decentralized sanitation system commonly used in India and Nepal. The specific objectives of the study are as follows:

- To make a life cycle inventory (material consumption and environmental releases) of small-scale sanitation systems.
- To identify the environmental hotspots for small-scale decentralized wastewater treatment system (WWTS) based on their environmental performance

1.2 Research Question

The following is the key questions on study:

- What are the major environmental burdens for the small scale decentralized wastewater treatment systems (DEWATS) ?
- How much the resources (energy and materials) are used in the DWATS?

1.3 Rational of the study

The main focus of this study is to access the sustainability or environmental impacts of small scale decentralized wastewater treatment systems. The scarcity of water has been experienced all over the world, as indirectly expressed as number of peoples are dying everyday due to the uptake of dirty water caused by poor sanitation. Therefore, the wastewater is necessary to treat before discharge into the water bodies. There are various methods for the treatment of wastewater. The quantity of wastewater is increasing day by day in the rural or semi-urban area where decentralized wastewater treatment is much popular because of the inadequate financial capacity for the development of infrastructure for conventional treatment. The scope of the study is based on the sustainability assessment of small-scale decentralized wastewater treatment units in south Asian countries (India and Nepal). Here, the life cycle assessment (LCA) is the method to identify the system sustainability for decision-making processes. This study will compare the environmental performance of the representative small-scale decentralized wastewater treatment units by using life cycle assessment (LCA). The results are intended to be useful to the decision makers and for the development of new guidelines with respect to the impacts onto the environment, economy and technology.

1.4 Overview of the Contents

The final output of this study consists of five main chapters along with reference and annexes. The brief descriptions are below:

Chapter 1 introduces the overall water and sanitation problem in the world and south Asia. Further, this chapter discusses the overview on wastewater treatment system in India and Nepal, statement of problems, objectives, research questions, scope and limitations.

Chapter 2 includes the review of literature. Literature review focused on the previous similar studies, tools used for the sustainability assessment of the WWTS.

Chapter 3 gives the details of the methodology used for the study. It provides a detailed description of the different DEWATS modules used in this study. It describes the method of LCA used, scope and goal, study of boundaries, functional units and limitations, and overview of ISO 14040, software 'SimaPro 7.0,

Chapter 4 presents the life cycle inventory data sheet and findings of the study under the topic results. Compute the life cycle inventory, environmental impacts and sustainability of both WWTS. Interpretation and discussion of findings developed from the computer-based software 'SimaPro' is presented in this chapter.

Chapter 5 gives the summary of the study; findings obtained in the study as well as finally suggested recommendation.

2. Literature Review

This chapter includes, an introduction on wastewater treatment and overview of small-scale decentralized wastewater components (DEWATS system). It also describes the LCA tool and its application for sustainability analysis.

2.1 Introduction on WWTS

The UNEP and UN-HABITAT defines the wastewater as "*….a combination of one or more: of domestic effluents consisting of black wastewater; water from commercial establishments and institutions, including hospital; industrial effluent, storm water and other urban runoff; agricultural, horticultural, horticultural and aquaculture effluent, either dissolved or as suspended matter* (Corcoran 2010)". The effluents of the wastewater contains various nutrients, have bio-accumulative characteristics, which impacts on river ecosystems, pollution on lakes, health and economy of the area. Therefore wastewater needs to treat before discharge into the water bodies. The purpose of the treatment of wastewater is usually to minimize the environmental load. The degree of treatment is depends on the discharge of effluents (Ramalho 2012).

In the past, biofilm reactors were mostly used for wastewater treatment in the developed countries (Angelakis and Snyder 2015; Henze, 2008). At present, advanced wastewater treatment technology like membrane bioreactor, advanced chemical treatment and disinfection technologies (UV, ozonization, oxidation etc.) are in use for the treatment of wastewater (Angelakis and Snyder 2015). The choice of treatment method depends upon the desired level of treatment required and the affordability.

Centralized wastewater management system was developed in early 19th century to solve the problems regarding unmanaged disposal of wastewater. Centralized wastewater system defined as ' a single treatment method, which is used to treat wastewater, collected through long sewer channel' (Kiernan et al., 2012). The system gradually becames successful in densely populated area of industrialized countries (Wilderer and Schreff 2000). However, centralized system has not been so viable to improved sanitation in developing countries. The reason behind the unsuccessful story of centralized system is the investment or high-cost for implementation (Wilderer and Schreff 2000). The Figure 2-1 shows different wastewater treatment steps viz: Primary treatment to secondary treatment and post treatment of wastewater.

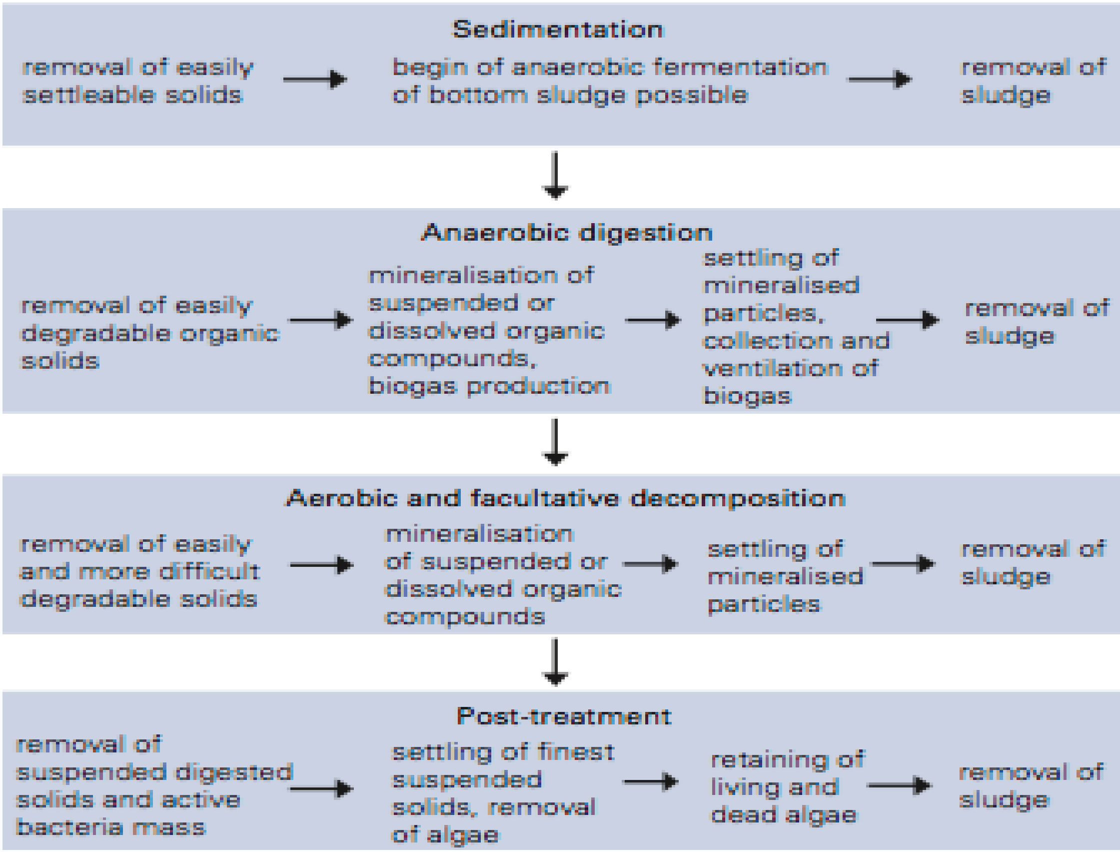


Figure 2-1: Wastewater treatment process (source: Gutterer, 2009)

2.2 Small-Scale Decentralized Wastewater Treatment System

In 1990, the international network of organization and experts offered the concept of small-scale wastewater treatment system called as 'DEWATS technique'. DEWATS technologies are designed for treatment, collection and reuse of wastewater for small communities, institution, industry, individuals dwellings (Crites and Technobanoglous 1998).

DEWATS method requires a low maintenance, and tolerates the high organic load with the principle of reliability and longevity (Frances 2013). Where, it does not require the energy to course the system i.e. natural system. It is designed to handle the domestic wastewater flow ranges from 1 – 1000 m^3/day and industrial sewage (Baetens 2004).

DEWATS is the small-scale and handy technology or smart alternative for the communities, which is highly cost effective, economical, green and sustainable (EPA 2005). The materials required for the construction of such system are locally available, which requires low control and maintenance and could be the possible option for potential energy source depends on the technical inputs. Therefore, the DEWATS system is principally more useful than centralized system in developing countries. This system is not only useful in rural area; it also works in semi-urban and urban area of developing countries. The process of the DEWATS system operates similar like as centralized treatment system.

2.3 Overview Of Small-Scale Decentralized Wastewater Treatment System

In DEWATS the process occurs in four different technical steps, which are presented below:

- Primary treatment: includes the sedimentation tank, septic tank, settler, and biogas-digester.
- Secondary anaerobic treatment: occurs in an anaerobic baffled reactor and anaerobic filter
- Secondary aerobic/facultative treatment: examples are constructed wetland both the horizontal and vertical or planted gravel filter
- Post treatment: includes aerobic ponds or polishing pond

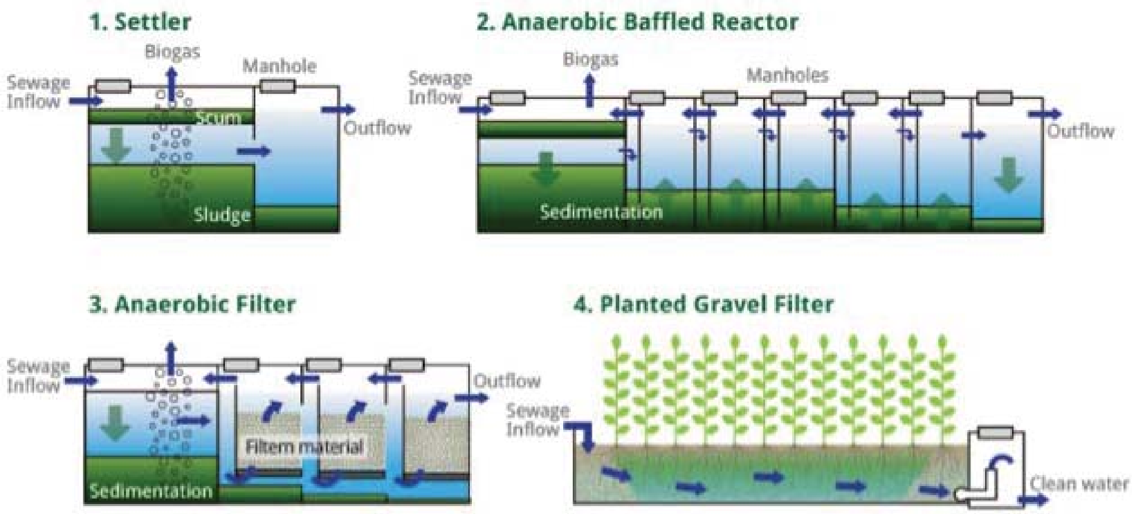


Figure 2-2: The main DEWATS component (BORDA)

The various treatment options are possible depends on the inflow/discharge and required outflow quality, local conditions and others (Gutterer 2009). The most important feature of the DEWATS are that it works without the input of electricity where sewage flows through the gravity system (Seshadri 2015).

2.4 Sustainability Assessment of wastewater treatment system

Decentralized wastewater treatment is a safe and reliable technique, which echoes economic and environmental advantages to communities (EPA 2005). Sustainability assessment is an important tool to assist any system towards sustainability or a process that directs decisions makers towards sustainability (Pope et al. 2004; Bond et al. 2012). Economy, environment and social factors are three major dimensions of sustainability or sustainable development (Muga et al., 2008; Hsu, 2010). For the improvement towards sustainability, decentralized wastewater treatment systems must consider all three major factors.

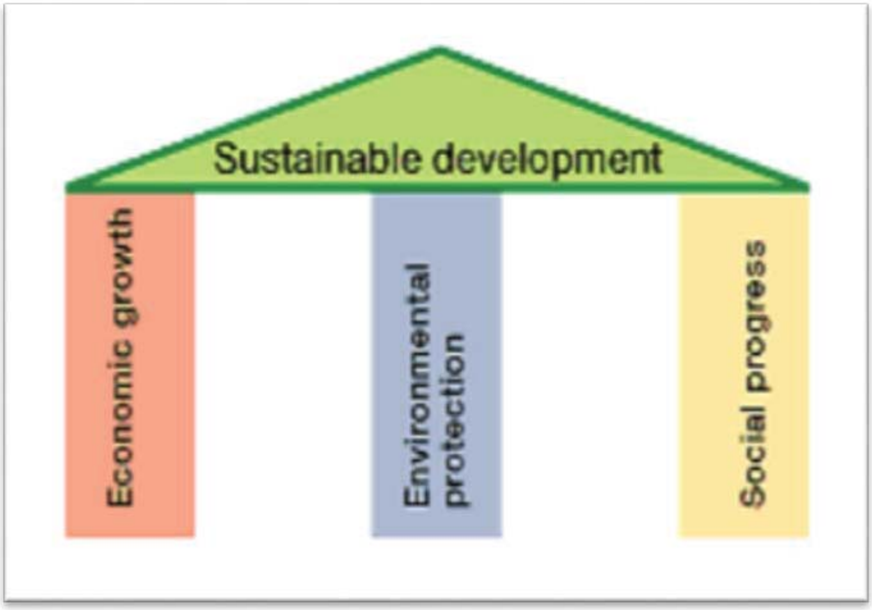


Figure 2-3: The three pillar of sustainable development
Source: IUCN, the world conservation union, 2006.

Various methods and tools are applied to measures the sustainability (Balkema et al. 2002). The various methods are used for sustainability assessment, for example; social assessment, life cycle costing, cost-benefit analysis, exergy analysis, economic assessment, environmental assessment (EIA) and life cycle assessment (LCA) with include multiple indicators (Doualle et al. 2015; Balkema et al. 2002). These sustainability indicators improve the reliability of the product or systems. The multiple dimensions can define the term sustainability. The details on the methodologies used for this study is further discussed in next chapter.

2.4.1 Environmental Assessment

Environmental assessment is usually done to identify the overall environmental performance of the system or product. To identify the environmental impacts of the system various methods has been used. Following are the example of environmental assessment method:

Environmental Impact Assessment (EIA)

Environmental impact assessment (EIA) is carried out before the implementation of project. EIA is a systematic process that initially examines the environmental consequences of development activities (Glasson et al. 2013). UK DoE 1989, operationally define environmental impact assessment as *" the term environmental assessment describes a technique and a process by which information about the environmental effects of a project is collected, both by the developer and from another sources, and taken into account by the planning authority in forming their judgments on whether the development should go ahead.*

Every project has both negative and positive environmental impacts directly or indirectly during the construction, operation and maintenance of the project. EIA assess whether the project is acceptable or not from the environmental point of view and make the project or system environmentally sustainable. EIA has different stages like screening, scoping, impact analysis, mitigation measures, alternative analysis and environmental management plan (EMP). The process of impact analysis identifies the possible positive and negative physical, biological, chemical, socio-economic and cultural impacts due to the project activities. Whereas, mitigation measures suggest the impact wise mitigation action to minimize the negative impact and augment the positive once. Alternative analysis of the project deals about the alternative project location, design, technology & infrastructure and EMP for the sustainable development of project (Kingsley 2011).

Life Cycle Assessment (LCA)

LCA is a well-established method to access the potential environmental impacts associated with product's output and inputs (i.e. cradle-to-grave) (ISO 1440 2006; Kingsley 2011). Only environmental burdens are calculated in LCA, whereas, social and economic factors are not considered. LCA is an established technique applicable for a wide range of products or system of urban water cycle that cannot be incorporated on the process of environmental assessment (Balkema et al. 2002; Barton et al. 1999; Kingsley 2011). The main objective of the LCA is to model the effect of change and methodological choice can be made in relation to set a goal and scope (Tillman 2000).

In this study LCA was used for a decision support tools for the sustainability analysis of the small-scale decentralized wastewater treatment systems. LCA framework is discussed further.

2.4.2 Social Assessment

Social impact assessment (SIA) is a holistic approach (Vanclay et al. 2011), which implies to assess the social issues and its correction. *The international principles for social impact assessment* defines SIA as *' the principle of analyzing, monitoring, and managing the* *intended and unintended social consequences; both positive and negative of planned interventions and any social change processes invoked by those interventions'* (Vanclay 2003; Vanclay et al. 2011). Social acceptances of the treatment system play a major role for the sustainability of wastewater treatment system (Vanclay 2003).

2.4.3 Economic Assessment

The economic assessment is more analytical than social and environmental assessment. Sustainability could easily be introduced into decision-making process, if it is seen in terms of money where the WWTS evaluated on the basis of economic theory (Balkema et al. 2002). At the starting of the project, tools such as: total cost estimation, cost-benefit analysis and life cycle costing are required for calculation a balance between expected cost and benefits (Kingsley 2011; Balkema et al. 2002). A calculation of real cost with different indicators for water services, economic assessment of wastewater treatment could provide a valuable recommendation for the sustainability.

2.5 Indicators for sustainable assessment of wastewater treatment system

Sustainability indicator is an important part for selection of suitable treatment system on a basis of those indicators. There are number of sustainable indicators (economy, environmental and social) (Singh et al. 2009) that evaluates the performance of the wastewater treatment system. The United Nations Commissions on Sustainable Development (UNCSD 1995) developed the sustainability indicators framework, focused on the environmental issues (Ness et al. 2007) for the evaluation of progress towards sustainable development goals.

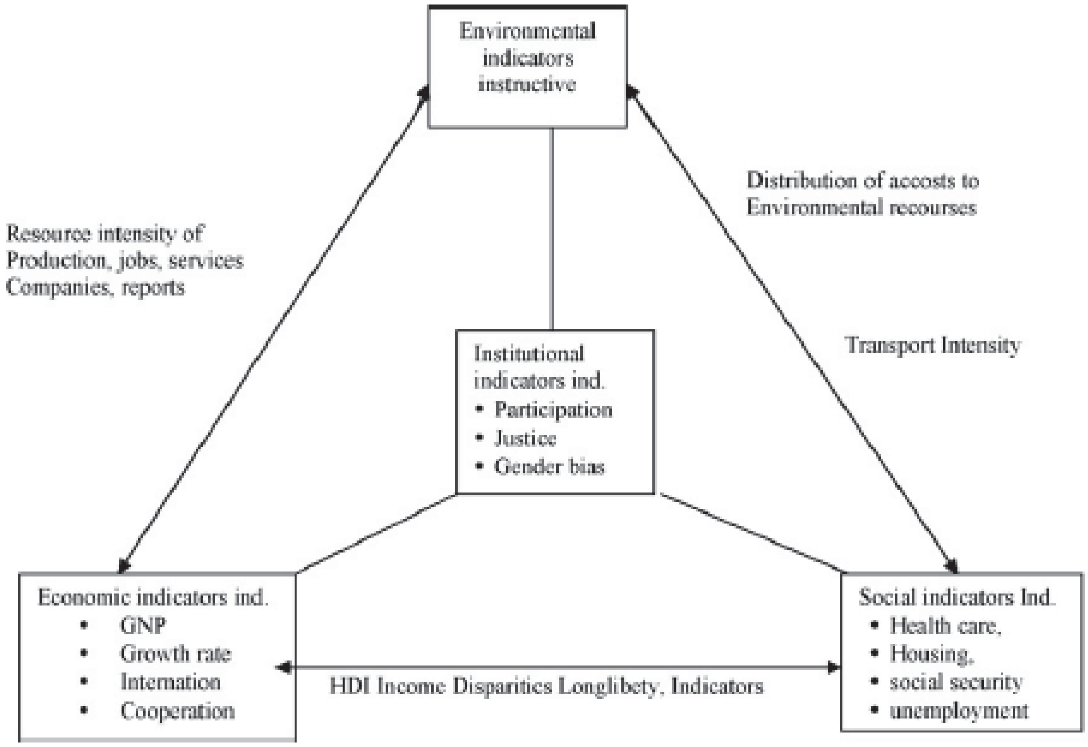


Figure 2-4: the Wuppertal Sustainable Development Indicator Framework (Singh et al., 2009)

As presented earlier, the sustainability indicators are important factors for the sustainable development of the system. For example, GNP, Growth rate, interaction and cooperation are the economic indicator, whereas healthcare, housing social security and unemployment are taken as social indicator (Balkema et al. 2002; Singh et al. 2009). Functional indicators determine the technical inputs requires to the solution. For example in wastewater treatment plant quality of effluent is measure as a function indicators for the sustainable development of the system. Other functional indicators are extension on capacity of treatment, durability, sensitivity and reliability etc. (Kinsley 2011). Economic, environment and social indicators are the important to insight into the efficiency of the solution, whereas, functional indicators shows the effectiveness of the solution.

Social indicators, defines the social acceptance of the solution. Geographical and demographical structure of communities depends on the selection of a set of indicators that has varying degrees of sustainability with technologies (Muga et al. 2008). Public participation is an important integral for social acceptance of the product or system. For the religious country like India and Nepal the cultural acceptance is also an important indicator for the evaluation and implementation of WWT technologies.

The commonly used economic indicators: total investment, cost-benefits, labor, maintenance, and operation etc. are decisive when choosing a technology in a practical solution (Balkema et al. 2002; Kingsley 2011).

Environmental indicators also known as environmental sustainability indicators (Kingsley 2011), define the environmental performance of the systems. With Addition on water, nutrient and energy, maximum utilization of resources is used as an indicator (Balkema et al. 2002). Additional indicators, land utilization, agricultural production and biodiversity are mentioned in several studies (Lund and Morrison 2002).

2.6 LCA as decision support tools for sustainability analysis

Every development activities have certain degree of impacts onto the environment economy etc., for the better understand of these impacts there has been developed various kind of method.

The LCA used for an identification and prediction of system environmental performance during its lifetime, thus use of LCA is an important tool in decision-making process (Akwo 2008). The LCA of wastewater treatment plant is thus more interest to identify the environmental burdens of DEWATS method, methods becoming more popular in developing countries. According to *Standards ISO 14040*, LCA can assist in:

- Introducing environmental opportunities to improve an environmental performance of product during lifetime.
- Recommend in decision-making process in various organizations (I/NGOs), government and industrial sectors; for example: design and planning, priority setting.
- Selection of sustainable indicators on environmental performance, and
- Create markets; for example, eco-labeling, environmental product declaration and environmental claim

2.6.1 Overview on LCA

Definition on LCA

Life cycle assessment (LCA) is also known as cradle-to-grave analysis. According to the International Organization for Standardization (ISO) (ISO 14040:2006), LCA is the *" Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle system (i.e. cradle-to-grave)"*. LCA profile an environmental impact of the system.

Further Definition on LCA:

- *Life Cycle Assessment (LCA), estimating the environmental impacts associated with a system (product, process or activity) from "cradle" to "grave", that is beginning with the extraction of raw materials, used in the system, and ending with dismantling and final disposal, constitutes an environmental management tool with increasing application in conception and project of systems in a perspective of sustainability (Machodo et al. 2006; Jensen et al. 1997).*

History of LCA

The application of LCA can be tracked back to 1960's (Curran 2006). In 1969, the coca cola company provided grant for a study to compare resource consumption and environmental release with beverage containers (Jensen et al. 1997). In Europe, similar studies were started at Open University in England, at EMPA Switzerland and in Sweden (Benedetto and Klemeš 2008). At the beginning the study were focus on energy used by system rather than other inputs and outputs. It is therefore the problem of electricity supply for the production during early seventies. In 1978, Ian Bousted developed the methodology applicable for all materials (Jensen et al. 1997; Friedrich 2001). Meanwhile in US, the Midwest Research Institute introduced LCA (Klöpffer 1997).

