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SUSTAINABILITY OF BIOREFINERY SYSTEMS

EVALUATION OF BIOFUEL PRODUCTIONS BY MEANS OF EMERGY AND LCA

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Abstract

The present dissertation is focused on the feasibility and sustainability study of biorefinery systems, to be implemented by using bioresidues and biowaste produced by agriculture and food-processing industry. Such energy productions represent an opportunity for developing countries that have a large availability of biomass resources (e.g. African countries) and most of all they contribute to meet the need of replacing fossil fuels with alternative energy sources (i.e. biofuels).

To this end the present work has explored hypothetical biofuel productions in the African continent from a sustainability standpoint, by adopting two environmental accounting methods such as emergy and life cycle assessment. The joint adoption of these two methodologies has been fundamental in order to provide a whole and complementary picture about the sustainability of the systems under study.

First of all some methodological aspects have been clarified with regard to the application of emergy to the different generation of biofuels, providing helpful guidelines for researchers and not-specialists as well that want to deal with emergy evaluation of biofuels. At the same time an innovative way to represent graphically emergy results has been developed. This representation is based on the principle of polar coordinates and it shows simultaneously quantitative and qualitative aspects of emergy outcomes.

Biofuel production chains have been evaluated on the basis of the different feasible biowastes that can be used to implement biorefinery systems (i.e. sugar and nutrient rich feedstocks). According to an emergy perspective, feedstocks like cassava peels and manure from grazing cattle proved to be the most promising biowaste in terms of potential production of biofuels and fertilizers, respectively.

With regard to the transformation phase of biowaste into final sustainable products, LCA outcomes have shown that lignocellulosic-based feedstock (i.e. corn stover) generates higher environmental burdens against starch-based feedstock (i.e. cassava peels), because of the higher energy requirement for treating biomass to make cellulose and hemicellulose accessible for the subsequent enzymatic hydrolysis.

In order to diminish the impacts of the by-products in output from biorefineries, part of the research has regarded the evaluation of the synergy that can be established between industrial and ecological systems, evaluating the ecosystems services provided by the latter as alternative to conventional solutions for treating plant emissions and waste production. From a methodological viewpoint this part of the

study has explored the possible support that emergy can provide to improve and interpret the so-called techno-ecological synergy framework (i.e. TES).

List of abbreviation

tf	traditional farming
cf	commercial farming
fg	free grazing
zg	zero grazing
Em	Emergy
τ	transformity
UEV	Unit Emergy Value
J	Joule [unit]
sej	Solar energy joule [unit]
R	emergy flow related to local renewable resources
N	emergy flow related to local non-renewable resources
F	emergy flow related to resources purchased outside the system
%R	fraction of emergy from renewable inputs
ELR	Environmental Loading Ratio
EIR	Emergy Investment Ratio
EYR	Emergy Yield Ratio
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
FU	Functional Unit
AP	Acidification potential
EP	Eutrophication potential
GWP	Global Warming Potential
SO_2 eq	Sulphure dioxide equivalent [unit]
PO_4^{3-} eq	Phosphate equivalent [unit]
CO_2 eq	Carbon dioxide equivalent [unit]
CH_4	Methane
N_2O	Nitrous oxide
E+	10^
TES	Techno-Ecological Synergy
V	sustainability metric
S	supply of ecosystem services
D	demand of ecosystem services