The Society of Environmental Toxicology and Chemistry (SETAC) and SETAC-Europe define terminology and structured the LCA framework or methodology (Klöpffer 1997; Benedetto and Klemeš 2008). ISO structured the LCA model through its ISO 14040 series. The model is differs from SETAC structure with the element 'Interpretation'. The following Figure 2-10 shows the structure defined by SETAC, it is also called SETAC triangle.

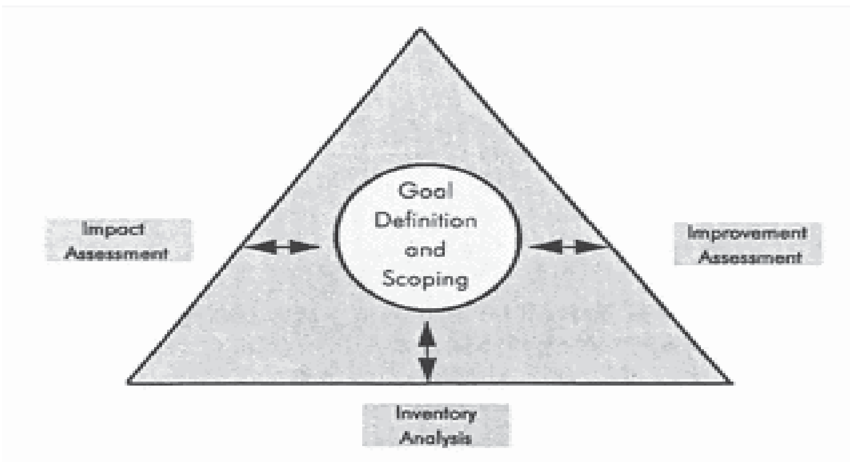


Figure 2-5: SETAC Triangle.

In 1991, the ISO developed the LCA methodology for decision support tools. The ISO offered different methodology on LCA. In 2002, the SETAC and United Nation Environmental Program (UNEP) jointly launched the program, the 'Life cycle initiative'.

2.7 LCA Framework

The LCA consists of four steps. The principle framework for LCA with a number of steps were purposed by ISO 14040:2006 includes;

2.7.1 Goal and Scope Definition

For the application of LCA, goal and scope definition is the first step of LCA study, which deals on the product and process of a system. It defines the context and identifies the boundaries for further assessment. Goal and scope of the study purposed the questions and formulates the answer through inventory, impact assessment and interpretation study. The result will vary on goal and scope of the study, therefore goal and scope definition is an important parts of LCA.

The development of models is the major challenge for LCA study, thus clear definition of goal and scope of the study is the best way to deals with this problem (Goedkoop et al. 2010). The goal and scope definition ensure the finest result of LCA study. The Goal and scope definition of the study carefully define the system boundaries and functional unit (Rebitzer et al. 2004) of the product or system.

The system boundaries set the area of scope that needs to be cover for investigation (Cruz-Diloné 2014). For example; to produce engine, metal is needed, to produce metal, energy is needed, and to produce energy coal is needed, during the production of energy various gases are released into the environment etc. so it is clear that all the inputs and outputs of a product system cannot be included in a study. Therefore system boundary should be defined at the beginning of the study.

The functional units of the quantify inputs and outputs materials delivered for a system is important basis for the comparison of two product or system (Goedkoop et al. 2010; Rebitzer et al. 2004; Cruz-Diloné 2014). The functional unit of the system has to be clearly defined and measurable. For example, the functional unit for a concrete block may be defined as unit wall protected for 10 years. The comparison and analysis is now possible if the functional unit of other concrete block types with the same functional unit. Functional units provide a reference to normalize the input and outputs data (Jensen et al. 1997).

2.7.2 Life Cycle Inventory Analysis (LCI)

In this process, it identifies and quantifies the used inputs and outputs materials, energy, waste and emissions into air, water and soil (Cruz-Diloné 2014) during the project construction, operation and demolition activity, in relation with a define functional unit (Frances 2013). The process involves creating the model for inventory and the management of data.

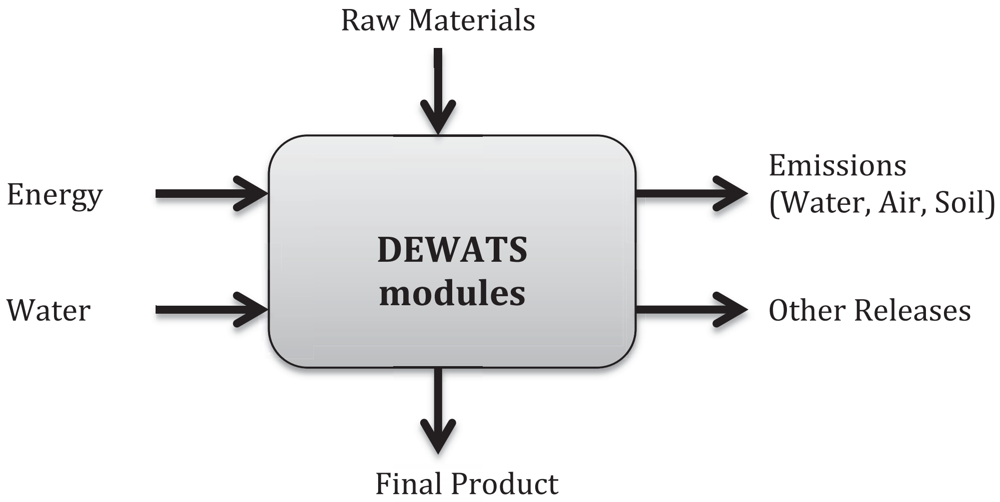


Figure 2-6: Inventory Analysis Model For LCA

2.7.2.1 Data Collection and calculation

Inventory analysis of the system involves the steps like data collection, data refining, data calculation & validation, sensitivity analysis. The data collection, refining and validation are the most time consuming part of LCA.

The quality of data is then most crucial components, which define time related coverage, geographical coverage and technology coverage (Jensen et al. 1997). Many commercial LCA database is also exist and can be found together with different LCA software. For example, the ecoinvent v2.0 database in order to model the product and processes comes with SimaPro.

The validation of data is required for the improvement of data quality. The data from other similar studies or commercial database can be used (Cruz-Diloné 2014) in LCA study. The number of software and programs are available for calculation of data (e.g. MS Excel).

2.7.2.2 Allocation

The process or product system usually has more than one product (i.e. output or function). Thus to handle all the outputs, allocation strategies are needed (ISO 14040:2006; Goedkoop et al. 2010). ISO recommended some procedure to deals with this problem. This problem can be solved either by expanding the system boundaries to cover all inputs and outputs or allocating the relevant environmental loads suited for the study (Jensen et al. 1997).

2.7.3 Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment (LCIA) is the third steps in LCA. After the inventory, the magnitude of potential environmental impact of the environmental resources will be identified by inventory result (Curran 2006). For example, what are the impacts of 1 Kg of methane emission from septic tank into the atmosphere? What are their potential impacts on ozone layer depletion, global warming?

The detail analysis of impacts depends on methodology used on goal and scope of the study (ISO 2006). The LCIA containing many elements like categorization, classification, characterization, normalization and weighing/valuation (Curran 2006).

2.7.3.1 Category definition

This is the first step in LCIA, which select the impact category based on the inventory result and goal & scope of the study (Pillary 2006). The various environmental impact categories consider for LCIA are; abiotic resources, land use, global warming, ozone layer depletion, acidification, eutrophication, ecotoxicologcal impacts (Jensen et al. 2006). Here, impact categories are on scientific analysis of relevant environmental processes (Roy et al. 2009).

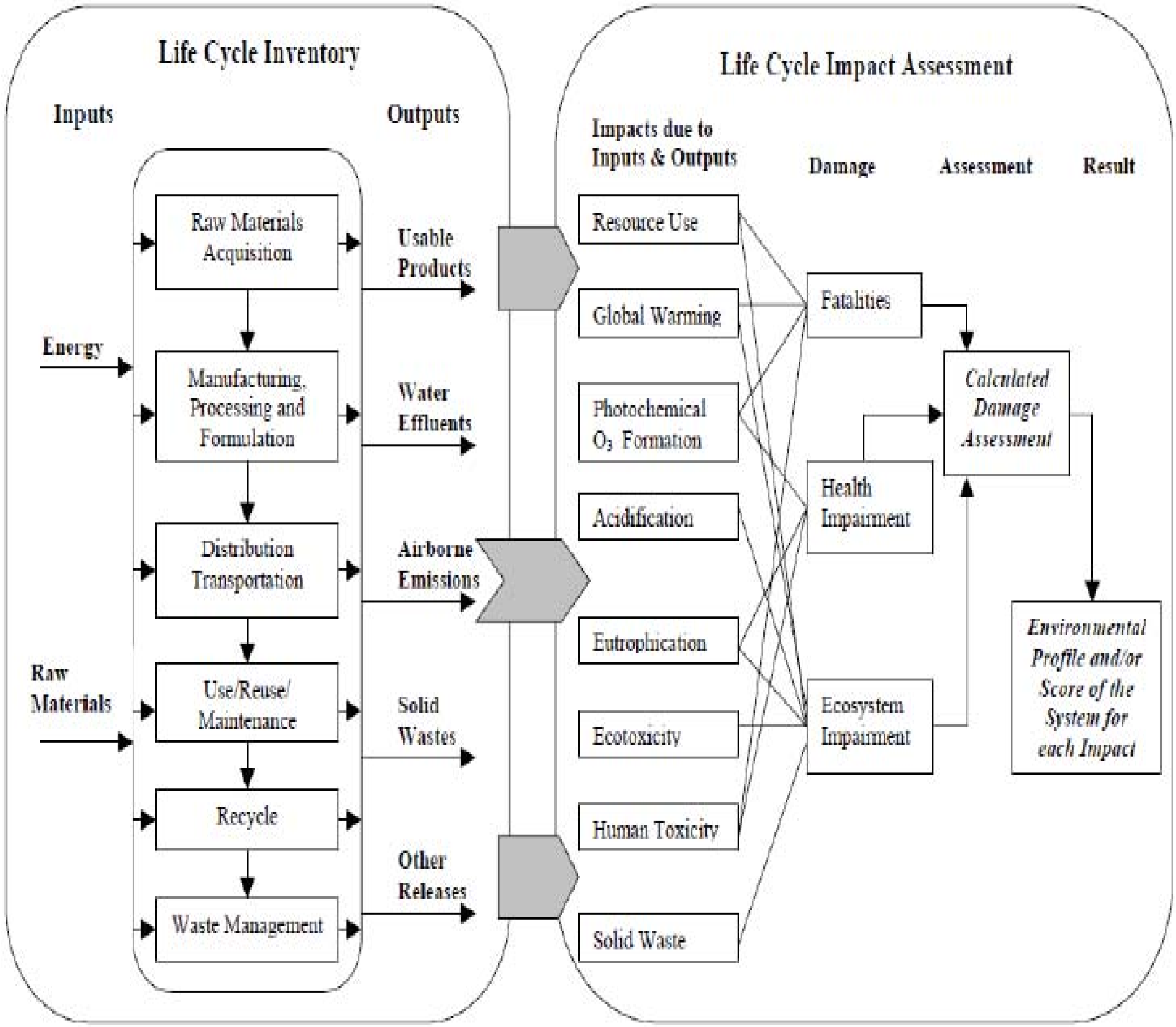


Figure 2-7: An Overview of LCI and LCIA (Frances 2013)

Selection of Method for Impact assessment

The choice for the selection of method for LCIA is depend on the goal and scope of the study. Here, the number of standard impact assessment method can help to perform LCA of product or system. Every method does not include all category and indicators (Ramirez 2012; Goedkoop et al. 2010). SimaPro include different methodologies used for LCIA; CML 2001, Eco-indicator 95, Eco-indicator 99, EPS 2000, CML 92 (Goedkoop et al. 2010).

Table 2-1: Impact Categories And Possible Indicator

Impact Category	Possible Indicator
Input Related Categories	
Extraction of abiotic resources	Resource depletion rate
Extraction of biotic resources	Replenishment rate
Output related categories	
Global warming Potential (GWP)	Kg CO_2 as equivalent unit for GWP
Stratospheric ozone depletion (ODP)	Kg CFC-11 as equivalence unit for LD
Human toxicity	HTP
Eco-toxicity	Aquatic eco-toxicity potential (AETP)
Photo-oxidant formation	Kg ethane as equivalence unit for photochemical ozone creation potential (POCP)
Acidification Potential (AP)	Release of H+ as equivalence unit for AP
Eutrophication potential (EP)	PO_4^{-3} equivalence unit for EP

Source: (Frances 2013; Ramirez 2012)

2.7.3.2 Classification

The numbers of input and output parameters (emission and resource extraction) were identified during the process of inventory of the system. Classification thus involves the grouping (Akwo 2008) of these inventory tables into different impact categories viz: Global warming potential (GWP), stratospheric ozone layer depletion potential (ODP), Eutrophication Potential (EP) and Acidification potential (EP). Then After life cycle inventory result (LCI) are grouped into the same impact category. For example, SO_2 and NH_3 both belong with the impact category of acidification and nitrogen and phosphorous are both assigned to the impact category of eutrophication potential. These impact categories are divided into different scale viz, Global, continental, regional and local impacts (Jensen et al. 1997). Associated with this, CML 2 baseline 2000 method were selected for characterization and normalization of the LCI result.

2.7.3.3 Characterization

It is the process for quantification and analysis of potential impacts within the impact category (Akwo 2008) in terms of indicators (Jensen et al. 1997). For example, emissions of 1 kg CO_2 contribute 25 times less than 1 kg CH_4 to GWP on baseline model of 100 years of the Intergovernmental Panel of Climate Change (IPCC) (ISO 14044:2006). Here the characterization factor for CO_2 and CH_4 are 1 and 25 respectively. Therefore, for the impact category of GWP the result can be obtained by multiplying the inventory result with the characterization Factor (Goedkoop et al., 2010). For example 1 kg ammonia = 1.88 kg SO_2 eq (Kietzmann 1998).

2.7.3.4 Normalization and Weighting

Normalization and **weighting** involves in this steps. **Normalization** is '*a procedure needed to show to what extent an impact category has a significant contribution to the overall environmental problem' (*Goedkoop et al. 2010). Normalization of the impact categorization is the best option for the better understanding of the relative magnitude for each indicator result (Ramirez 2012).

For example; the normalized eutrophication potential (EP) for the considered product is calculated as follows.

$$\textbf{Normalized EP} = \frac{\text{EP}}{\text{Norm. ref.}_{\text{EP}}}$$

Where, normalization reference is the unit 'impact potential per person per year' (Stranddorf et al. 2005) in the area (i.e. global, regional or local).

The normalization reference is calculated as (Stranddorf et al. 2005):

$$\textbf{Norm. ref.}_{\text{EP}} = \frac{\text{Impact Potential}}{\text{Capita}}$$

Where, the impact potential = product of emitted quantity of substances and equivalence factor

Weighting helps to rank or weight of each impact category in order to their relative importance (Akwo 2008). In the present study, weighting step is not included.

Calculation of Characterization and Normalization

Characterization

For example,

Amount of CO_2 = 10 Kg and Amount of CH_4 = 5 Kg, whereas, Characterization factor for CO_2 and CH_4 is 1 and 25 respectively.

Therefore

Global Warming Potential (GWP) = 10 kg CO_2 (GWP=1) + 5 kg CH_4 (GWP=25) = 10 *1+5*25 kg CO_2 equivalent = 135 kg CO_2 equivalent

i.e. **GWP = 135 kg CO_2 equivalent**

Normalization

For example; the normalized Global Warming Potential (GWP) for the considered product is calculated as follows.

$$\textbf{Normalized GWP} = \frac{\text{GWP}}{\text{Norm. ref.}_{\text{GWP}}}$$

Here, for example, 8.7 ton CO_2 – eq /capita/year (Stranddorf et al. 2005) is the normalization reference for global warming potential in europe.

Therefore,

Normalized GWP = 135/ 8.7 = 15.51 Kg CO_2 equivalent

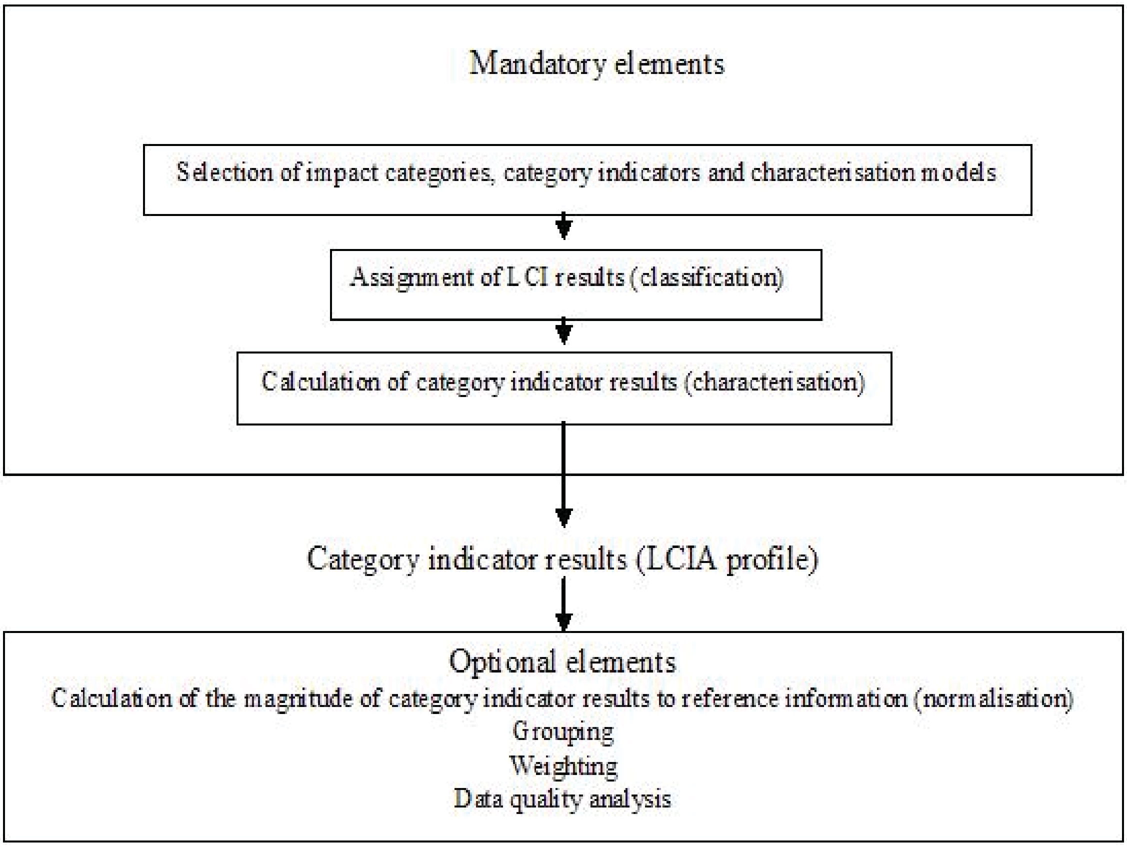


Figure 2-8: Showing The Steps Of LCIA (@ISO 2000. From ISO 14042:2000 (E))

2.7.4 Life Cycle Interpretation

Interpretation is the last phase of the LCA framework, where findings from the LCI and LCIA are evaluated and summarized. The conclusions and recommendation are purposed on the basis of goal and scope definition of the study. Interpretation is the last steps on LCA. Interpretation consists of the following three principle steps (ISO 1443:2006):

- Identification of potential environmental issues based on LCI and LCIA results
- Evaluation and analysis
- Conclusion, recommendation and report writing.

Interpretation also reflects the findings from sensitivity analysis.

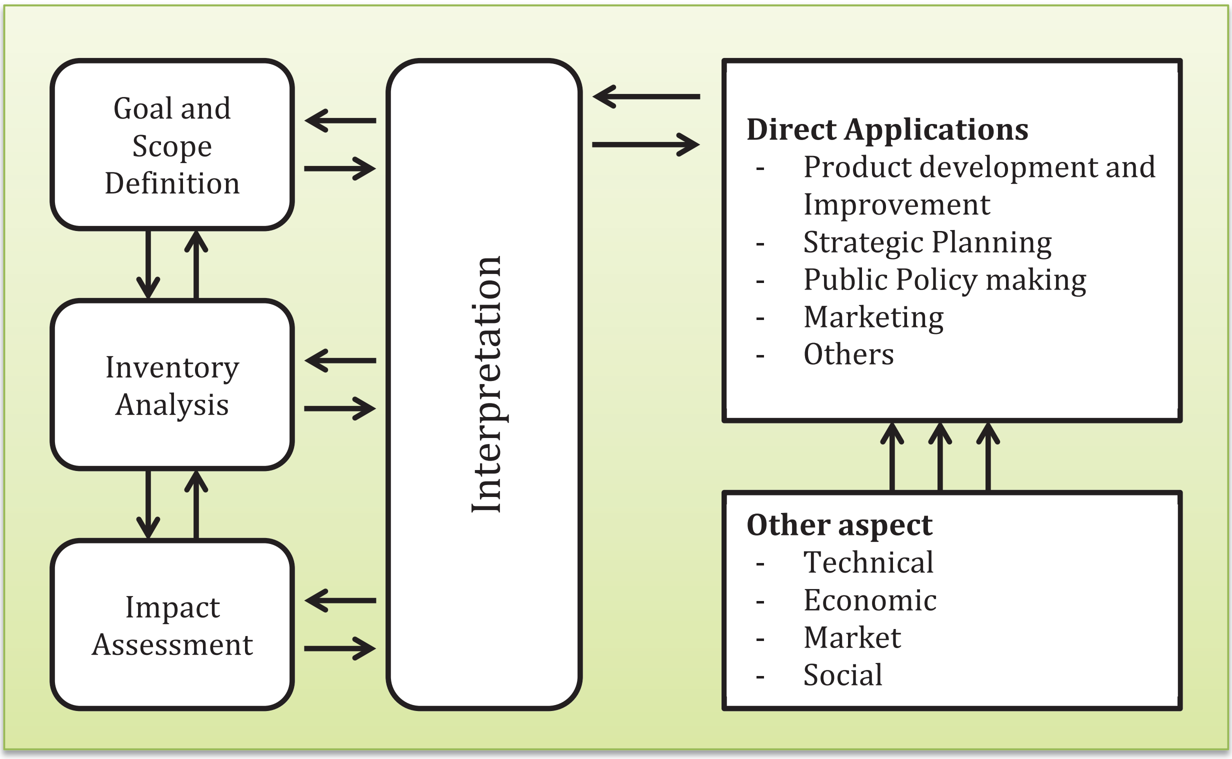


Figure 2-9: LCA framework (ISO 14040:2006)

2.8 Preview of LCA studies for Wastewater treatment system

Many studies has already been carried out on LCA to analyze the environmental burdens of different wastewater treatment systems, including both DEWATS and conventional treatment plants. Review on LCA studies with the context of the study are presented below:

In 1995, a study of LCA regarding wastewater treatment plant was published. It was the first study on wastewater done by Emarson et al. in 1995. They summarized findings that the operational stage is the highest energy contributors at the overall life span. However, study had various limitations as comparer with the recent studies.

In 2013 Frances applied LCA to determine the area of improvements for BORDA WWTS by comparing with the Schleswing centralized WWTS. The functional unit used in this study was per person equivalent over a period of 20 years with preferred treatment of 1 m^3. The study highlights that BORDA DEWATS contribute significantly less environmental burdens per person equivalent is significantly less than centralized system. It further demonstrates that the problem of eutrophication is more in BORDA DEWATS by 38% than Schleswing centralized WWT system.

The Author (Friedrich et al. 2009) presented study to identify the information on environmental profile of the life cycle of water treatment process. The environment life cycle assessment approach was adopted in the study and finally produced environmental profile. These study conclude that system approach and process approach is needed to identify the environmental performance of the systems. In this study, researchers pointed out that activated sludge process -used in wastewater treatment reflect the highest contribution (i.e. environmental impact).

In 2006, the study was compared the environmental impact of natural wastewater treatment plants using the LCA with data available from the system (Machado et al. 2006). The functional unit adopted for he study was 100 populations equivalent for 20 years life cycle. In the study system boundaries were focused on the construction, operation and disassembling phases of two energy saving system. The conclusion was made that slow rate infiltration and constructed wetland relatively use less materials and energy than activated sludge system. The study further discussed that activated sludge system absorbs less CO_2 and contribute more for global warming.

3. Materials and Methods

This chapter described method and methodology used to carry out study. Chapter focused on the method of LCA and its framework used on this study.

3.1 Research Work

Research followed the LCA approach for the sustainability assessment of decentralized wastewater treatment system (Balkema et al. 2002). In this approach, the environmental impacts of a product over course of its lifetime can be encounter. For the research purpose small-scale decentralized wastewater treatment system developed by BORDA DEWATS for India has been taken into account. The following flowchart in Figure 3-1 shows the details study framework.

3.1.1 Literature Review

Related literatures were reviewed from different scientific papers, reports and documents. Literatures were reviewed for the better understanding of the research.

3.1.2 Data Collection

Primary and secondary data were used for the study. Primary data were provided by '4S' project IMV, NMBU. Whereas, secondary data were collected from published journal article, web links, previous similar studies, official's records by I/NGOs and books etc.

3.1.2 Data Analysis and Report Writing

Primary and secondary data obtained through different sources were processed and analyzed by using MS-Excel. The computer based Life Cycle Assessment software programs 'Sima Pro 7.0' was used for data interpretation and analysis. The results obtained from the software were analysis and graphically presented in structure pattern in MS-Word.

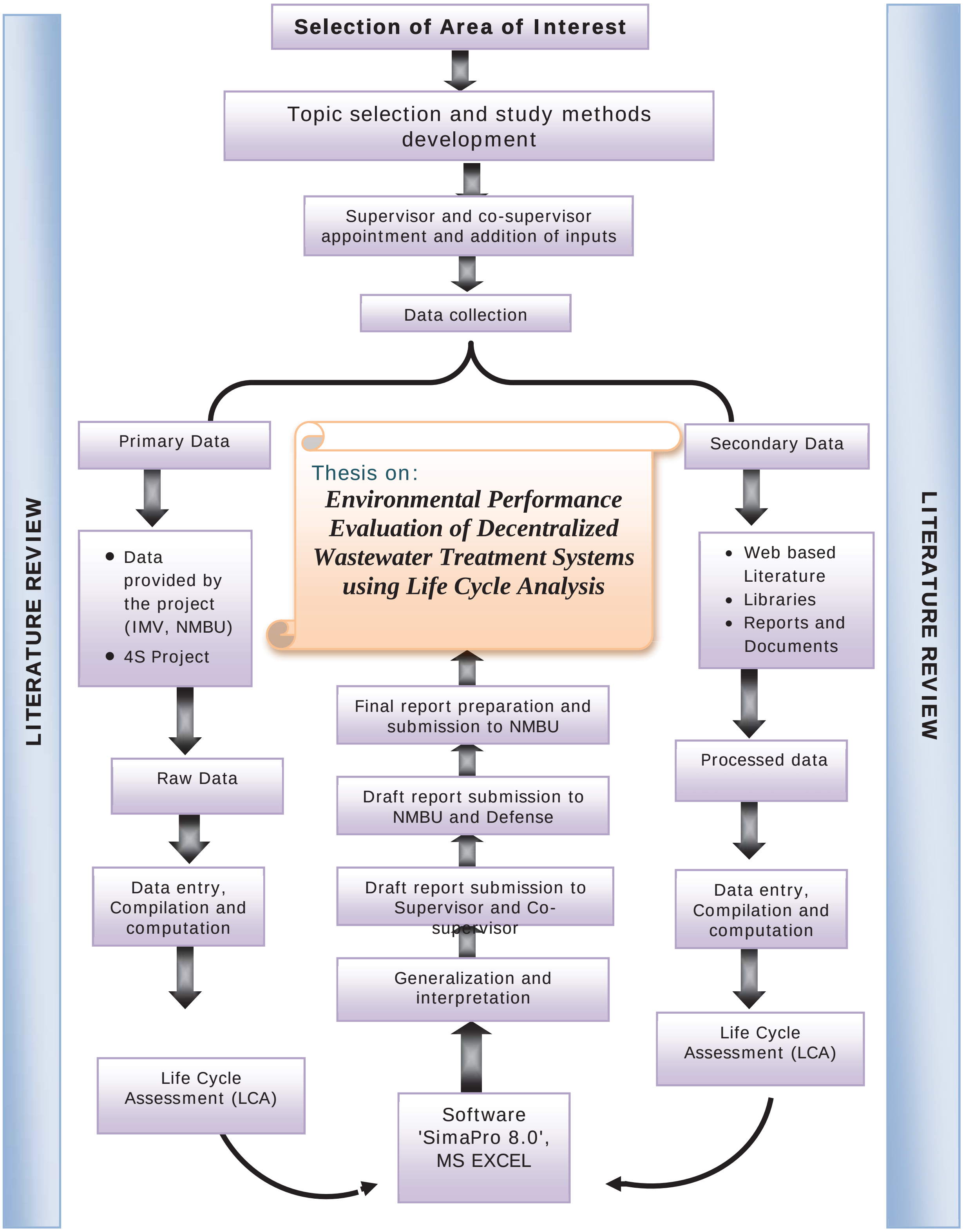


Figure 3-1: Flow Chart Showing The Structure Of Study.

3.2 Description on Treatment system

The brief description on decentralized wastewater treatment applications are discussed below.

3.2.1 Biogas Digester (BD)

It is the unit of pre-treatment unit that works on the principle of anaerobic digestion. In this process, pressurized biogas is produced. The produced biogas can be used for household purposes like cooking, heating, lightening and electricity. It is the dome or ball-shaped, combined with digester chamber and gas storage chamber. Organic fraction of the substrate is the mechanism of gas production (Sasse 1998). At this unit of the treatment system BOD_5 reduction is 25 % to 60 % (Mang and Li 2010; Reynaud 2014). The Figure 3-2 shows the fully mixed biogas digester.

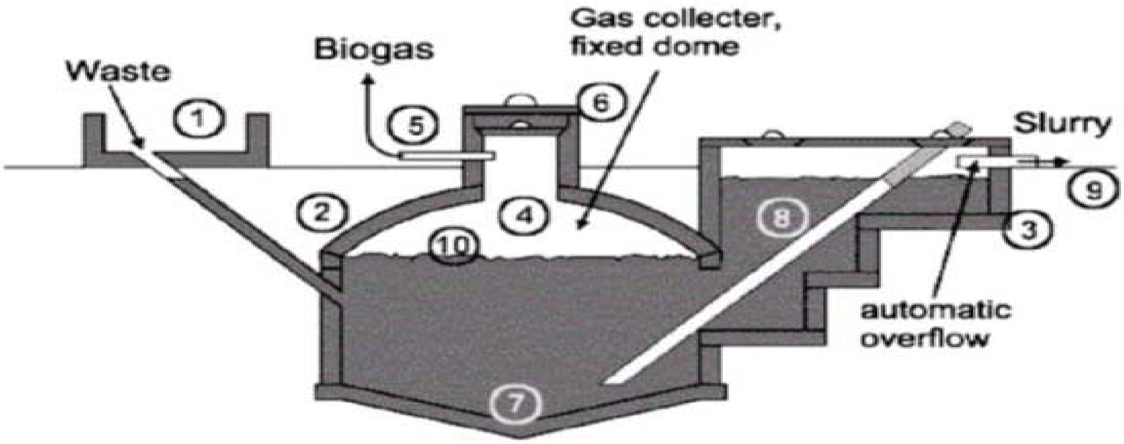


Figure 3-2: A Fixed Dome Plant Nicarao Design (Sasse 1998)

3.2.2 Settler / Septic Tank

The settler commonly termed, as septic tank is a most common treatment process used for pre treatment in DEWATS. Settlers are sedimentation tanks for primary treatment that retain all settable organic matter and stabilize the settled sludge by anaerobic digestion (Sasse 1998). It is much useful for the treatment of domestic wastewater. A septic tank consists of 2 or 3 compartment. The treatment efficiency of settler or septic tank is generally found to be 30 % to 50 % BOD_5 reduction (Reynaud 2014). The Figure 3-3 shows the flow principle of the settler/septic tank.

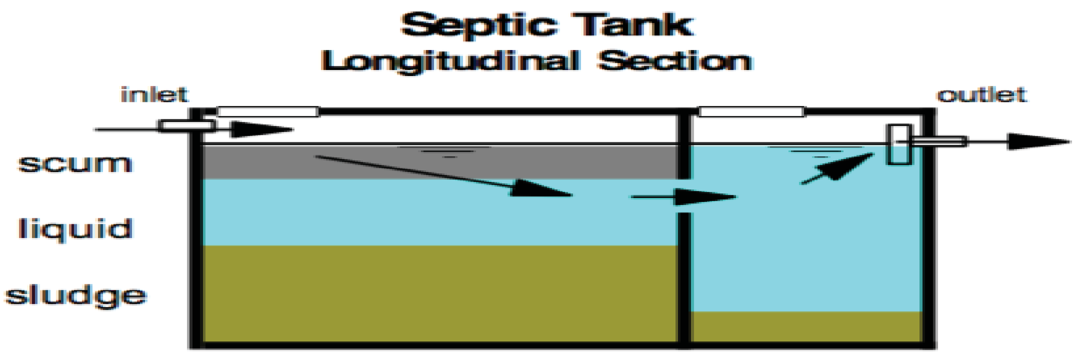


Figure 3-3: The Flow Principle Of The Settler/Septic Tank (Sasse, 1998).

3.2.3 Anaerobic Baffled Reactor (ABR)

The anaerobic baffled reactor is a part of secondary treatment. It is an improved septic tank with a series of baffle but slightly more complicated to install than septic tank (SSWM 2015). In this unit the wastewater flow repeatedly by the forces of baffles, therefore contact between organic pollution and biomass increase. ABR is recommended in constructed wetland of vertical flow type (Gutterer 2009). ABR is also suitable for both domestic and industrial wastewater with high organic load and low BOD/COD ratio (Frances, 2013). At ABR the reduction of BOD_5 in wastewater is 70 % to 95 % (SSWM 2015). The Figure 3-4 shows the flow principle of anaerobic baffled reactor.

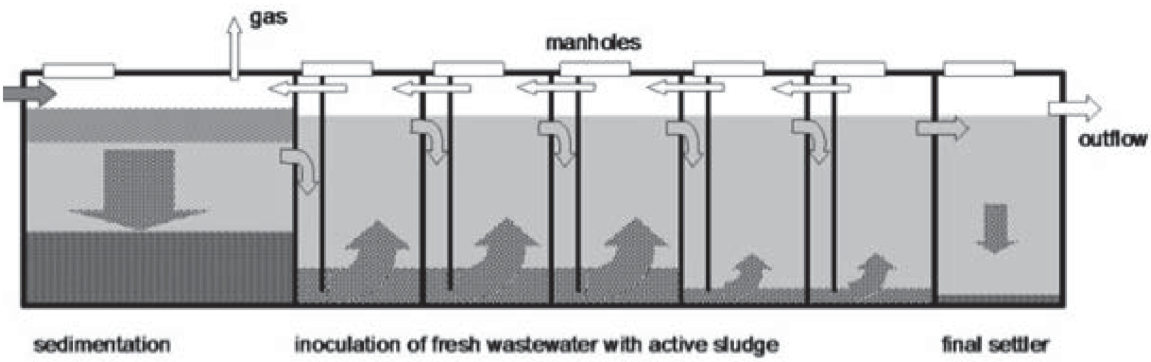


Figure 3-4: The Flow Principle Of Anaerobic Baffled Reactor (BORDA Network).

3.2.4 Anaerobic Filter (AF)

Anaerobic filter is also known as fixed film reactor, which is slightly different with septic tank and ABR. It includes the treatment of non settable solids by channelized the wastewater through active microorganism (Sasse 1998; Gutterer 2009). After the initial treatment (septic tank), anaerobic filter received low percentage of total suspended solids and limited BOD/COD ratio (Gutter 2009). If the AF is well operated the quality of treatment is range between 70 % to 90 % BOD removal while 25 to 30 percentages of filter masses may be inactivated due to the problem of clogging (Sasse 1998). The Figure 3-5 shows the flow principle of anaerobic filter.

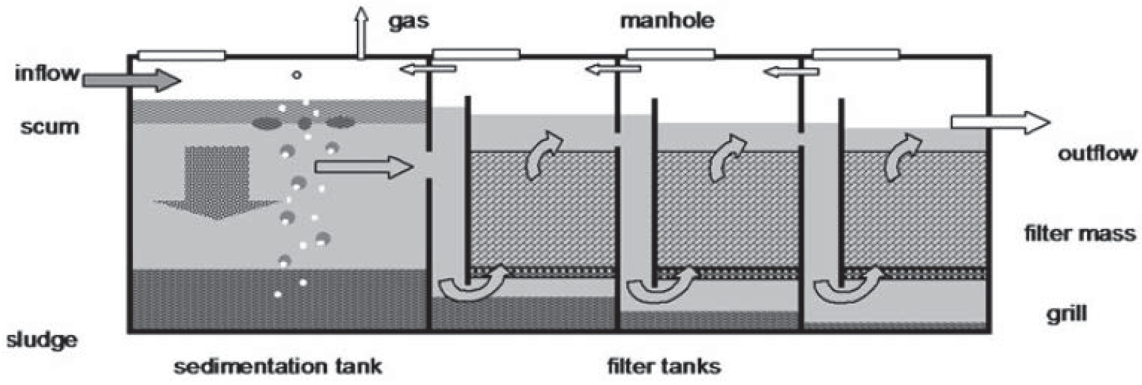


Figure 3-5: The Flow Principle Of Anaerobic Filter (BORDA, India).

3.2.5 Constructed Wetland / Planted Gravel Filter (PGF)

The Horizontal constructed wetland and vertical constructed wetland is a secondary treatment commonly used in DEWATS. Basically, constructed wetlands are of two types, vertical and horizontal flow types. The shallow area is filled with sand and gravel that looks as natural system. The system acts as the combined mechanism of the filter media and plant growing on filter media. The PGF method has the treatment performance of BOD_5 97 to 99 %, NH_4-N 80 to 99 % and phosphate 50 to 69% (Shrestha et al. 2001). The Figure 3-6 shows the flow principle of constructed wetland.

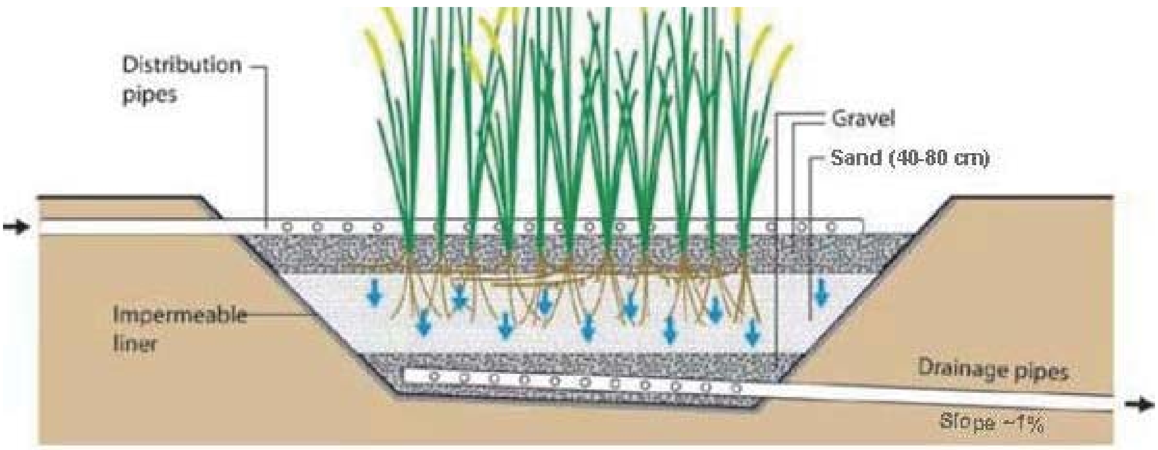


Figure 3-6: The Flow Principle Of Constructed Wetland (Morel 2006).

3.3 Description on DEWATS Model

In this study three-wastewater treatment scenario that consists of a combination of different small scale decentralized treatment methods are considered. The design capacities of the treatment model used in the present study are 10 m^3/day and 50 m^3/day. The models used in the study are as follow:

3.3.1 DEWATS module 1 (DM 1)

The DEWATS module installed are settler (S), anaerobic baffled reactor (ABR) and constructed wetland (PGF). The wastewater generated at the area is treated in small-scale system with treatment capacity of 50 m^3/day. The total number of users is about 1000 numbers. The Figure 3-7 shows the flow diagram of model 1.

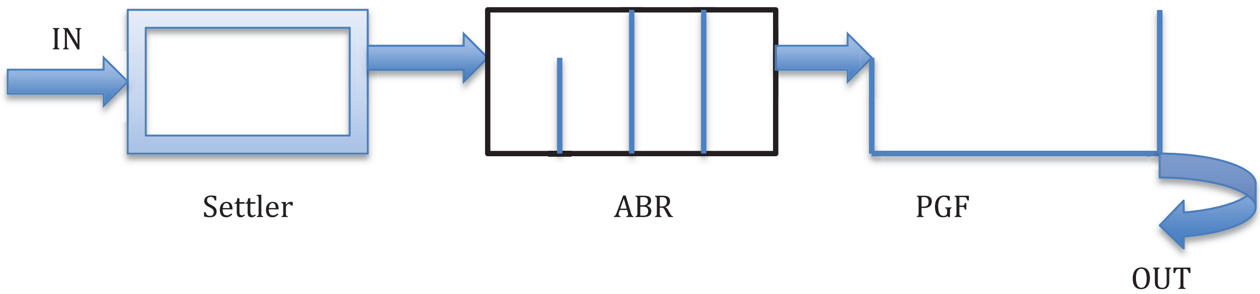


Figure 3-7: Shows The Flow Diagram Of Model 1

3.3.2 DEWATS module 2 (DM 2)

The DEWATS module installed are settler (S), constructed wetland (PGF) and collection tank (CT). The wastewater generated at the area is treated in small-scale system with treatment capacity of 10 m^3/day. The total number of users is about 800 numbers. The Figure 3-8 shows the flow diagram of model 2.

Figure 3-8: Shows The Flow Diagram Of Model 2

3.3.3 DEWATS module 3 (DM 3)

The DEWATS module installed are settler (S), and constructed wetland (PGF). The wastewater generated at the area is treated in small-scale system with treatment capacity of

50 m^3/day. The total number of users is about 700 numbers. The Figure 3-9 shows the flow diagram of model 3.

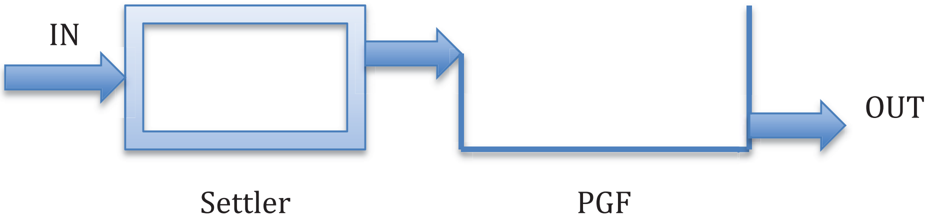


Figure 3-9: Shows The Flow Diagram Of Model 3.

3.4 LCA Methodology

3.4.1 Goal and Scope definition

The goal of the sutyd is to compare the three DEWAT module in terms of their environmental performance. The scope of the study is limited to constructional and operational phases. The study was done with the tool of Life Cycle Assessment based on ISO standards 14040-14044. The computer based software 'SimaPro' is used on the study. The result is more useful to the decision makers for the development of new guidelines, in relation with choosing the most appropriative wastewater treatment methods.

3.4.2 Functional Unit

The DEWATS model used in the study is designed by BORDA network. These all model are installed in South Asian countries (India, Nepal, and Bangladesh). The functional unit assumed for this study is the treatment of wastewater generated by person equivalence over a period of 20 years (i.e. g or kg/pe/day). The functional unit is the center for the assessment of different treatment methods (Akwo 2008). The design capacities of the treatment models are 10 m^3 and 50m^3. A design period of 20 years was expected for the comparison of DEWATS modules.

3.4.3 System Boundaries

The system boundaries are set in accordance with scope and objectives of the study. For this study only tow phases: construction and operation have been considered. The Figure 3-10- illustrates the system boundaries considered for this study. The sewer network transporting sewage from the individual household to the treatment unit is assumed to be similar in layout and size in the three modules and therefore not included in the inventory study common to all. All the inputs and outputs for construction and operation are taken into account. The background information for such phases are retrieved from LCI database tool 'SimaPro 7'. Maintenance phase is also neglected in this study.

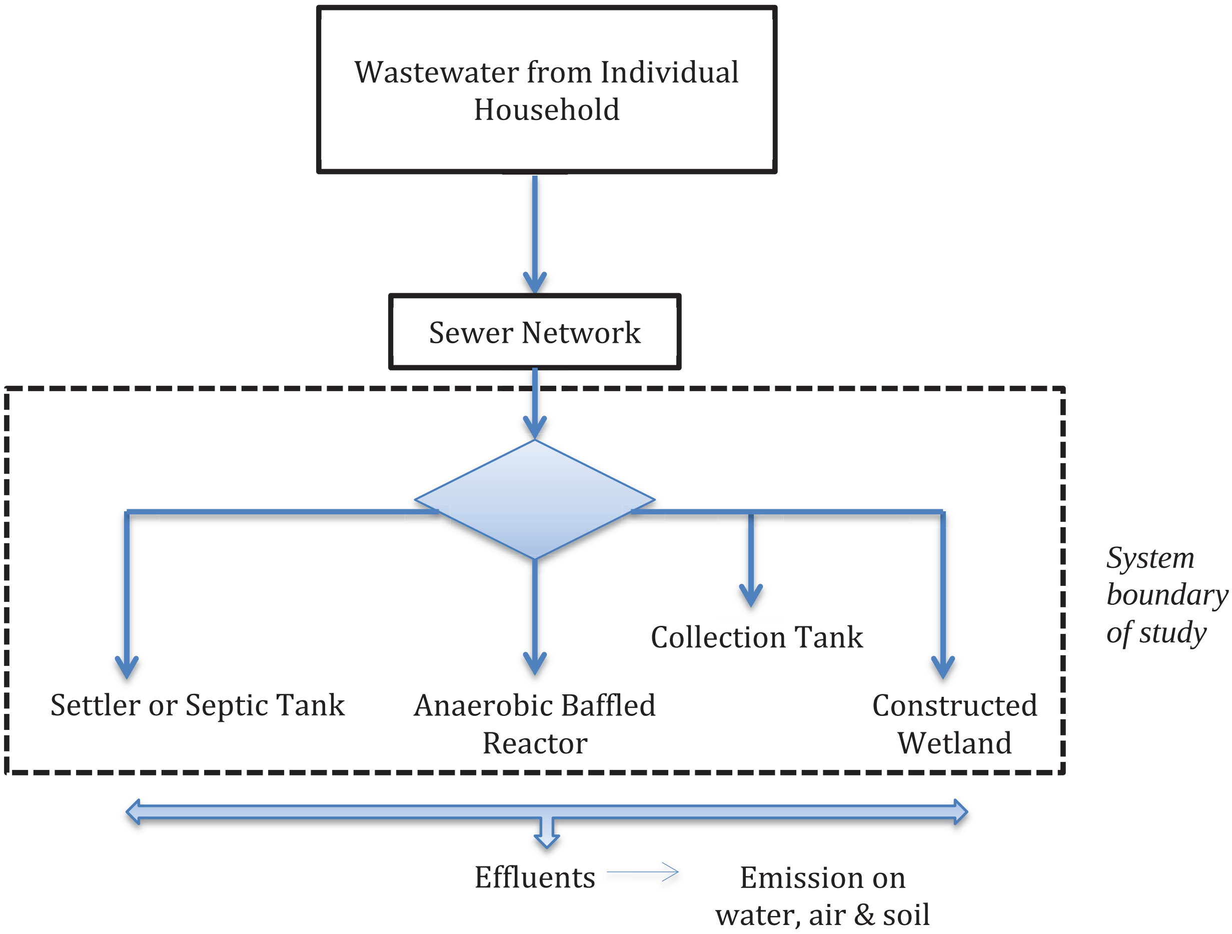


Figure 3-10 (1): shows the general system boundaries of the study

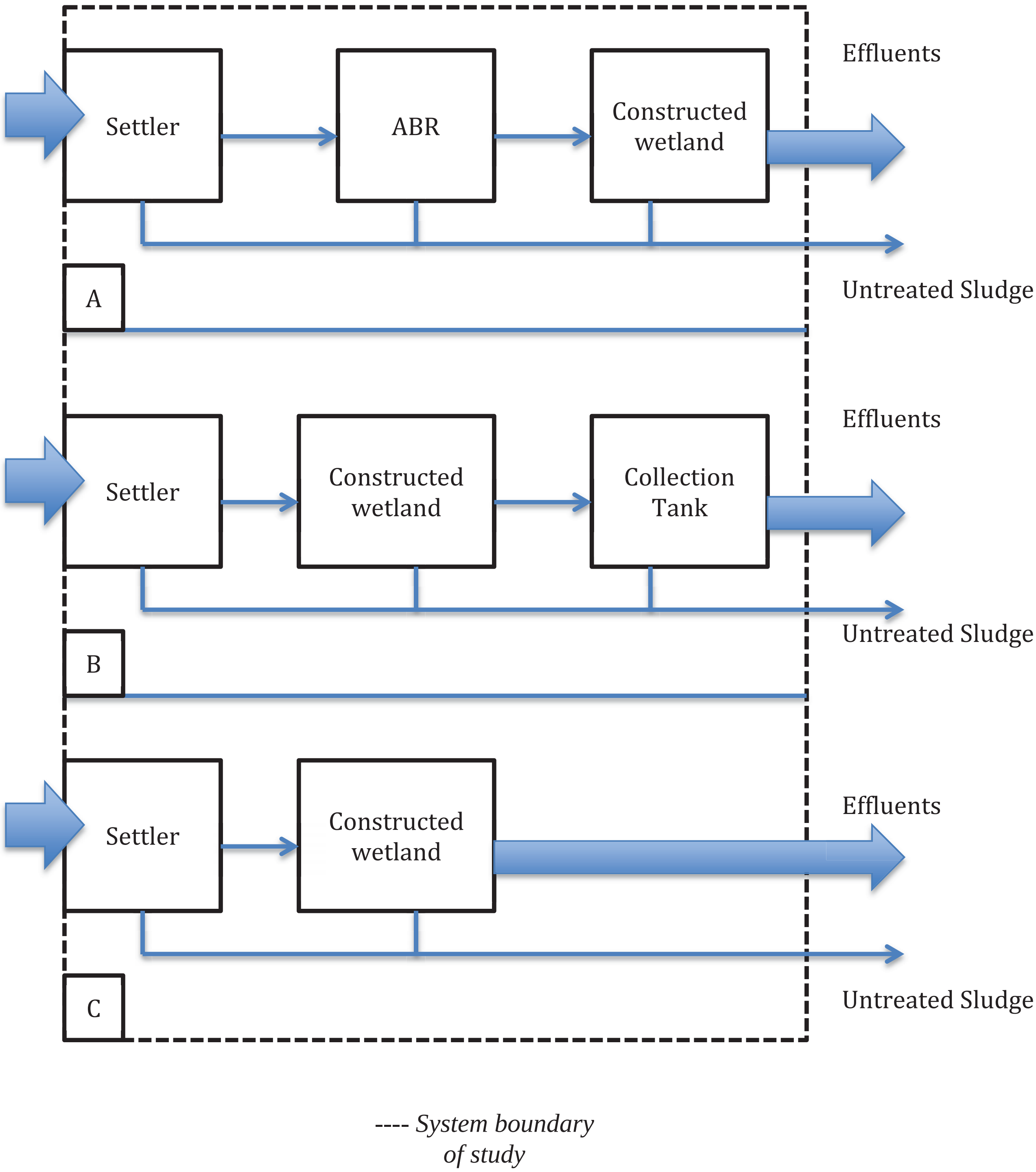


Figure 3-10 (2): system and system boundaries: (A) DEWATS module 1 (B) DEWATS module 2 (C) DEWATS module 3

3.4.3 Inventory

The environment input and outputs were quantified and calculated during this phase of LCA. The inventory table was prepared in MS-Excel. The table 3-1 was taken as a reference for the calculation of BOD, COD, TN, and TP in effluents. Whereas, output related impacts (GWP, EP, ODP, and AP) were analyzed using software SimaPro.

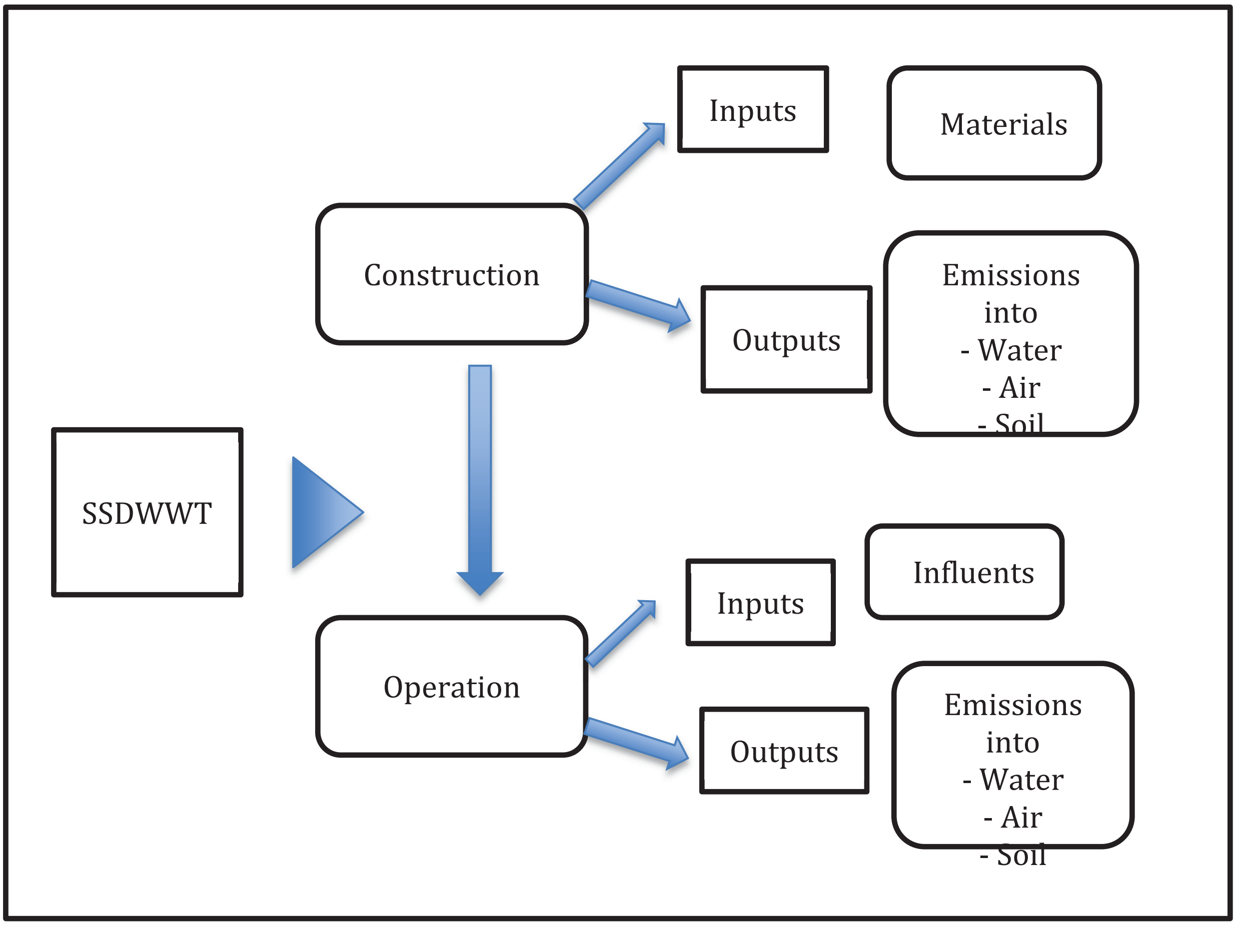


Figure 3-11: Shows the Overview of Input and Output at Different Phases

Table 3-1: The Volume And Composition Of Separated Domestic Wastewater; BOD, COD, TN And TP (Kujawa-Roeleveld, K. and Zeeman, G., 2006)

Volume and composition of separated domestic wastewater							
S.N.	**Parameter**	**Unit**	**Urine**	**Faces**	**Grey water**	**Kitchen refuse**	**Total**
1	Volume	gorL/pe/day	1.3	0.12	91.3	0.2	92.92
2	Nitrogen	g/pe/day	9.5	1.75	1.2	1.7	14.15
3	Phosphorous	g/pe/day	0.8	0.5	0.4	0.25	1.95
4	BOD	g/pe/day	5.5	23.5	27	-	56
5	COD	g/pe/day	11	50	52	59	172

3.4.3 Impact Assessment Methods

CML 2 baseline 2000 method has been chosen to evaluate the impact. CML 2 baseline method comprises 10 impact categories viz: Abiotic depletion, Acidification, Eutrophication, Global Warming Potential (GWP 100), ozone layer depletion (ODP), Human toxicity, Fresh water aquatic ecotox, Marine aquatic ecotoxicity, Terrestrial ecotoxicity and photochemical oxidation. In this method the impact category are based on the IPCC equivalency factors (Goedkoop et al., 2010). The Impact categories chosen in the present study is ***Acidification, Global Warming or Greenhouse effect, Ozone Layer Depletion, and Eutrophication*** to the relevancy of the study goal. These impact categories are more accurate with environmental burdens due to the wastewater treatment (Frances 2013).

This method is relatibvely straightforward and the impact can be explicity expressed in terms of commonly encountered environmental problems such as greenhouse gas emission or eutrophication. Whereas, other method likes the Eco-indicator 99, the calculation of possible indicator is difficult and result is more uncertain (Goedkoop et al., 2010). For example, the indicator for acidification is quantified in the percentage, whereas, the indicator for climate change is quantified in Disability Adjusted Life Years.

The short description of the impact categories chosen for the study are presented below:

Global Warming Potential (GWP): GWP is used to determine the climate impact by substances, which is the major global issue. GWP is depends on heat trapped by the green house gases exist in atmosphere. The examples of greenhouse gases are carbondioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and Water vapor. In life cycle assessment the radiation effect by CO_2, CH_4, N_2O are considered in impact assessment process (GHK 2006). CO_2 is taken as equivalence factor for GWP value that is considered for a time span of 100 years.

Acidification Potential (AP): AP is an atmospheric pollution usually by sulphur and nitrogen oxides. To access the impact of AP, the ability of formation of H^+ ions is calculated (GHK Annex 5). For acidification potential, SO_2 is set as an equivalence factor.

Eutrophication Potential (EP): eutrophication is another global issues due to the anthropogenic activities. Sources of water are effected, by the substances associated with phosphorous and nitrogen. Eutrophication is the enrichment of phosphorous and nitrogen content into the water bodies. The problem is associated with the increment of production of organic matter and decreased biodiversity. For example; the algal bloom in aquatic ecosystem. The PO_4^{-3} is set as an equivalence factor for EP.

Ozone Layer Depletion (ODP): the ozone layer is found about 15 to 50 Km high in the stratosphere. In LCA, the inventory of ozone depleting substances is evaluated for the assessment of ODP. CFCs are the major substances for ozone depletion. For the impact analysis CFC-11 is taken as a equivalence factor for ozone layer depletion potential.

3.5 Sensitivity analysis

Sensitivity analysis is done in order to see the influence of the assumption made for the study (Goedkoop et al., 2010). Sensitivity analysis was carried out to check the validity of findings. In this study the WWT system taken has design capacity of 50 m^3/day and 10m^3/day. Therefore the sensitivity analysis is carried out to check the effect of change in capacity on the environmental impact indicators.

3.6 Software

The number of software is available to accomplish LCA study. Software is very useful to simplify the study. The most available software use in the world to study LCA are; SimaPro 7, Gabi 5, EcoPro, Sima tool, Umberto, Team and Eco-IT (Frances 2013; Rice et al., 1997). The software has different features for assessment that make them distinct from each other. Open database LCA software tools are also available for LCA study. For example, OpenLCA is a free excess LCA and footprint software created by GreenDelt since 2006 (OpenLCA 2015).

3.6.1 SimaPro 7

SimaPro 7 is a world's most widely used LCA computer based software tool, used to calculate or identify the environmental performance of the system. The software tools are used for storage data, calculation, sensitivity analysis and contribution analysis. The software is developed in accordance with ISO standards ISO 14040 and ISO 14044.

Goal and scope definition in SimaPro 7

Here, a description on goal and scope for each project is available. There are two sections (Goedkoop et al., 2010):

- Text fields: this field describes the different aspects required for a goal and scope of the study. The text entered in this field can be copied and paste in the report.
- Libraries section: here one can find the predefinition of libraries with standard databases, which are considered in appropriate for the project. For example, if the LCA study is relevant for USA, one can switch-off the Europe database.

Inventory in SimaPro 7

SimaPro provides the inventory result by interpreting the process structure. Roughly, LCA can be made within few hours, through the data available in SimaPro. SimaPro is a only tool that visualize the non-looped data by hierarchical tree structure and network structure. This software contains details of input and output database (Goedkoop et al., 2010).

Impact Assessment in SimaPro 7

SimaPro contains the variety of standard impact assessment methodologies, which can support to perform LCA. All the methods used in SimaPro are set according to ISO standards. The Impact assessment method in SimaPro is classification, characterization, normalization, damage assessment, and valuation.

Interpretation in SimaPro 7

In SimaPro this section is designed as a checklist, which covers the relevant environmental burden as mentioned in the ISO standards. This section also suggests the sensitivity analysis at the end of the LCA.

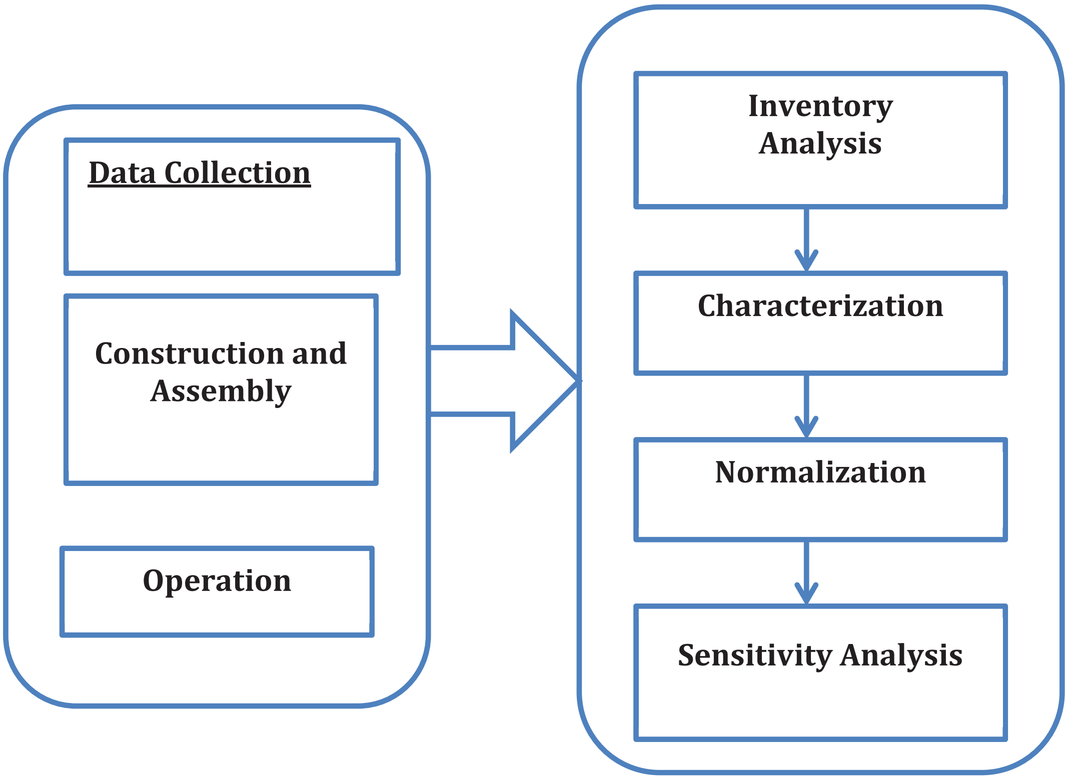


Figure 3- 12: Work Layout on SimaPro 7.0

4. Results, Discussion and Interpretation

4.1 Life Cycle Inventory (LCI)

In this phase of LCA, involves the calculation to quantify the inputs and outputs of three DEWATS module. The detailed description on life cycle inventory is presented at previous two chapters. The Table 4-1 shows the general overviews of input and output at different phases.

The DEWATS modules (DM1, DM2, DM3) operate as a natural system i.e. no energy inputs. Therefore no additional inputs of energy and any materials (Chemicals) are expected during operation process. The transportation of raw material from the processing site to the intended used site is also neglected in this study.

4.1.1 Construction Phase Inventory

Materials Used for the Construction

The material considered for different WWT modules (DM1, DM2, and DM3) consists of: sand, cement, gravel, reinforcement steel, brick, and plastic. The following tables shows the materials used on construction phase for three DWATS module. The details inputs are shown in annex3 and annex 4.

Table 4-1: Summary Of Materials Used For Construction Of DEWATS Module 1

S.N.	Item	Unit	System Units		
			S	ABR	PGF
i	Sand	Kg/pe	18.27253	47.4551	26.6785
ii	Cement	Kg/pe	8.9786	23.0981	17.0477
iii	Aggregate	Kg/pe	28.58374	73.7074	36.1234
iv	Steel	Kg/pe	1.2274	3.1281	2.7233
v	Bricks	Kg/pe	33.0368	121.3376	117.5936
vii	Plastics				
	a) PVC	lb/pe	0.01375	0.6875	0.088
	b) UPVC	lb/pe		0.01525	

Table 4-2: Summary Of Materials Use For Construction Of DEWATS Module 2

S.N.	Item	Unit	System Units		
			S	PGF	CT
i	Sand	Kg/pe	8.60875	23.495	7.385
ii	Cement	Kg/pe	2.7725	8.6625	2.14625
iii	Aggregate	Kg/pe	10.24125	31.095	7.8025
iv	Steel	Kg/pe	0.43375	1.5075	0.2975
v	Bricks	Kg/pe	22.664	64.576	10.696
vii	Plastic (PVC)	lb/pe	0.0175	0.0175	0.0175

Table 4-3: Summary Of Materials Use For Construction Of DEWATS Module 3

S.N.	Item	Unit	System Units	
			S	PGF
i	Sand	kg/pe	26.104	38.11
ii	Cement	kg/pe	12.827	24.35
iii	Aggregate	kg/pe	40.834	51.60
iv	Steel	kg/pe	1.753	3.89
v	Bricks	kg/pe	47.195	167.99
vii	Plastic (PVC)	lb/pe	0.020	0.13

(Where: S= settler, ABR=anaerobic baffled reactor, PGF=constructed wetland, CT=collection tank and pe=person)

4.1.2 Operational Phase Inventory

During the operation phase the treatment performance of each treatment unit was derived and analyzed. The emission compositions of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphorous (TP) into the water are calculated by using the reference value (Table 3-1) for the all treatment modules (DM1, DM2, and DM3). The contaminant removal efficiency of each system is presented below. The details of the performance analysis are shown in annex8.

Table 4-4: The Process Parameter For Three DEWATS Modules

S.N.	Parameters	DM1	DM2	DM3
		Emission into Water (g/pe/day)	Emission into Water (g/pe/day)	Emission into Water (g/pe/day)
1	TN	11.32	3.113	3.53
2	TP	1.053	0.682	0.585
3	BOD	17.12	25.48	6.56
4	COD	48.29	72.65	64.96

4.1.3 Impact Category Indicator Result

The total impact from all compartment (waterborne emission and airborne emission) was identified and presented below. The airborne and raw material emission are reported as a construction phase emission, whereas, waterborne emission was found during the operation of the treatment units. The inventory results of treatment modules DM1, DM2 and DM3 for each impact categories are shown in following tables.

Table 4-5: The Construction and Operation Phase Emissions From DM1

S.N.	Substance	Impact Unit	ABR	PGF	S
1	Airborne emission	Kg PO_4^{-3} eq	0.042	0.0179	0.00706
		Kg CO_2 eq	75.1	64.9	24.3
		Kg CFC eq	2.52E-6	2.44E-6	7.13E-7
		Kg SO_2 eq	0.261	0.213	0.0903
2	Waterborne emission	Kg PO_4^{-3} eq	1.46	0.00418	0.00375

Table 4-6: The Construction and Operation Phase Emissions From DM2

S.N.	Substance	Unit	CT	PGF	S
1	Airborne emission	Kg PO_4^{-3} eq	0.00192	0.00946	0.00315
		Kg CO_2 eq	6.79	34.4	11.5

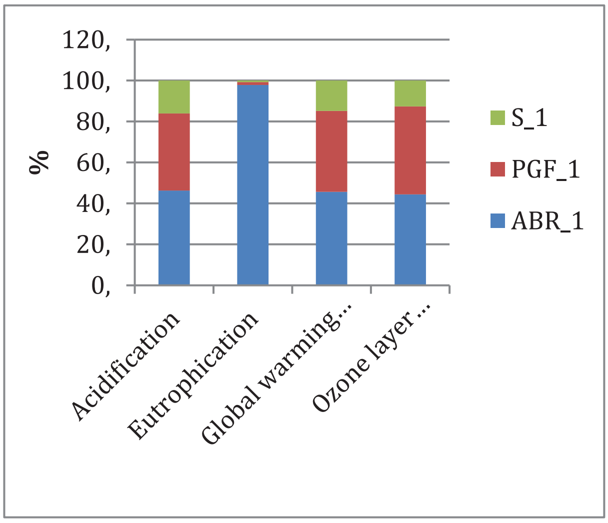
		Kg CFC eq	2.26E-7	1.33E-6	4.58E-7
		Kg SO_2 eq	0.0238	0.111	0.0366
2	**Waterborne emission**	Kg PO_4^{-3} eq	0.000298	0.00664	0.00304

Table 4-7: The Construction and Operation Phase Emissions From DM3

S.N.	Substance	Unit	PGF	S
1	Airborne emission	Kg PO_4^{-3} eq	0.0255	0.0102
		Kg CO_2 eq	92.1	35.2
		Kg CFC eq	3.45E-6	1.04E-6
		Kg SO_2 eq	0.303	0.131
2	Waterborne emission	Kg PO_4^{-3} eq	0.00892	0.00374

4.2 Life cycle Impact Assessment and Interpretation

The life cycle inventory (LCI) result was analyzed with regards to the potential environmental impacts. The contribution of each individual treatment units to the environment burden is presented in Figure 4-1. Environmental burdens contributed by the modules (DM1, DM2, and DM3) are presented in Figure 4-2. The Figure 4-3 presents the comparative environmental performance of each module



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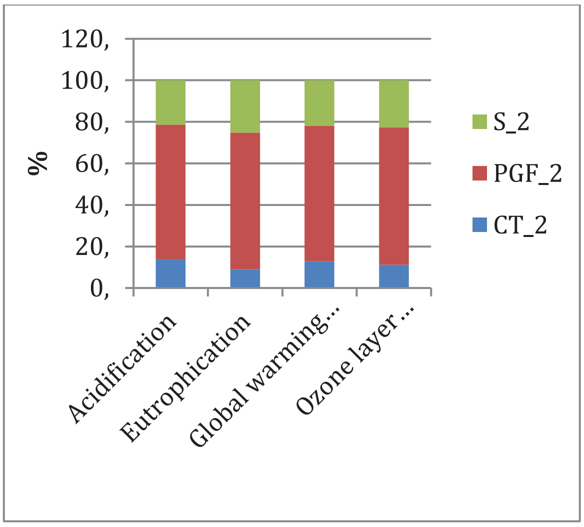

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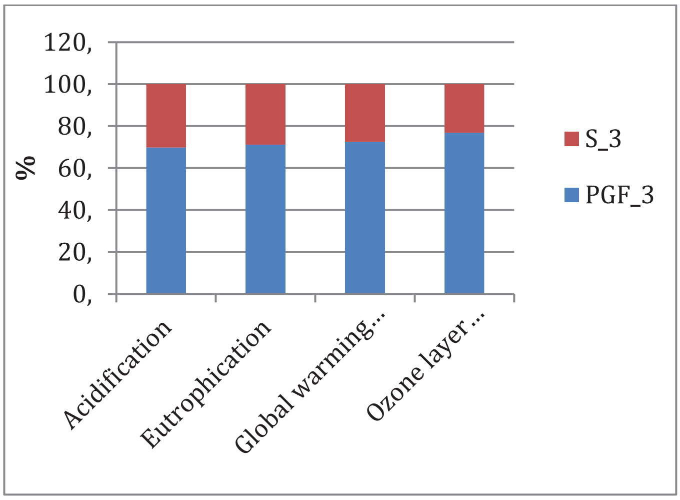

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Figure 4-1: Contribution Of Each Individual Treatment Units To The Environment Burden: (A) DEWATS module 1 (DM1) (B) DEWATS module 2 (DM2) (C) DEWATS module 3 (DM3)

DEWATS module 1 (DM1): settler (S), anaerobic baffled reactor (ABR) and constructed wetland (PGF) are three unit in DM 1. Figure 4-1 (A) compares the environmental burdens or impacts of each treatment units installed in DM1. All the impact categories are relevant with the different life cycle phases. The impact categories, AP, and ODP are relevant with the construction phase, whereas, GWP and EP is associated with construction and operation stages. The normalized value for each impact category was as follows: AP (18.66%), EP (66.79%), GWP (14.42%) and ODP (0.123%) are significant for different life cycle phases. Table 4-8 below presents the contribution to environmental burden by DM 1. It is clear that most impacts are attributed to ABR. In contrast, settler has far the lowest Figures. In ABR, Eutrophication potential was found almost 97.82 % followed by PGF (1.46 %) and S (0.71%). About 96.6 % of EP was contributed by ABR during operation period. The ABR is effective in removing BOD and COD, showed efficiency up to 80% (Motteran et al. 2013). The Nitrogen removal efficiency of ABR is quite good, whereas, the phosphorous removal efficiency is significantly very less (Jamshidi et al. 2014). Whereas, phosphorous is the main factors that causes the potential of eutrophication.

The GWP, AP and ODP were found almost equal in both ABR and PGF. Here, the settler contributes less GWP, AP and ODP into the environment. The GWP, AP and ODP were also found high in ABR, which is also due to the airborne emission during construction period. The Portland cement used on construction of treatment units is mostly responsible for GWP and AP, whereas, for ODP, brick was the major factor (Annex 5). During the production of cement, the chemical compounds like CO_2, NO_x and SO_2 were produces and high energy are consumed during the processes. This may effect on the concentration of greenhouse gas into the environment. Thus GWP, AP and ODP are more identified during construction period.

Table 4-8: The Normalized Value For Identified Environmental Potential In DM1

Impact Category	Normalized value Pe*a	%
AP (Kg SO_2 equivalence)	8.42E-10	18.66
EP (Kg phosphate equivalence)	3.01E-09	66.79
GWP (Kg CO_2 equivalence)	6.51E-10	14.42
ODP (kg CFC equivalence)	5.79E-12	0.128

DEWATS module 2 (DM2): settler (S), constructed wetland (PGF) and collection tank (CT) are three units in DM 2. The Figure 4-1 (B) compares the percentage of impact category in DEWATS module 2 per person equivalent. Table 4-9 below presents the normalized value for four-impact category in DM 2. Out of four impact categories, acidification potential (49.6%) was noticeably higher in DM2, followed by GWP, at 40.5%. The EP and ODP were found very less is about 9.5% and 0.4% respectively. The potential impact of AP, and ODP was 100% during the construction phase, whereas, GWP and EP were found on both construction and operational phases. In DM2, the AP was found high in PGF, this is due to the used of brick during construction period. The brick contribute to the impact category AP was about 55.9%, whereas, cement and steel contributed 18.1% and 16.1 % respectively (Annex 6, A).

In this module, PGF is the highest contributor for all four-impact categories, followed by S, and CT contributes least to identify impact categories. It is observed that structure of the PGF is bigger than other two units. Therefore the required quantity of material is more for construction of PGF and hence higher airborne emission. One important difference in DM2 is that, the unit CT is not responsible for the impact category of EP. CT is only a collection tank is used to collects the effluents from the PGF.

Table 4-9: The Normalized Value For Identified Environmental Potential In DM2

Impact Category	Normalized value P*a	%
AP (Kg SO_2 equivalence)	2.56E-10	49.6

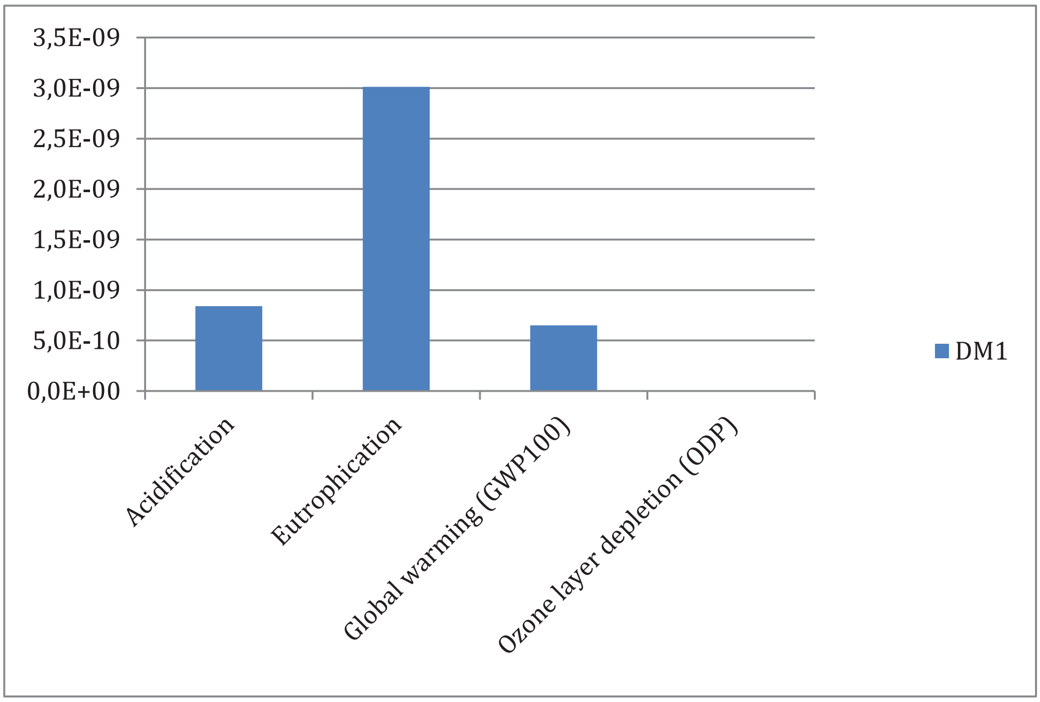
EP (Kg phosphate equivalence)	4.88E-11	9.5
GWP (Kg CO_2 equivalence)	2.09E-10	40.5
ODP (kg CFC equivalence)	2.05E-12	0.4

DEWATS module 3 (DM3): settler (S), and constructed wetland (PGF) are the two units in DM 3. Figure 4-1 (C) shows the percentage of four impact categories for DM3 contributed by different treatment units. The impact category, AP, GWP, EP and ODP identified in construction and operational phases were 51.6%, 40.3%, 7.7% and 0.6% respectively. As in DM2, EP is relevant for both construction (73.85%) and operation phases (26.15%), whereas AP and ODP are related with only construction stage for DM3. The Table 4-10 below presents the normalized value for identified impact category in DM 3. As compare with S and PGF, PGF shows the highest contribution for each impact category. PGF has noticed more than 69% contribution to all impact categories where S accounts 31% only. As discussed earlier, the PGF has largest structure than S and therefore it affects into the environment more than other units during construction phase. The use of cement and brick for the construction of S and PGF was the major contributor for the impact category of AP, and EP, whereas use of brick is sole responsible for ODP (Annex 7). Beside cement and brick, transportation of raw materials emits CO_2 relates with GWP in DM3. PGF is mainly for reduction the concentration of N and P from the wastewater, and it is found that PGF is effective for reducing N and P (Nichols 1981). In this module the EP was found 7.7% only. The PGF acts as source of GWP by emission of methane to air as well as it also acts as carbon sink by photosynthetic assimilation of CO_2 from the wetland soil (Brix et al. 2001). In this module, GWP was found about 40.3% account mostly from the construction periods.

Table 4-10: The Normalized Value For Identified Environmental Potential In DM3

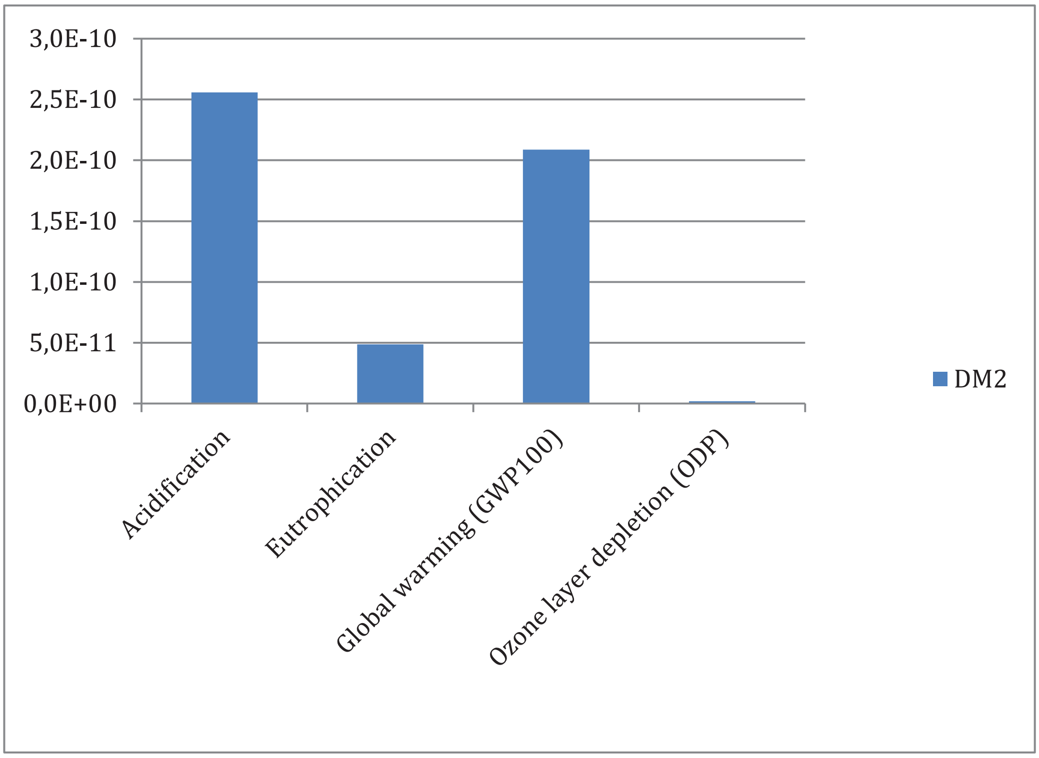
Impact Category	Normalized value Pe*a	%
AP (Kg SO_2 equivalence)	6.46E-10	51.6
EP (Kg phosphate equivalence)	9.62E-11	7.7
GWP (Kg CO_2 equivalence)	5.04E-10	40.3
ODP (kg CFC equivalence)	4.58E-12	0.4

A



3,5E-09
3,0E-09
2,5E-09
2,0E-09
1,5E-09
1,0E-09
5,0E-10
0,0E+00
Acidification
Eutrophication
Global warming (GWP100)
Ozone layer depletion (ODP)
DM1

B



3,0E-10
2,5E-10
2,0E-10
1,5E-10
1,0E-10
5,0E-11
0,0E+00
Acidification
Eutrophication
Global warming (GWP100)
Ozone layer depletion (ODP)
DM2

C

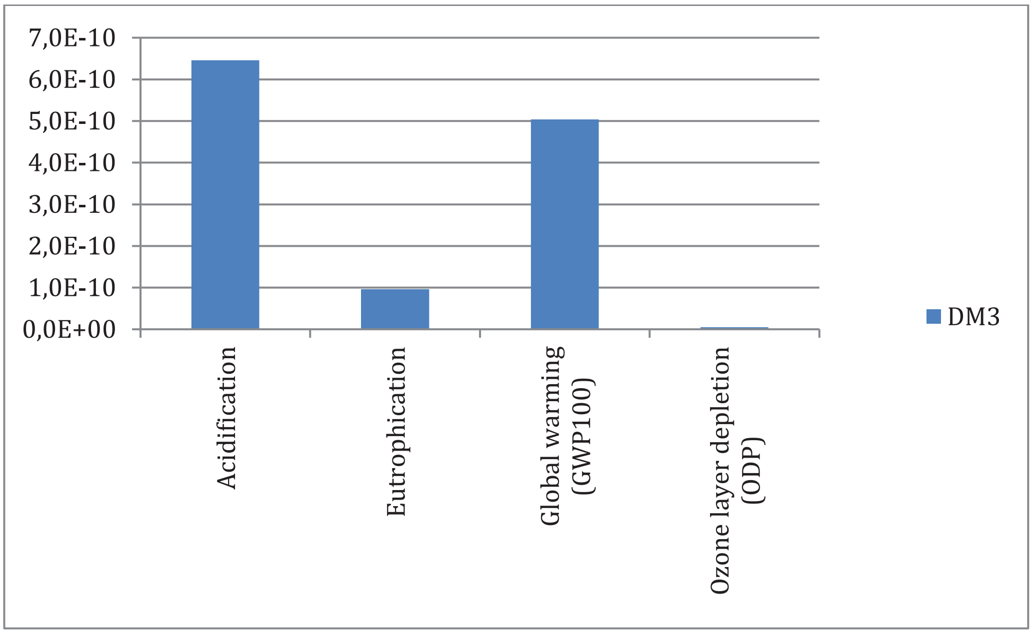


Figure 4-2: Environmental Burdens Contributed By The Modules: (A) DM 1 (B) DM 2 (C) DM 3

4.2.1 Global Warming Potential (GWP 100)

The GWP is identified for each module for a period of 100 years. The normalized value for global warming potential (GWP) is presented in Table 4-11. The DM2 showed the best GWP balance followed by DM3 and DM1. Thus DM2 is the best module for the treatment of wastewater as regards to global warming potential. The DM2 contributed 52.7 kg CO_2 equivalent to the impact category GWP, whereas, DM1 and DM3 contributed 164.3 and 127.3 kg CO_2 equivalent.

Table 4-11: Normalized Value For Global Warming Potential In kg – eq /Pe / day

DM 1 (S+ABR+PGF)	DM 2 (S+PGF+CT)	DM3 (S+PGF)
6.51E-10	2.09E-10	5.04E-10

For the Construction of wastewater treatment system the commercial product like cement, brick, gravel and steel were used. Thereafter, the materials processing and consumption during the construction phase contribute highest green house gas effect as compared with operation phase. The bituminous coal, clinker and electricity used for the production of cement and brick is the major substances that emits compounds likes CO_2, CH_4, and N_2O, contribute to GWP. Similarly, greenhouse effect from the centralized system is also found during the construction phase (Pandey et al., 2015). The anaerobic treatments of wastewater also contribute to the impacts category GWP (Akwo 2008). The compounds that contribute to the green house gas effect are CO_2, CH_4 and N_2O. The emission of CH_4 is also identified from the beds of PGF (Mander et al. 2005; Brix et al. 2001). The BOD and COD removal efficiency for ABR is 65 – 90 % and 70 – 95 % respectively (Krishna et al. 2009; Gutterer 2009). Which explained that most of the treatment takes place at ABR. Since, during the operation stage the emission was found very less as compared with construction stage. Here, in the present study, DEWATS module 1, contributes 45.7%, %, 39.5% and 14.8% (Fig 4-3 (A)) GWP balance by ABR, PGF and S respectively. During the construction and installation phase, excluded longest one, the relative impacts were identified from the raw materials (i.e airborne emission) (Table 4-5). The PGF also contribute 0.21 Kg CO_2, which is very uncertain. The fact is constructed wetland act as Carbon sinks and helps to reduce the amount of CO_2 into the atmosphere (Brix et al., 2001).

Carbondioxide (CO_2) is the main element for global warming (IPCC 2006), and the emissions were identified mostly from construction stage. Coal, oil and natural gas used for the production of energy contribute 97 – 98% CO_2 into the environment (Benetto et al., 2009), damage resources.

4.2.2 Eutrophication Potential (EP)

The COD and nutrients on the effluents indicate the basis for eutrophication. In these module scenarios the total nitrogen and total phosphorous discharged into the water was the major contributors to the EP. Eutrophication potential is mainly due to the emission of nitrogen and phosphorous. The overall accounting of EP (Kg PO_4^{-3} eq) in DM1, DM2, and DM3 are 1.51, 0.0245 and 0.0484 respectively. The normalized values for eutrophication from each module are shown in the Table 4-12. Both DEWATS modules DM2 and DM3 shows the least impact of eutrophication, as compared with DM1. In this study, more than 50% of eutrophication potential was found in the operation stage. The impact of eutrophication is relatively lower in treated wastewater than direct discharge of wastewater into surface water (Machado et al 2006). The LCA evaluate the eutrophication impact of nitrogen and phosphorous in phosphate equivalents.

Table 4-12: Normalized Value For Eutrophication Potential In kg – eq /Pe / day

DM 1 (S+ABR+PGF)	DM 2 (S+PGF+CT)	DM3 (S+PGF)
3.01E-09	4.88E-11	9.62E-11

The potential of eutrophication was found to be higher, due to the minimal reduction of nutrients by DEWATS modules (Gutterer 2009). The operation process as well as raw materials used in ABR, make this unit quite inefficient (Akwo 2008) relate to the eutrophication potential (Figure 4-1: A). On the same type of study, the EP accounts 100% for overall impacts categories (Frances 2013). The impacts are mainly due to the emission of NH_3 (67.2%) and Phosphate (25.6%) (Frances 2013) into the air and water. It was also found that, the phosphorous removal efficiency of the constructed wetland (PGF) is fairly low (Vymazal 2005).

4.2.3 Acidification Potential (AP)

The problem of acidification arises due to the presence of acidifying gases like NOx, SOx and NH_3 into the atmosphere. The emission of Kg SO_2 as equivalent is an indicator for acidification potential. In this study, compare with AP of the different module, module DM2 considered the least impact. The AP found for DM2 was 0.172 Kg SO_2 eq., whereas, DM1 and DM3 contribute 0.565 and 0.434 Kg SO_2 equivalent respectively. The normalized value (kg SO2 as equivalent) found in the different module as shown on Table 4-13.

Table 4-13: Normalized Value For Acidification Potential In kg – eq /Pe / day

DM 1 (S+ABR+PGF)	DM 2 (S+PGF+CT)	DM3 (S+PGF)
8.42E-10	2.56E-10	6.46E-10

In the entire life cycle of WWT the emission of SO_2 is mostly during the incineration process of cement clinker (Akwo 2008). It was found that natural gas or electricity used for brick production, bituminous coal for cement production and steel converter were responsible for AP in to the environment. In this study, AP accounts almost 100% from construction and installation stage. A study by Frances (2013), suggested that AP accounts for 97.7% of environmental profile during construction stage and rest are by the emission from transportation. Other study, found that electricity and incineration process is the highest contributor of SO_2 and NOx emission into the air (Akwo 2008).

4.2.4 Ozone Layer Depletion Potential (ODP)

Volatile organic carbon (VOC) emission is the main contributor to the impact category ODP. All three modules (DM1, DM2 and DM3), presents near about similar normalized value for ODP, 5.79E-12, 2.05E-12 and 4.58E-12 respectively. Cement production emits VOC for at least 95% (Frances 2013). Regarding the contribution to ODP, module 2 is the best option. Here, in the construction stage contribution is almost 100% to ODP category. Here in the present study, DM1 represents the highest contributor to ODP, 5.67 E-6 kg CFC-11 equivalent. As compared with all three-treatment modules, the quantity of cement used for the installation of modules depends on the Kg CFC-11 equivalent. Other raw materials like light fuel oil, crude oil represents the productions of CFC-11 contribute to the impact category of ODP.

Table 4-14: Normalized Value For Ozone Layer Depletion Potential In kg – eq /Pe / day

DM 1 (S+ABR+PGF)	DM 2 (S+PGF+CT)	DM3 (S+PGF)
5.79E-12	2.05E-12	4.58E-12

4.3 Evaluation of DEWATS modules:

Based on the impact categorization, the comparison was made between three DEWATS modules. Figure 4-3 present the diagram showing the comparison of environmental performance of the modules (DM1, DM2 and DM3). The comparison was based on the physical unit installed in each module systems.

Table 4-15 : Comparison Of The Total Of All Compartment Of Selected Modules

Impact Category	DM1	DM2	DM3
GWP (Kg CO_2 eq)	164	52.7	127
EP (Kg PO_4^{-3} eq)	1.51	0.0245	0.0484
AP (Kg SO_2 eq)	0.565	0.172	0.434

ODP (Kg CFC-11 eq)	5.67E-6	2.01E-6	4.49E-6

The table 4-15 and Figure 4-4, clearly shows the comparison of each impact category contributed to all compartment from selected DEWATS modules. As shown in Figure 4-3, DM1 represent the 100% of overall impact categories. This impact has expected during the construction process, this is because the quantity of materials used owns higher airborne emission. The GWP expected in different treatment modules, almost 100% impact are identified during construction stage, whereas, emission of CH_4 during the anaerobic treatment of wastewater is also expected. The collection of methane gas would be the better options for further reducing the impact of GWP. As compared with three treatment modules, DM1 had eutrophication impact (Figure 4-3) in higher amount than DM2 and DM3. As discussed earlier, In DM1 the EP is expected, at 97.8%, from anaerobic treatment of wastewater. EP could be minimized, by adding the secondary aerobic process that enhances the nutrient removal efficiency of the system (Li et al. 2013). One study suggested that insertion of aerobic polishing stage within the structure of ABR gives the better treatment results (Barber and Stuckey 1999). The impact of ODP is expected very low within all treatment modules.

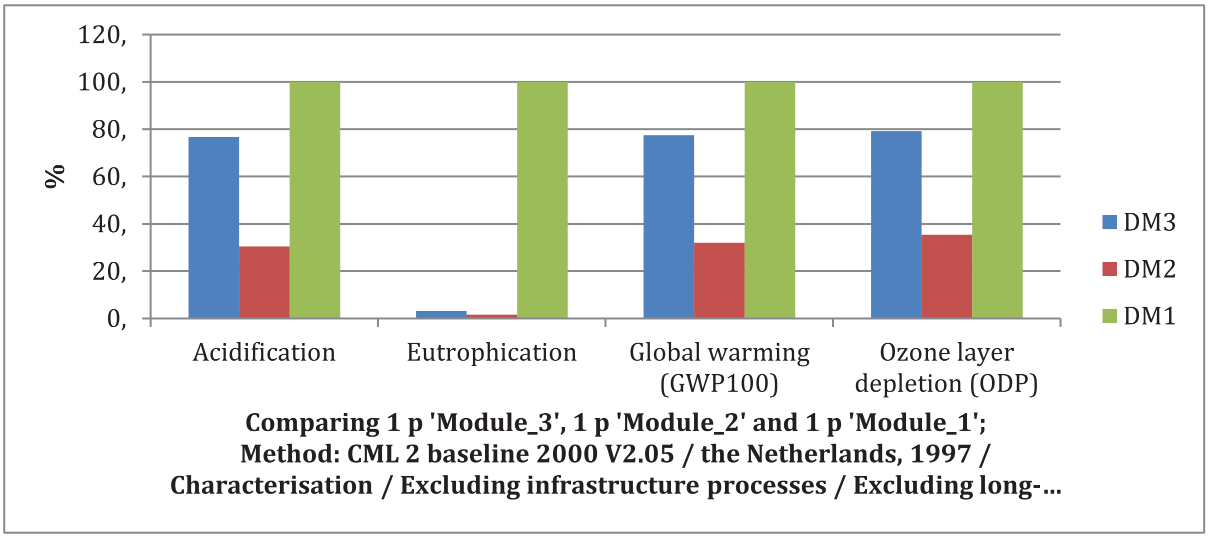


Figure 4-3: Comparison Of The Environmental Performance Of Treatment Modules DM1, DM2 And DM3.

As compared with the operational performance of the DM1 and DM2, DM1 showed best performance due to the presence of ABR unit. ABR reduced the large volume of organic matter, which has BOD and COD removal efficiency up to 90% (Krishna et al. 2009). It also identified that ABR required large volume of materials during construction. It affects by large percentage on overall impact categories. Otherwise, DM1 showed the best operational performance and showed less waterborne emission. Therefore, it is clear that more treatment option is available, less impact to the water bodies and vice versa. The physical unit like PGF and ABR required more materials than S and CT and it is expected more environmental burdens within PGF and ABR units. It is due to the airborne emission and raw material during construction and installation of treatment units. However, enhancing the use of local available resources could decrease the impacts identified during the life cycle inventory of small-scale DEWATS.

4.4 Sensitivity Analysis

On the basis of assumption made for the study, a sensitivity analysis is performed to check the reliability of DEWATS modules used for the study. The sensitivity analysis was done to compare the change in impact result when design capacity of treatment units is changed. Functional unit used to analyze the uncertainty was same taken same as main scenario. The sensitivity analysis is used to find out the change in impact category when the treatment capacity of the modules increased from 10 m^3/day (Scenario 1) to 50 m^3/day (Scenario 2).

Table 4-16 Result Of Comparison Between DEWATS Scenario (Normalized Value For Different Scenario)

Impact Category	Scenario 1 (10 m^3/day)	Scenario 2 (50 m^3/day)
GWP (Kg CO2 eq)	3.13E-07	9.26E-07
EP (Kg PO4-3 eq)	4.22E-08	1.16E-07
AP (Kg SO2 eq)	2.62E-07	7.05E-07
ODP (Kg CFC-11 eq)	2.68E-09	6.12E-09

Increased in the capacity of wastewater treatment results in the reduction of water and air emission. For EP, the normalized value (Table 4-16) was found less in Scenario 2, comparison with scenario 1. In the case of GWP, the absence of ABR results in decrease in emission of CH_4, decreased the environmental burdens for scenario 1. For the impact categories GWP, AP and ODP; 1:3 ratios were found in between Scenario 1 and Scenario 2.

In Scenario 2, the presence of ABR unit decreased the overall impact identified during operational performance. It can be conclude that, results in air emission is closed to the used of quantity of materials for Scenario 2. Therefore, through the sensitivity analysis it was observed that there was important changes into the impact category contributed by different DEWATS modules with the design capacity of 10 and 50 m^3/day.

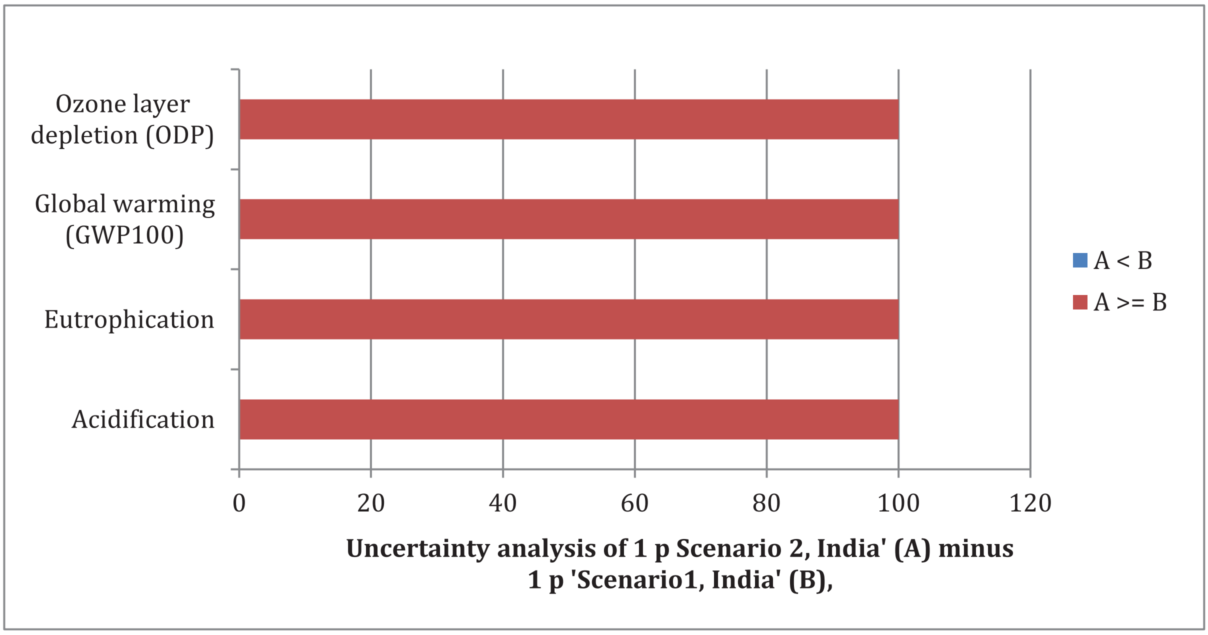


Figure 4-4: Impact Categories For Two Different DEWATS Scenario (95% Confidence Interval)

As shown in Figure 4-4, the confidence interval is clearly overlap, and it is not possible to distinguished, which scenario is best than other, in terms of contributions to the impact category. The Table 4-16, might therefore best indicator for the selection of a suitable scenario for wastewater treatment. For the comparison of variation in result the analysis should performed between large numbers of data.

5. Conclusions and Recommendations

5.1 Conclusions

In the present study, the Life Cycle Assessment (LCA) tool has been used for the sustainability assessment of small-scale decentralized wastewater treatment systems (DEWATS). The LCA is supportive to analyze the environmental burdens of WWTP that need to be a part of decision-making process towards sustainability. The following conclusion was made from the study. The data used in study was taken from a small-scale DEWATS designed for the community in Bangalore, India. Three types of DEWATS modules are used to identified the environmental burdens based on GWP, EP, AP and ODP. The results of the study show that DM1 is best for operational performance of community wastewater treatment. But the impact is different between the individual units installed within the modules. It is found that DM2 is the best module on the overall impact analysis during the different life cycle phase of the modules. The impact of ABR, S, PGF and CT are also found different from each other. All the units have distinct functional roles or operational performance to remove the pollutants from wastewater. For example, ABR remove the high organic loads from wastewater, whereas, PGF mainly controls the BOD, COD, TN and TP. It means that ABR and PGF are more useful to decrease the impact of EP and GWP during operational stage. On the other side, the impact of AP and ODP and GWP identified during the construction is very high. This is mainly the amount of materials required for the construction of the modules. The environmental impact is due to the cement clinker, transportation, electricity, natural gas, and bituminous coal used. It is also noticed that different units requires different quantity of materials for installation. It means that environmental burdens of the units are also different. Sensitivity analysis of the study also shows that confidence intervals clearly overlap, and it is not possible to distinguished, which scenario is better than the other, in terms of contributions to the impact category. Therefore, it is not possible to say which method or unit is best for decentralized wastewater treatment. Now, it can be conclude that increase in the number of units or treatment steps of the modules increases the performance of the system and hence decreases the environmental burdens and vice versa. Whereas, increases the units in the modules increases the amount of require materials for construction and hence increases the impacts into the environment. The followings are others major findings from this study.

- The results for the impact assessment identifies that the possible indicators for the impact categories; AP and ODP are found 100 % on construction period. The same result mentioned above is also presented in other studies on the same topic.
- The other environmental impact, GWP and EP are confirmed from both construction and operation stages. The construction stage contributes more than 95% of greenhouse gas effect, and the rest is found from anaerobic treatment of wastewater.
- About 97.8% of EP was found on operation stage by ABR in DEWATS modules 1. Eutrophication potential is due to the emission of TN and TP into the fresh water. It means that operational performance of the ABR to treat TN and TP is small. In addition, the emissions of NH_3 during anaerobic treatment of wastewater also responsible for EP.
- Cement clinker, brick, bituminous coal, natural gas, oil and electricity used for the raw material processing were major factors responsible for the emission of indicators that falls under the impact category.
- Through the sensitivity analysis, it is concluded that increase in the capacity of wastewater treatment increases the environmental loads and vice versa. It is also verified that an environmental burden depends on how many treatment steps or units that is installed within the system and what treatment capacity the modules have.

In summary, based on the evaluation of different DEWATS modules, it cannot be said that which module is the best, but it helps to identify the environmental hotspots in the treatment system and offers opportunity to improve the environmental performance of the systems through modification in the design or change in the layout and arrangements of the units.

5.2 Recommendation

Following recommendations are made based on the present study.

- The life cycle assessment study is recommended to compare the environmental performance of the small scale decentralized wastewater systems and the commonly used centralized systems in developing countries like pond and oxidation ditches.
- Local available resources should be used to decrease the impact identified during the construction periods.

- The aerobic treatment units should be recommended after the anaerobic treatment of wastewater for the better operational performance of anaerobic treatment units. For example; in ABR, attachment of aerobic stage help to reduce the total impacts of EP.

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Annexes

Annex 1: Raw data for DEWATS module (10 m^{3}/day)

S.N.		Item	Unit	System Units			
				Settler	Anaerobic Baffle Reactor (ABR)	Planted Gravel Filter (PGF)	Collection Tank
				Quantity			
1		**EARTH WORK EXCAVATION**					
	a	Total earthwork excavation	cum	66,15	118,16	209,03	65,80
	b	Earth Refilling	cum	41,95	67,71	79,24	37,83
	c	Removal of excess earth debris	cum	24,20	50,45	129,80	27,96
2		**Brick Bat filling in Distribution Channel (for PGF)**	cum			1,04	
3		**Plane Cement Concerete (PCC) 1:4:8**	cum	1,05	1,93	0,18	1,19
4		**Reinforced Cement Concerete (RCC) 1:1.5:3**				14.76	
	a	Top slab	cum	1,00	1,60		1,22
	b	Base slab	cum	4,08	8,49		1,58
5		**Reinforcement for slab, beams and columns**	Kg	346,9	721,3	1205,5	238,0
6		**SBM with motor for wall(partition wall, support wall, long wall and short walls)**	sqmt	32,80	79,16	71,90	26,30
7		**Plastering with Motor**					
	a	Total for external surface	sqmt	33,04	58,19	75,81	30,40
	b	total for Internal surface	sqmt	33,24	102,00	88,11	24,19
	c	Plastering to base slab top surface	sqmt	4,59	11,83	52,00	6,00
	d	plastering to external top slab	sqmt	6,25	11,49		7,65
	e	total for internal top slab	sqmt	3,61	7,27		5,02
	f	total for internal plastering	cum	52,49	2,48		47,66
8		**0.075 m thick RCC pre-cast slab cover**	Nos	2,00	1,00	5,84	2,00
9		**waste water pipes**					
	a	0.11 mtr dia inlet and outlet pipe fixing	Rmt	1,40			1,00
	b	PVC tee pipes	Nos	2,00			2,00

c	110 mm dia PVC pipes fixing	Rmt		13,00	1,50	
d	110 mm dia PVC tees fixing	Nos		25,00	3,00	
e	110 mm dia baffle pipe fixing (PVC)	Rmt		50,00		
f	110 mm dia vertical pipes fixing @ outlet	Rmt		4,00		
g	160 mm dia desludging pipe fixing	Rmt		6,00		
h	0.11 m dia, UPVC air vent pipe with vent cowls	Rmt		5,00		
i	55 mm dia distribution pipes fixing (PVC)	Rmt			4,00	
j	110 mm dia perforated pipe fixing	Rmt			4,00	
k	110 mm dia, sampling pipes fixing	Nos			3,00	
10	**0.075 m thick pre-cast Perforated slab**	sqmt		1,46		
11	**Kadapa Stone for the first chamber for ABR**	sqmt		0,17		
12	**Total quantity for inculation in ABR**	cum		0,03		
13	**Filler Materials for AF chamber**	cum		2,30		
14	**Hydraulic testing**	cmt	9,18	5,99	30,00	6,00
15	**Air Vent Pipe**	Rmt	5,00			3,00
16	**Filter Materials for PGF**					
a	100 to 120 mm size @ inlet side	cum			1,69	
b	100 to 120 mm size @ outlet side	cum			1,35	
c	100 to 120 mm size @ center	cum			1,80	
d	16 to 18 mm size @ inlet side	cum			12,75	
e	10 mm size @ outlet side	cum			12,75	
f	10 mm size @ top surface	Cum			3,19	

Annex 2: Raw data of DEWATS module (50m³/day)

S.N.	Item	Unit	System Units			
			Settler	Anaerobic Baffle Reactor (ABR)	Planted Gravel Filter (PGF)	Collection Tank
			Quantity			
1	**EARTH WORK EXCAVATION**					
a	Total earthwork excavation	cum	142	362.6	364.03	121.18
b	Earth Refilling	cum	66.43	113.92	55.93	45.56
c	Removal of excess earth debris	cum	75.57	248.68	308.11	75.62
2	**Brick Bat filling in Distribution Channel (for PGF)**	cum			1.79	
3	**Plane Cement Concerete (PCC) 1:4:8**	cum	3.3	8.67	16.9	2.98
4	**Reinforced Cement Concerete (RCC) 1:1.5:3**	cum	14.44	37.04	33.46	7.92
5	**Reinforcement for slab, beams and columns**	Kg	1227.4	3148.1	2723.3	672.8
6	**SBM with motor for wall(partition wall, support wall, long wall and short walls)**	sqmt	62.93	217.82	143.26	42.08
7	**Plastering with Motor**	sqmt	129.6	339.04	259.94	210.12
8	**0.075 m thick RCC pre-cast slab cover**	Nos	2,00		12.26	2
9	**waste water pipes**					
a	0.11 mtr dia inlet and outlet pipe fixing	Rmt	1,40			1
b	PVC tee pipes	Nos	2,00			2
c	110 mm dia PVC pipes fixing	Rmt		50	5.5	
d	110 mm dia PVC tees fixing	Nos		99	16	
e	110 mm dia baffle pipe fixing (PVC)	Rmt		200		
f	110 mm dia vertical pipes fixing @ outlet	Rmt		16		
g	160 mm dia desludging pipe fixing	Rmt		24		
h	0.11 m dia, UPVC air vent pipe with vent cowls	Rmt		5		
i	55 mm dia distribution pipes fixing (PVC)	Rmt			10.4	

j	110 mm dia perforated pipe fixing	Rmt			8	
k	110 mm dia, sampling pipes fixing	Nos			4	
10	**0.075 m thick pre-cast Perforated slab**	sqmt		11.43		
11	**Kadapa Stone for the first chamber for ABR**	sqmt		19.7		
12	**Total quantity for inculation in ABR**	cum		4.21		
13	**Filler Materials for AF chamber**	cum		8.78		
14	**Hydraulic testing**	cmt	41.25	76.44	81	24
15	**Air Vent Pipe**	Rmt	5,00			3
16	**Filter Materials for PGF**					
a	100 to 120 mm size @ inlet side	cum			3.04	
b	100 to 120 mm size @ outlet side	cum			2.43	
c	100 to 120 mm size @ center	cum			3.24	
d	16 to 18 mm size @ inlet side	cum			36.45	
e	10 mm size @ outlet side	cum			36.45	
f	10 mm size @ top surface	Cum			9.11	

Annex 3: Construction materials for DEWATS Module ((10 m^3/day)

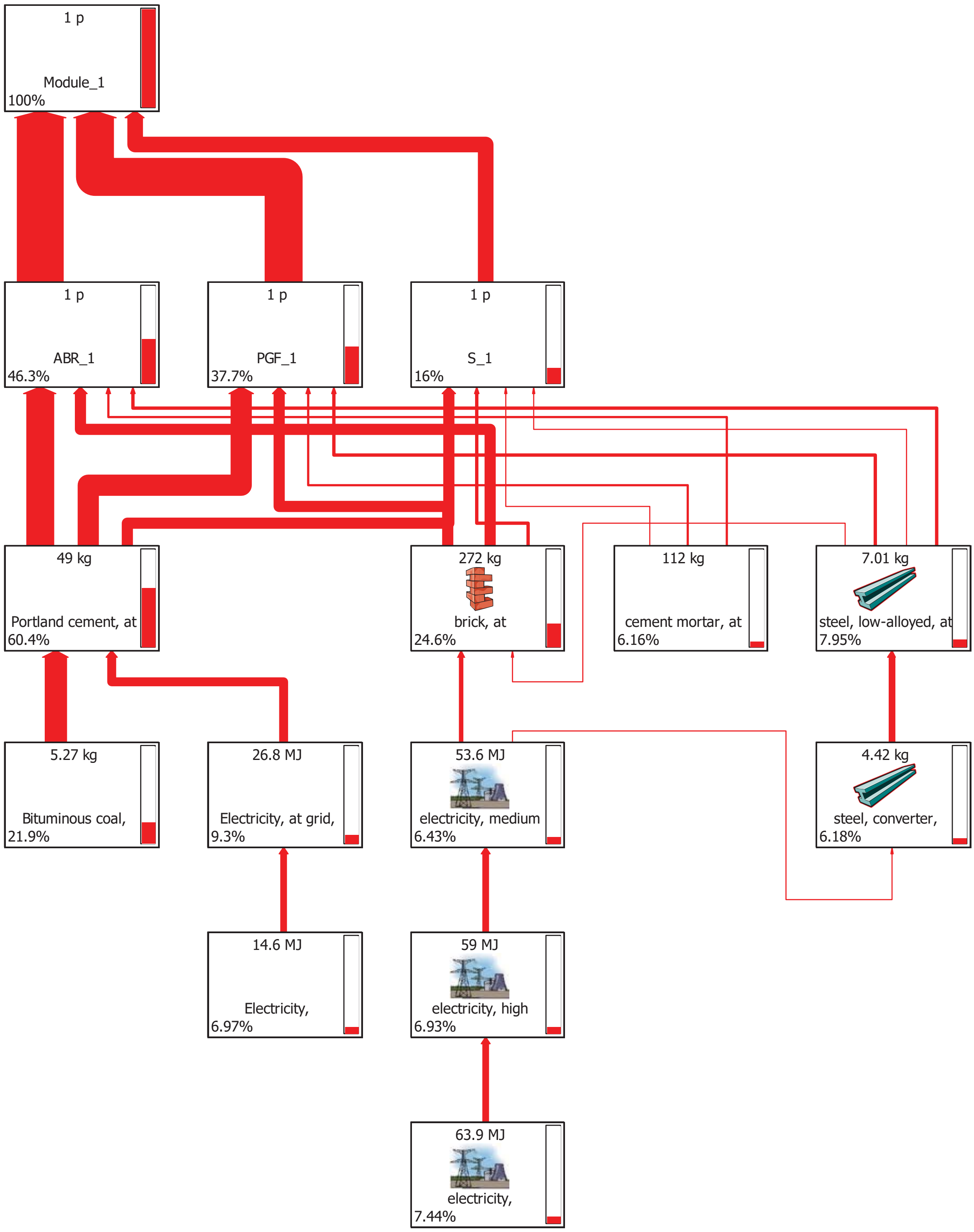
S.N.	Item	Unit	System Units			
			Settler	Anaerobic Baffle Reactor (ABR)	Planted Gravel Filter (PGF)	Collection Tank
			Quantity			
1	Plane Cement Concerete (PCC) 1:4:8					
i	Sand	kg	700	1299	109	796
ii	Cement	Kg	175	325	27	199
iii	Aggregate	kg	1401	2598	218	1591
2	Reinforced Cement Concerete (RCC) 1:1.5:3					
i	Sand	kg	2264	4723	8219	1550
ii	Cement	Kg	1509	3149	5480	1033
iii	Aggregate	Kg	6792	14169	24658	4651
iv	Steel	kg	347	721	1206	238
3	Plastering					
i	Sand	kg	3923.00	10083	10468	3562
ii	Cement	Kg	534	1374	1423	485
4	SBM with mortar, 1:6					
i	Bricks	Nos	5666	16124	16144	2674
ii	Cement	Kg	1165	3314	3318	551
iii	Mortar	kg	7437	21177	21202	3514
iv	Sand	kg	8567	24354	24378	4043

Annex 4: Construction materials for DEWATS Module ((50 m^3/day)

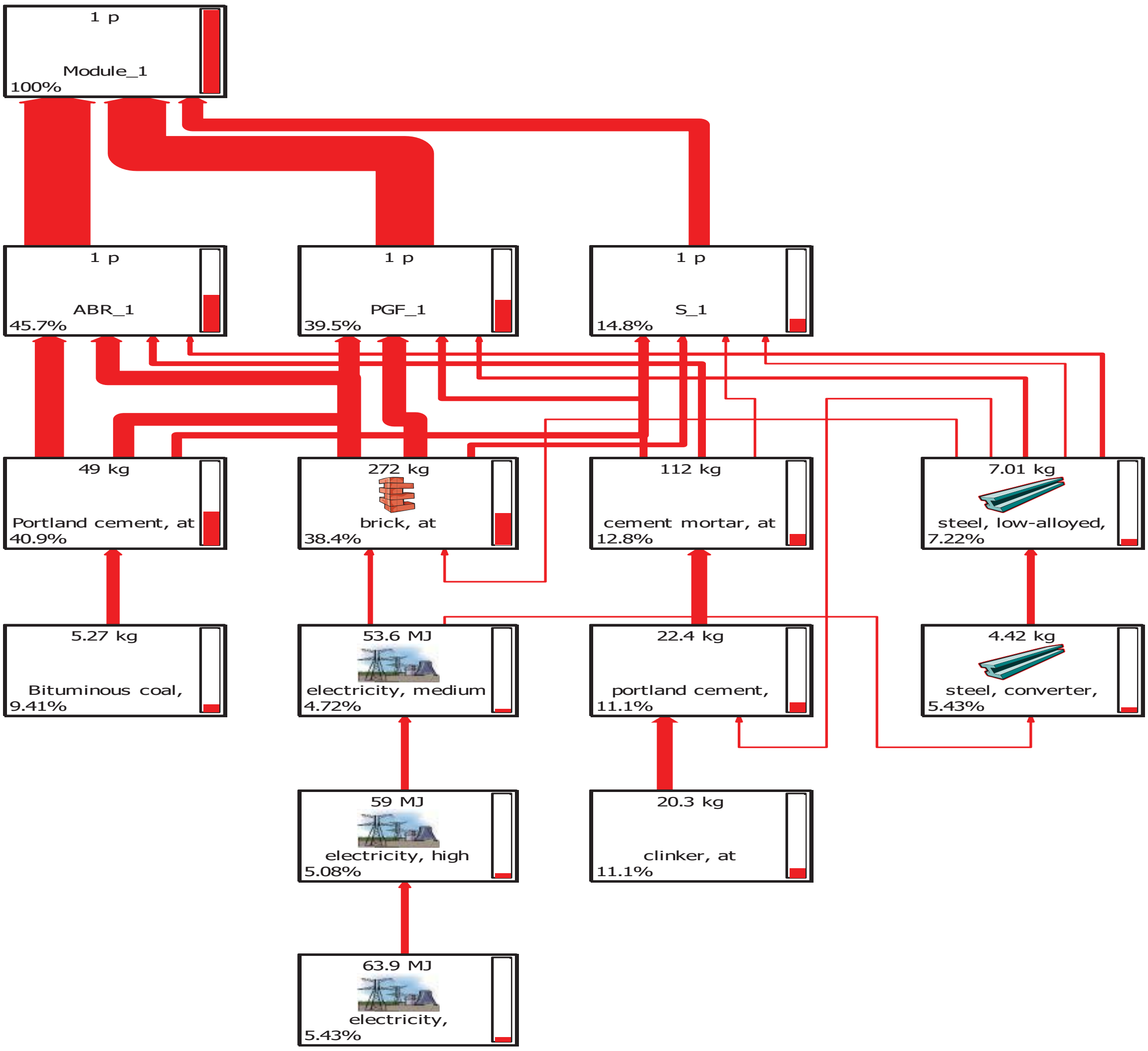
S.N.	Item	Unit	System Units			
			Settler	Anaerobic Baffle Reactor (ABR)	Planted Gravel Filter (PGF)	Collection Tank
			Quantity			
1	**Plane Cement Concerete (PCC) 1:4:8**					
i	Sand	kg	557.63	1472	2870	503
ii	Cement	Kg	2300	5889	11479	2013
iii	Aggregate	kg	4461.04	11778	22958	4026
2	**Reinforced Cement Concerete (RCC) 1:1.5:3**					
i	Sand	kg	8040.9	20643.1	4388.5	4405.2
ii	Cement	Kg	5360.6	13762.1	2925.7	2936.8
iii	Aggregate	Kg	24122.7	61929.4	13165.4	13215.6
iv	Steel	kg	1227.4	3128.1	2723.3	672.8
3	**Plastering**					
i	Sand	kg	9674	25340	19420	8038
ii	Cement	Kg	1318	3447	2643	1094
4	**SBM with mortar, 1:6**					
i	Bricks	Nos	10324	37918	36748	4280
ii	Cement	Kg	2123	7792	7552	881
iii	Mortar	kg	13549	49791	48275	5631
iv	Sand	kg	15594	57275	55518	6473

Annex 5: Details Network of inputs in LCA for DM1

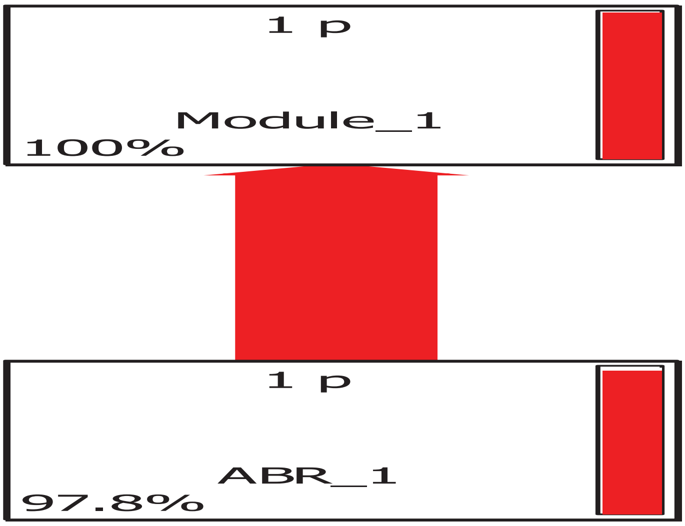
(A) For Acidification potential



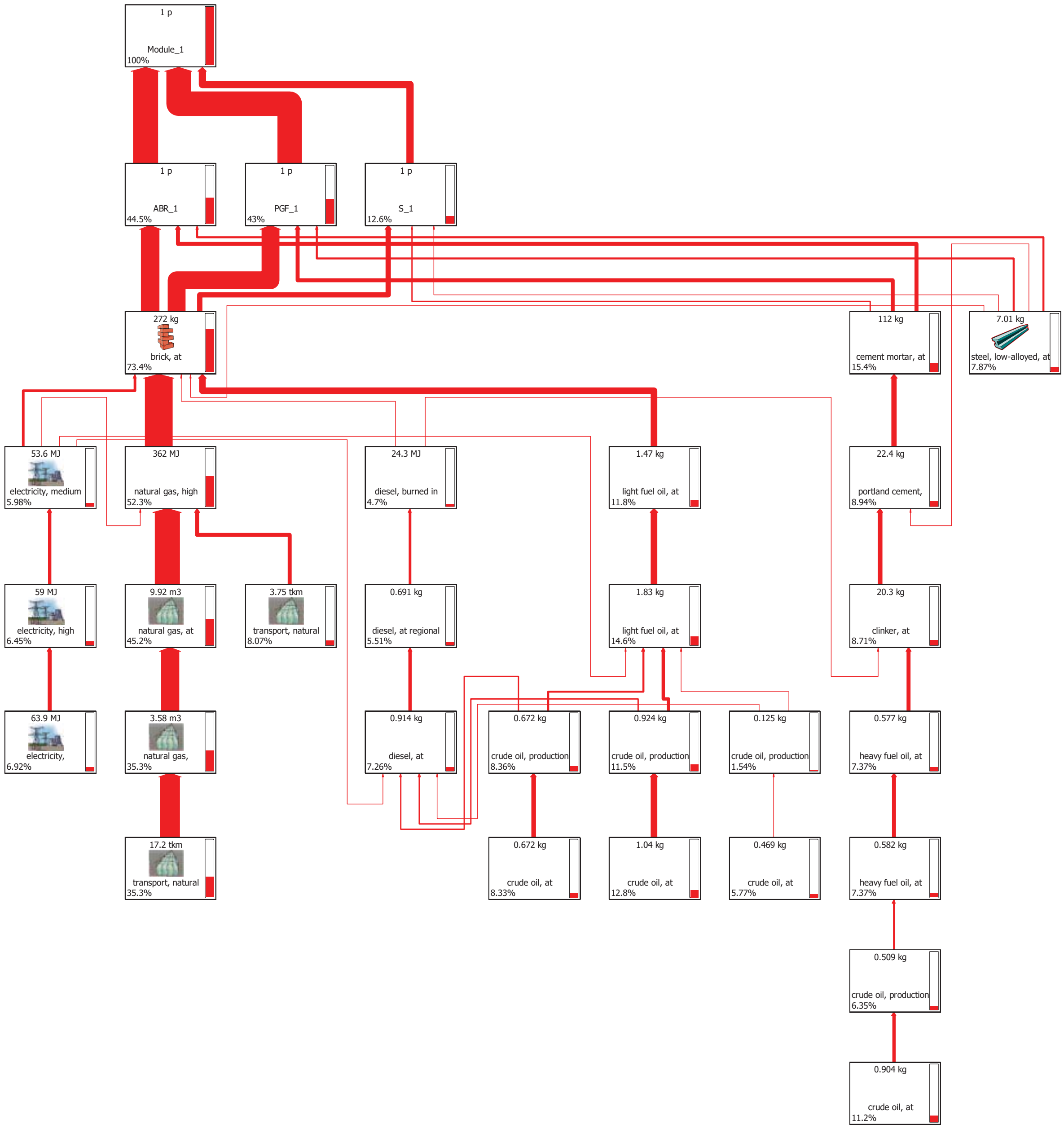
(B) For Global Warming Potential



(C) For Eutrophication Potential

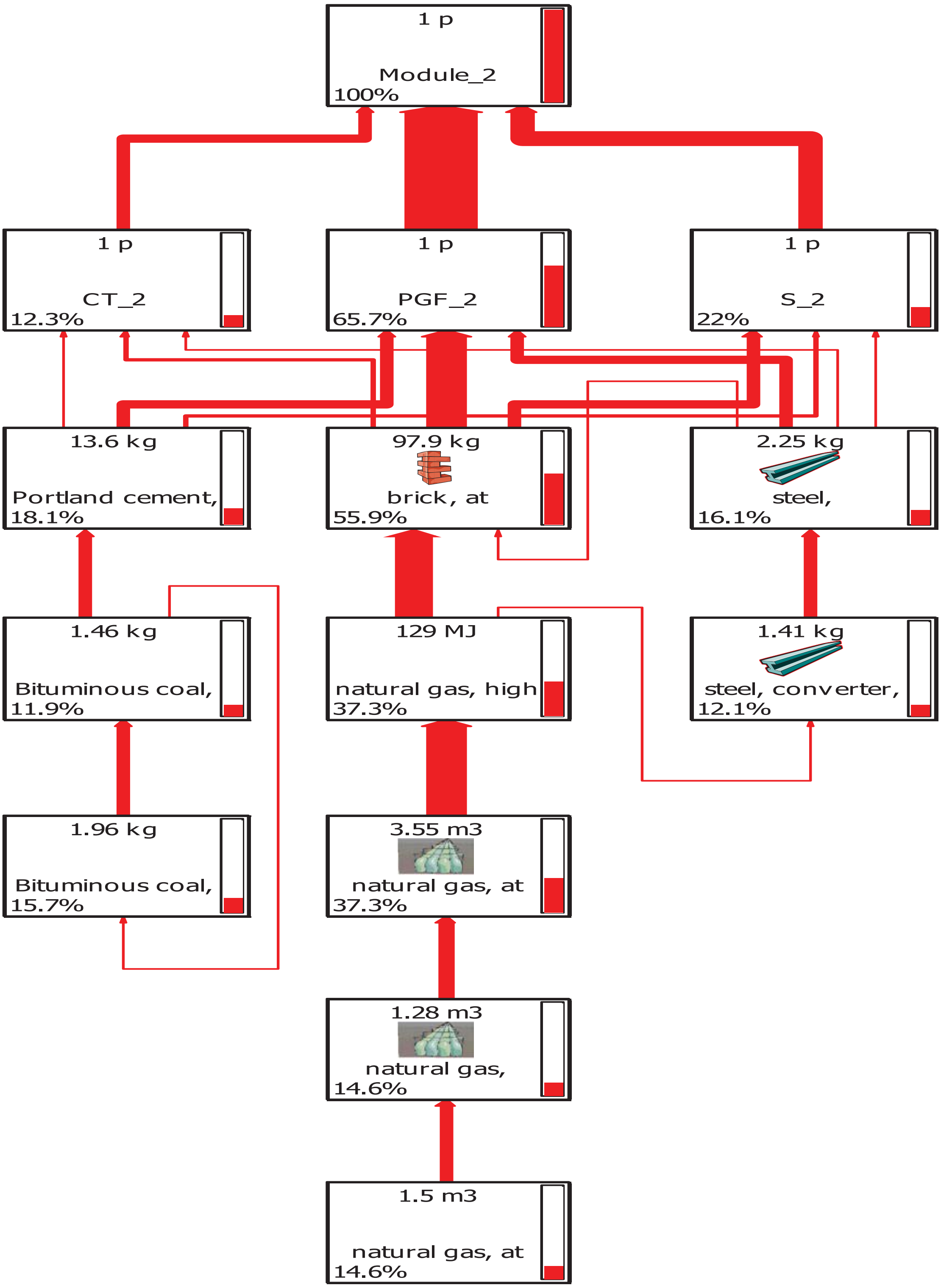


(D) For Ozone Layer Depletion Potential

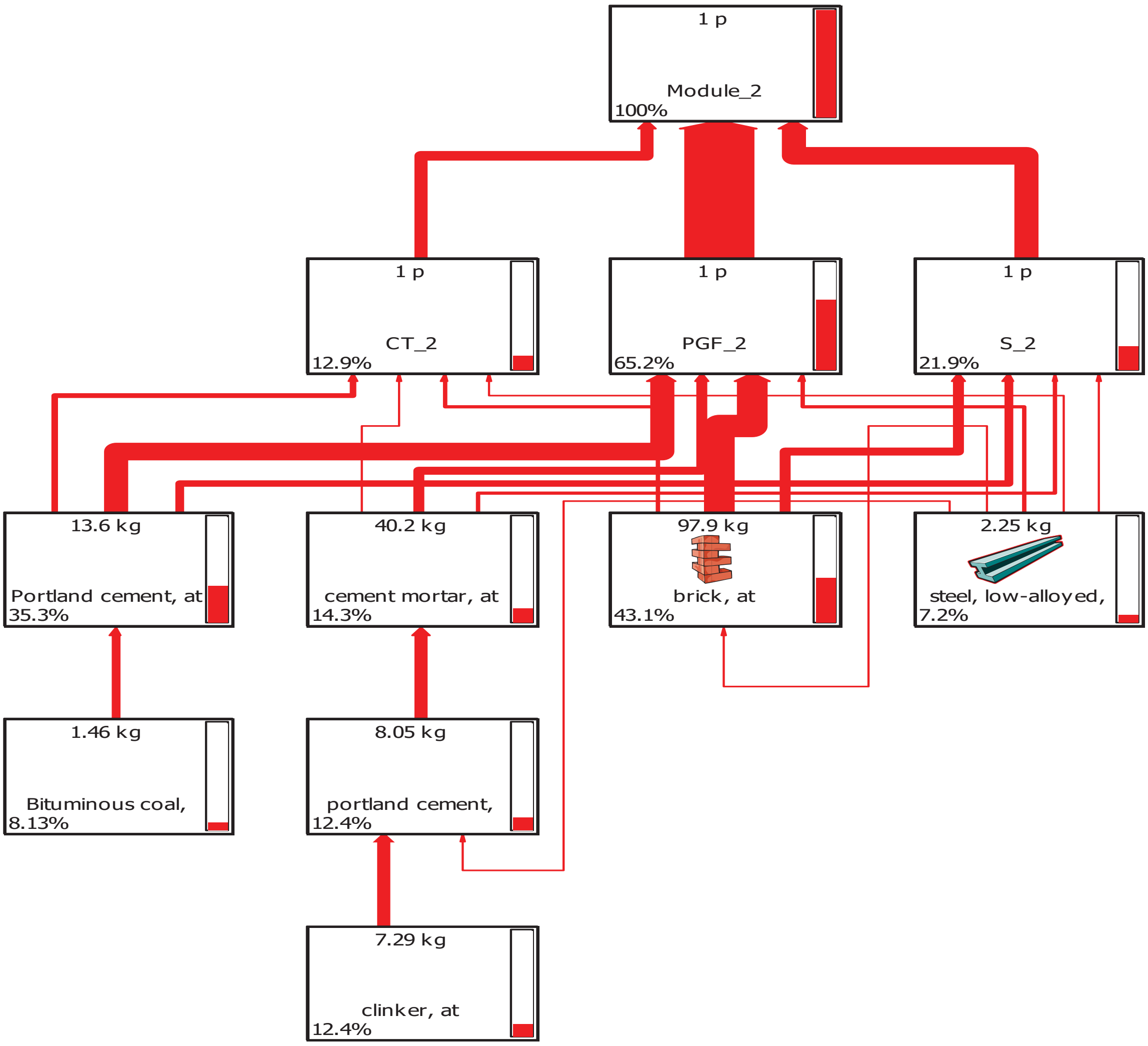

1 p
Module_1
100%
1 p
ABR_1
44.5%
1 p
PGF_1
43%
1 p
S_1
12.6%
272 kg
brick, at
73.4%
112 kg
cement mortar, at
15.4%
7.01 kg
steel, low-alloyed, at
7.87%
53.6 MJ
electricity, medium
5.98%
362 MJ
natural gas, high
52.3%
24.3 MJ
diesel, burned in
4.7%
1.47 kg
light fuel oil, at
11.8%
22.4 kg
portland cement,
8.94%
59 MJ
electricity, high
6.45%
9.92 m3
natural gas, at
45.2%
3.75 tkm
transport, natural
8.07%
0.691 kg
diesel, at regional
5.51%
1.83 kg
light fuel oil, at
14.6%
20.3 kg
clinker, at
8.71%
63.9 MJ
electricity,
6.92%
3.58 m3
natural gas,
35.3%
0.914 kg
diesel, at
7.26%
0.672 kg
crude oil, production
8.36%
0.924 kg
crude oil, production
11.5%
0.125 kg
crude oil, production
1.54%
0.577 kg
heavy fuel oil, at
7.37%
17.2 tkm
transport, natural
35.3%
0.672 kg
crude oil, at
8.33%
1.04 kg
crude oil, at
12.8%
0.469 kg
crude oil, at
5.77%
0.582 kg
heavy fuel oil, at
7.37%
0.509 kg
crude oil, production
6.35%
0.904 kg
crude oil, at
11.2%

Annex 6: Details Network of inputs in LCA for DM2

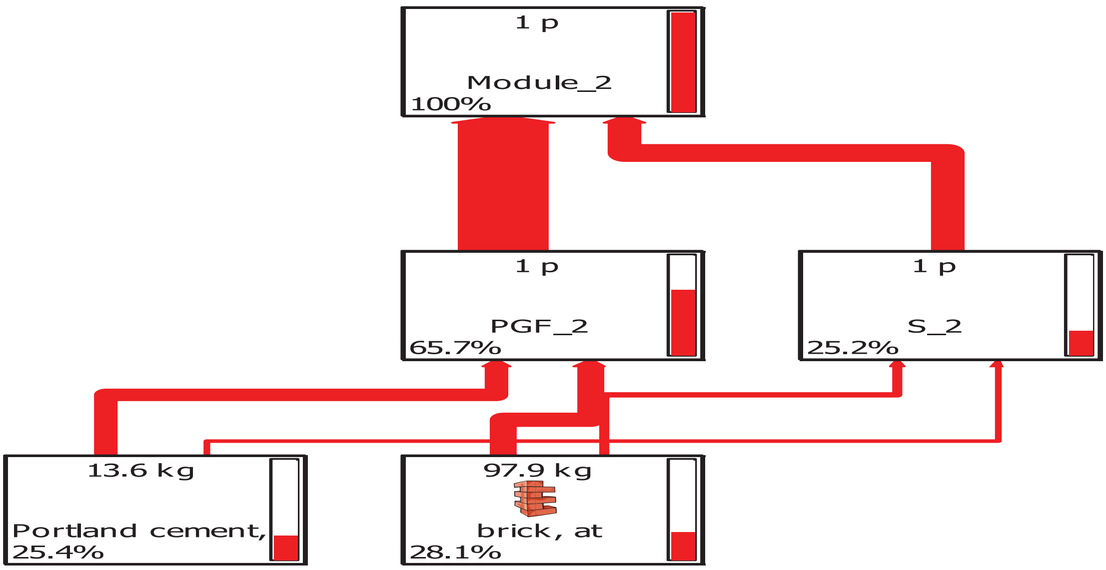
(A) For Acidification potential



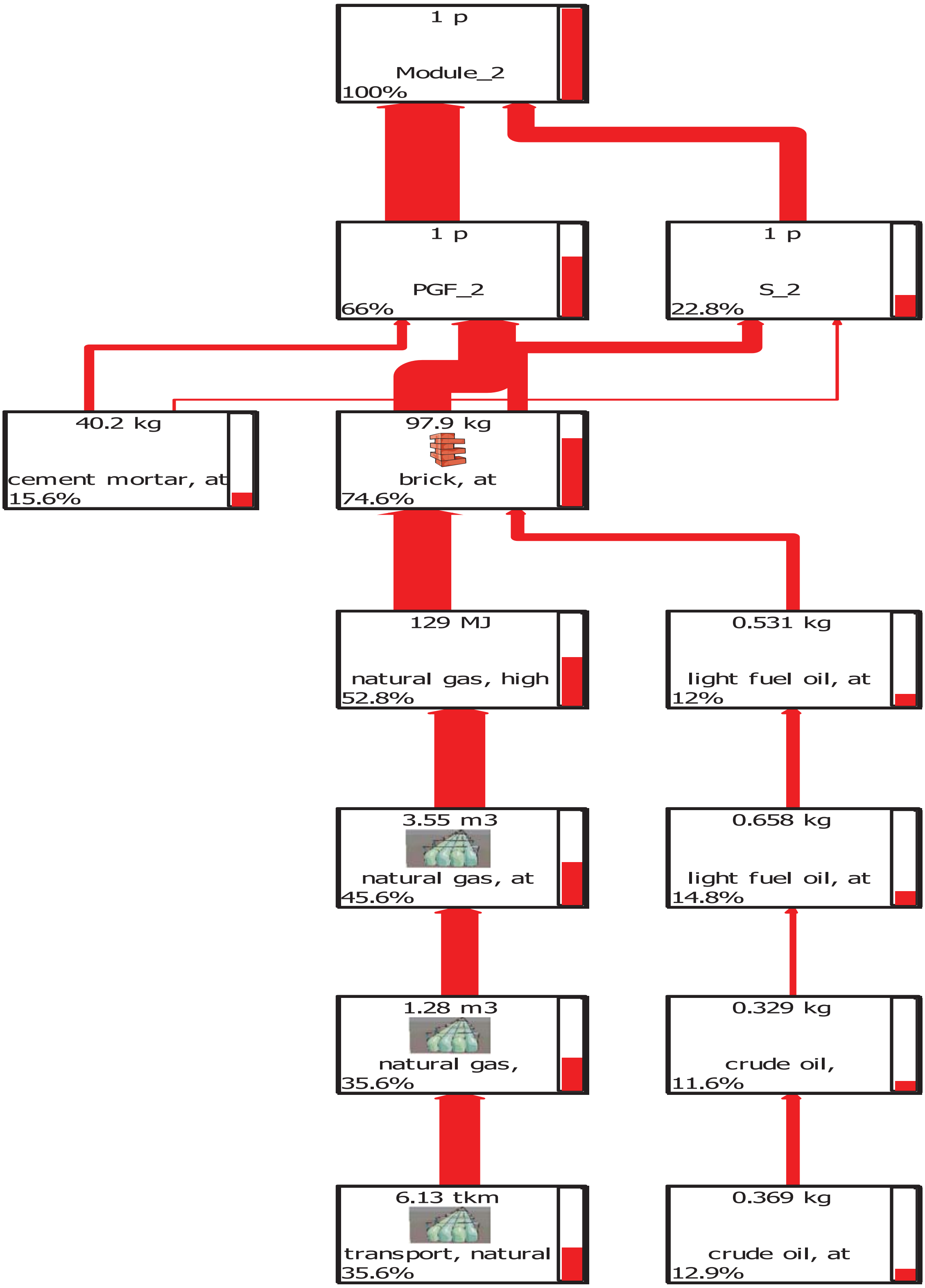
(B) For Global Warming Potential



(C) For Eutrophication Potential

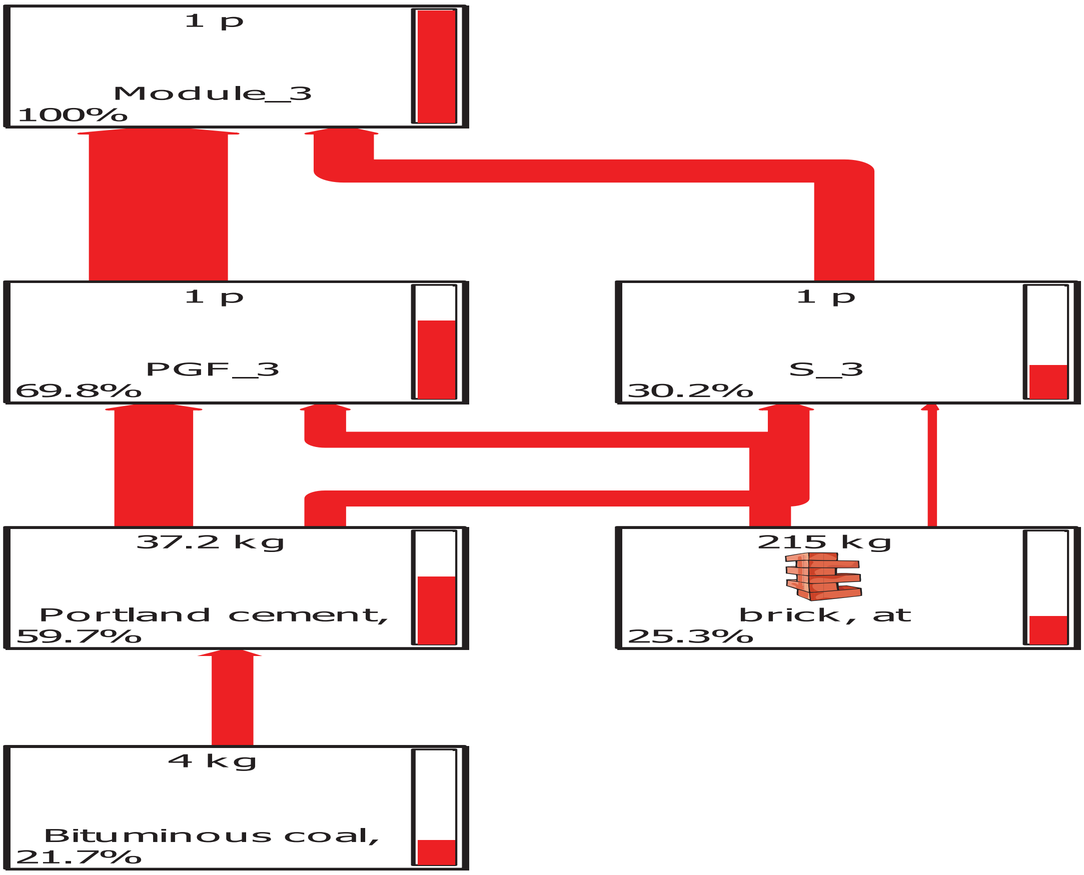


(D) For Ozone Layer Depletion Potential

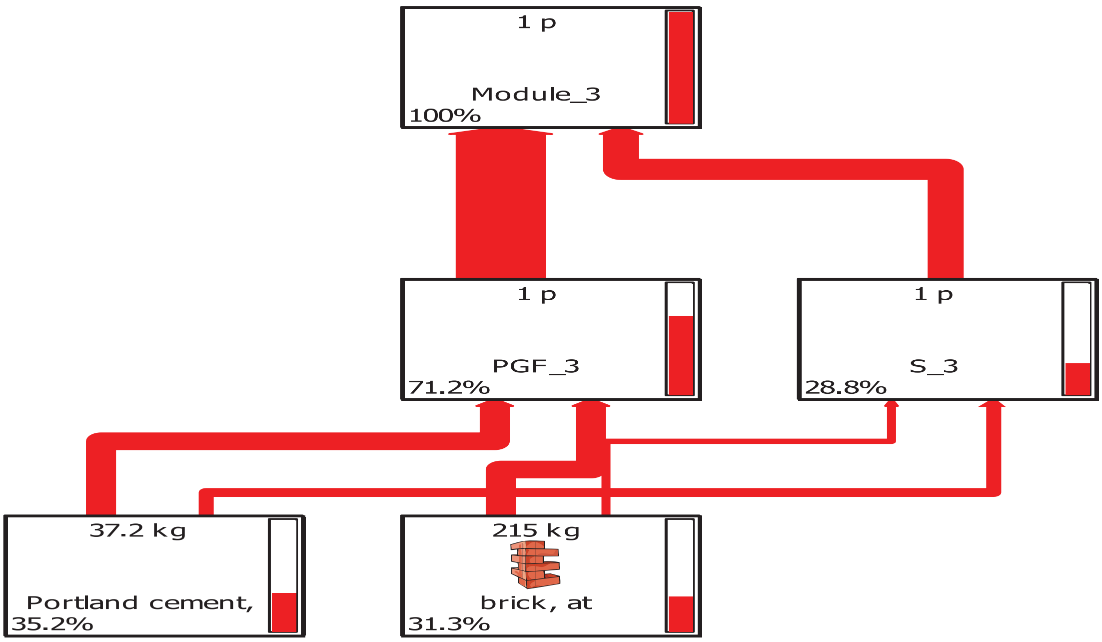


Annex 7: Details Network of inputs in LCA for DM3

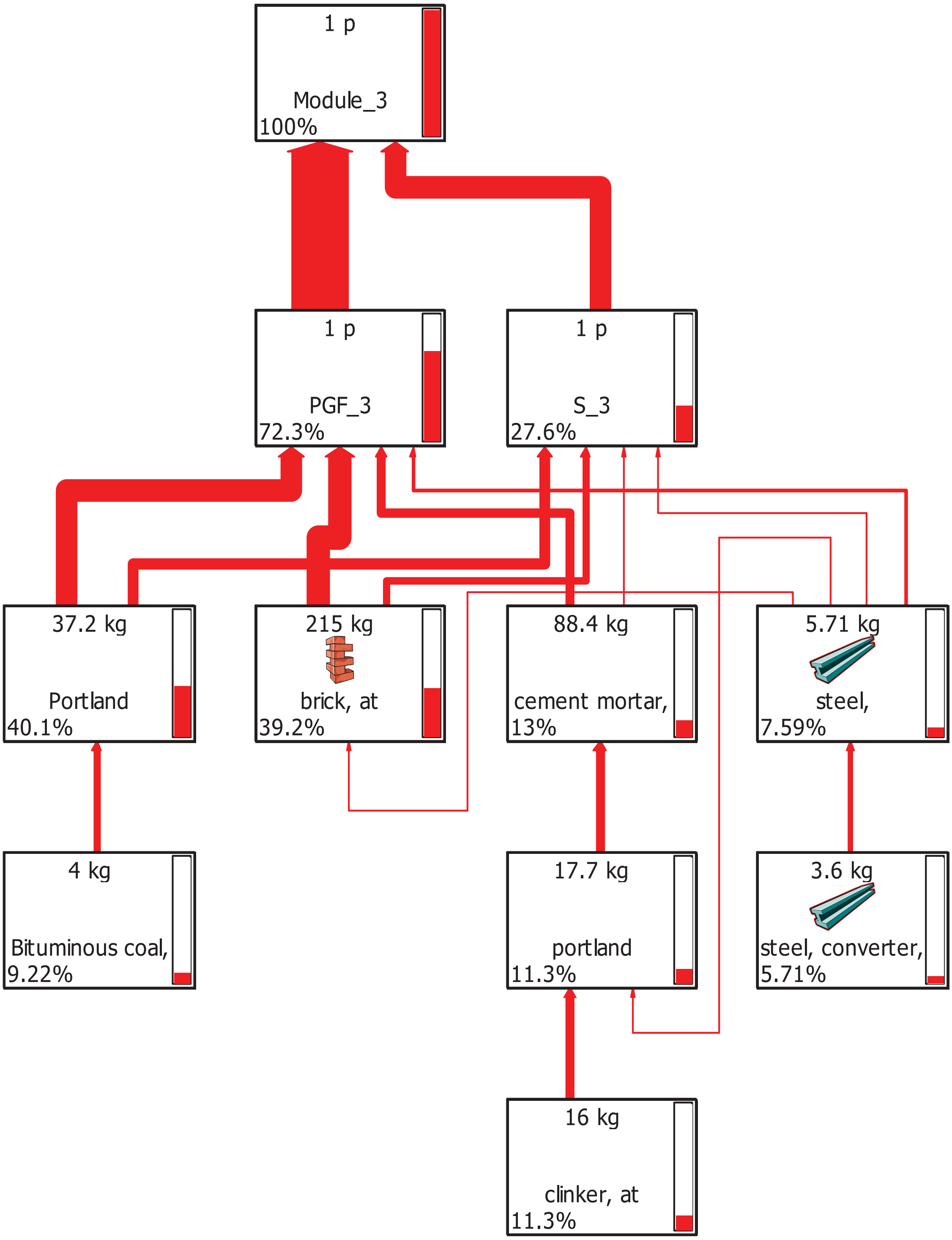
(A) For Acidification potential



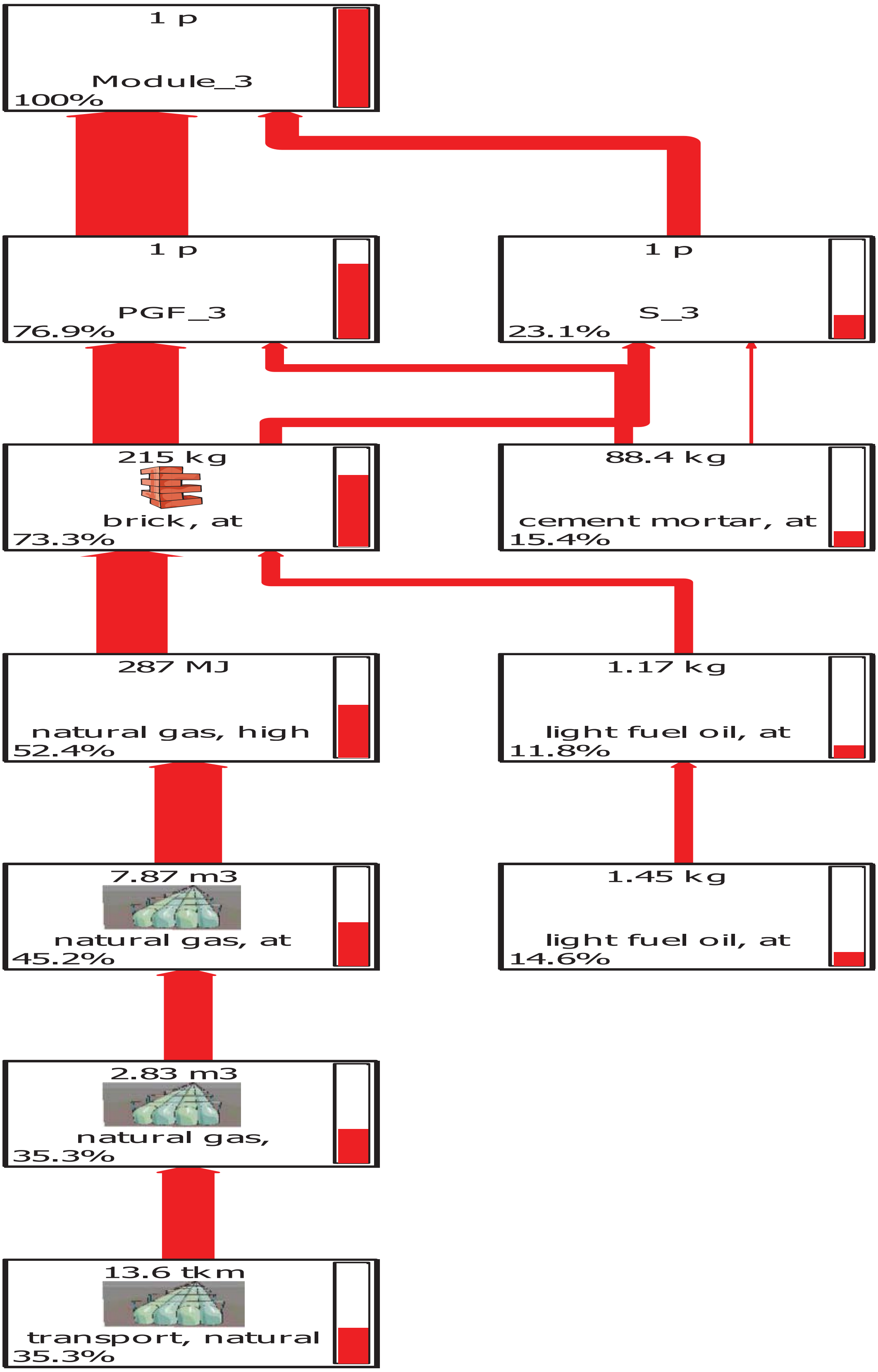
(B) For Eutrophication Potential



(C) For Global Warming Potential



(D) For Ozone Layer Depletion Potential



Annex 8: Performance Analysis Of DEWATS Module

Module 1: Performance Table

		Settler			ABR			Constructed Wetland		
S.N.	Parameter	Influent (g/p/day)	Removal efficiency (%)	Effluent	Influent	Removal efficiency	Effluent	Influent	Removal efficiency	Effluent
1	N	14.15	0	14.15	14.15	-	14.15	14.15	80	11.3
2	P	1.95	0	1.95	1.95	-	1.95	1.95	54	1.1
3	BOD	56	27	40.88	40.88	41	24.12	24.12	29	17.1
4	COD	172	26	127.28	127.28	48	66.19	66.19	27	48.3

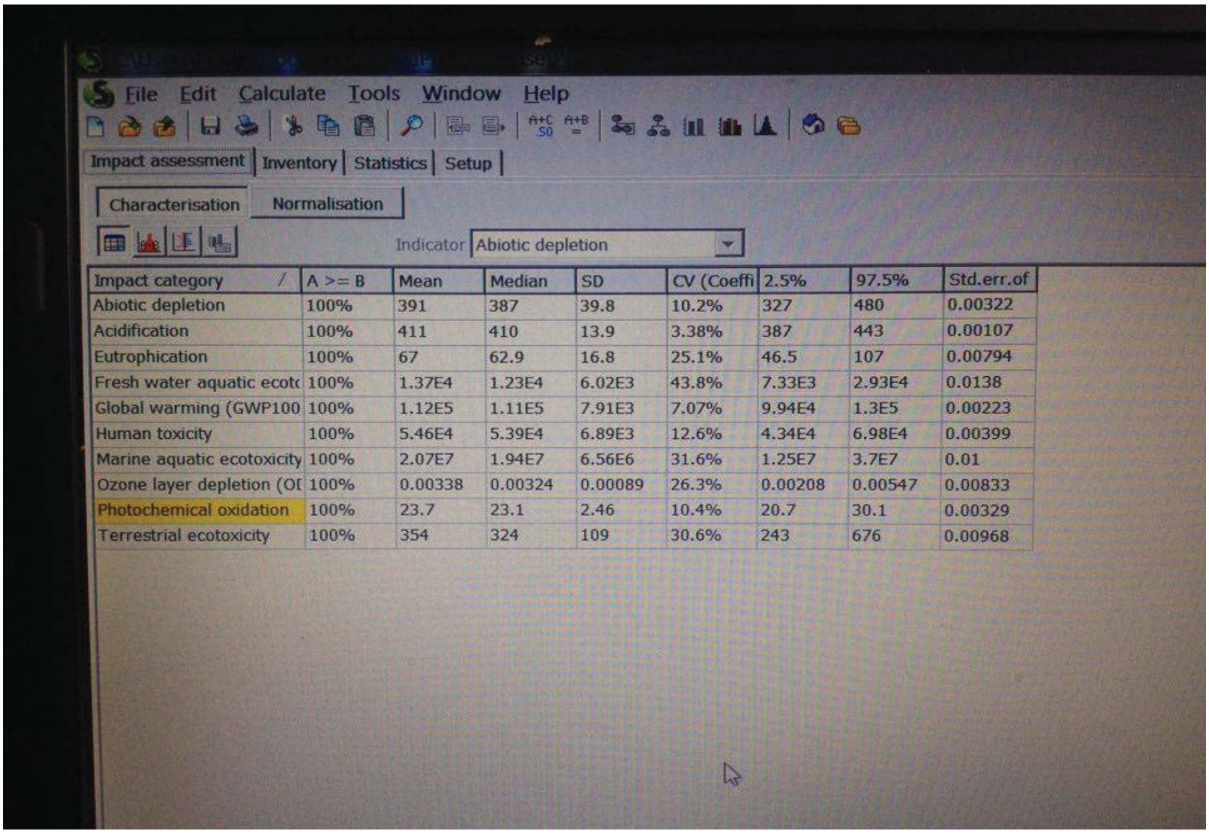
Module 2: Performance Table

		Settler			Constructed wetland			CT		
S.N.	Parameter	Influent (g/p/day)	Removal efficiency (%)	Effluent	Influent	Removal efficiency	Effluent	Influent	Removal efficiency	Effluent
1	N	14.15	0	14.15	14.15	78	3.113	3.113	-	
2	P	1.95	0	1.95	1.95	65	0.682	0.682	-	
3	BOD	56	30	39.2	39.2	35	25.48	5.88	-	
4	COD	172	34	113.52	113.52	36	72.65	20.33	-	

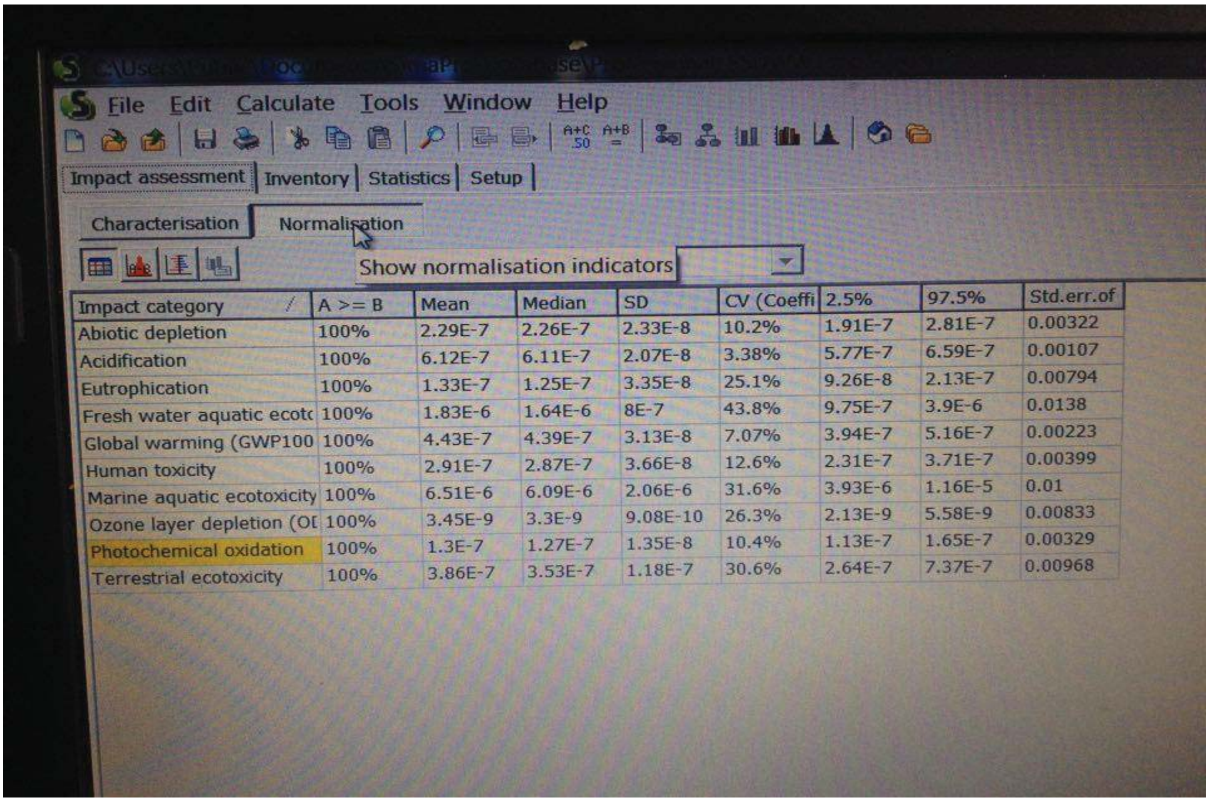
Module 3: Performance Table

		Settler			Constructed wetland					
S.N.	Parameter	Influent (g/p/day)	Removal efficiency (%)	effuluent	Influent	Removal efficiency	effuluent			
1	N	14.15	0	14.15	14.15	75	3.53			
2	P	1.95	0	1.95	1.95	70	0.585			
3	BOD	56	82	10.08	10.08	35	6.56			
4	COD	172	41	101.48	101.48	36	64.96			

Annex 9: Uncertainty Analysis of DEWATS scenario



Impact category	A >= B	Mean	Median	SD	CV (Coeffi	2.5%	97.5%	Std.err.of
Abiotic depletion	100%	391	387	39.8	10.2%	327	480	0.00322
Acidification	100%	411	410	13.9	3.38%	387	443	0.00107
Eutrophication	100%	67	62.9	16.8	25.1%	46.5	107	0.00794
Fresh water aquatic ecotc	100%	1.37E4	1.23E4	6.02E3	43.8%	7.33E3	2.93E4	0.0138
Global warming (GWP100	100%	1.12E5	1.11E5	7.91E3	7.07%	9.94E4	1.3E5	0.00223
Human toxicity	100%	5.46E4	5.39E4	6.89E3	12.6%	4.34E4	6.98E4	0.00399
Marine aquatic ecotoxicity	100%	2.07E7	1.94E7	6.56E6	31.6%	1.25E7	3.7E7	0.01
Ozone layer depletion (OI	100%	0.00338	0.00324	0.00089	26.3%	0.00208	0.00547	0.00833
Photochemical oxidation	100%	23.7	23.1	2.46	10.4%	20.7	30.1	0.00329
Terrestrial ecotoxicity	100%	354	324	109	30.6%	243	676	0.00968



Impact category	A >= B	Mean	Median	SD	CV (Coeffi	2.5%	97.5%	Std.err.of
Abiotic depletion	100%	2.29E-7	2.26E-7	2.33E-8	10.2%	1.91E-7	2.81E-7	0.00322
Acidification	100%	6.12E-7	6.11E-7	2.07E-8	3.38%	5.77E-7	6.59E-7	0.00107
Eutrophication	100%	1.33E-7	1.25E-7	3.35E-8	25.1%	9.26E-8	2.13E-7	0.00794
Fresh water aquatic ecotc	100%	1.83E-6	1.64E-6	8E-7	43.8%	9.75E-7	3.9E-6	0.0138
Global warming (GWP100	100%	4.43E-7	4.39E-7	3.13E-8	7.07%	3.94E-7	5.16E-7	0.00223
Human toxicity	100%	2.91E-7	2.87E-7	3.66E-8	12.6%	2.31E-7	3.71E-7	0.00399
Marine aquatic ecotoxicity	100%	6.51E-6	6.09E-6	2.06E-6	31.6%	3.93E-6	1.16E-5	0.01
Ozone layer depletion (OI	100%	3.45E-9	3.3E-9	9.08E-10	26.3%	2.13E-9	5.58E-9	0.00833
Photochemical oxidation	100%	1.3E-7	1.27E-7	1.35E-8	10.4%	1.13E-7	1.65E-7	0.00329
Terrestrial ecotoxicity	100%	3.86E-7	3.53E-7	1.18E-7	30.6%	2.64E-7	7.37E-7	0.00968

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