INTRODUCTION

1. Background

We are currently living in an epoch that scientists define Anthropocene, where human being is the global geophysical force responsible for the most significant impacts on the Earth system (Steffen et al., 2007). The concentration of carbon dioxide in the atmosphere, i.e. the gas that represents the main driving force of anthropogenic greenhouse effect, is one of the most known indicators usually adopted to investigate the pressure of human activities on the biosphere. Greenhouse-gas emissions from human productions started rising progressively with the Industrial revolution, around 1800, and they have seen a dramatic rise after 1950. While during the pre-industrial period the atmospheric CO_2 concentration was around 270-275 ppm, the threshold of 400 ppm has been recently overshot (Keeling, 2016). There are several concerns about this parameter because of its cause-effect relationship with anthropogenic climate change (Eggleston et al., 2006), whose effects risk to severely affect in an irreversible way the environment and human civilizations as we know them today. According to Rockström et al. (2009) there are some planetary boundaries we cannot transgress if we want to avoid undesired and irreversible environmental change. Such boundaries circumscribe a so-called 'safe operating space' humanity can run within, avoiding negative consequences for the biosphere and human systems. With regard to the climate change issue we are currently operating out of such safe space, as the proposed boundary of 350 ppm for atmospheric CO_2 concentration has been largely exceeded. The overexploitation of fossil fuels as main energy source to support the global economy is identified as the main responsible of such a critical situation from environmental viewpoint.

Besides the negative effects related to global warming issues, another critical aspect of using fossil fuels to make human systems work is the fact that they represent a limited and non-renewable resource. Scientific community has long debated on the theory known as 'peak oil', elaborated by M.K. Hubbert in the 1950s, according to which the production pattern of crude oil can be described by means of a bell-shaped curve, whose peak represents the maximum production (Hubbert, 1956). Currently it is fair to distinguish between early- and late-peak advocates: while the former argue that oil has just peaked, the latter affirm it has not peaked yet (Chapman, 2014). The debate on peak oil has assumed a public dimension, involving the civil society and producing different attitudes of perceiving this issue (Bardi, 2009).

Due to the limited availability of a non-renewable energy source such as crude oil and in the light of several negative implications for the environment and human being as consequence of its exploitation, recent decades have seen a rising awareness about the need of a transition of human society from the dependence on fossil fuels towards the use of sustainable energy sources. In this regard the adoption of the Sustainable Development Goals in September 2015 (United Nations, 2015a) and the Paris agreement about the reduction of global emissions for addressing climate change, in December of the same year (United Nations, 2015b), represent two crucial milestones.

The need to replace fossil fuels has posed the attention on alternative energy sources such as biofuels, in both developed and developing countries (Lamers et al., 2011). Among the main producing countries of biofuel for transportation, USA and the UE have set specific targets for the future. USA has planned to substitute 20% of road transport fuel with biofuel by 2022 (U.S. Congress, 2007), while UE has adopted 10% as a goal of biofuel for transport energy by 2020 (EU, 2009).

According to the FAO definition (FAO, 2006), biofuels are "fuels produced directly or indirectly from biomass such as fuelwood, charcoal, bioethanol, biodiesel, biogas (methane) or biohydrogen". Biomass is "material of biological origin excluding material embedded in geological formations and transformed to fossil, such as energy crops, agricultural and forestry wastes and byproducts, manure or microbial biomass".

Biofuels are usually grouped in different categories known as first, second and third generation biofuels (IEA, 2008), depending on the feedstocks and conversion technology used for their production:

- First-generation biofuels are produced from dedicated cultivation of bioenergy crops (i.e. food-crop feedstock). They are mainly made from sugar, starch and vegetable oil.
- Second-generation biofuels are bio-based products that come from non-food feedstock, that is lignocellulosic biomass such as agricultural and forestry feedstock. They include residues produced by agricultural and food processing systems (discarded biomass).
- Third-generation biofuels are produced from aquatic cultivated feedstock (i.e. algae).

First generation biofuels can also be defined as *conventional biofuels*, while both second and third generation biofuels can be indicated as advanced biofuels (European Commission, 2015).

The implementation of biorefinery systems for producing biofuels is one of the actions that have been taken against climate change, because such productions are considered a valuable and sustainable alternative to oil refineries. The biorefinery concept relies on the integrated approach according to which the value of biomass is maximized by converting it into a variety of products, such as energy vectors, biomaterials, feed and fertilizers (Kamm and Kamm, 2004). While oil refineries rely on non-renewable source, biorefineries are fed by renewable raw material like biomass feedstocks. Furthermore the combustion of fossil fuels interferes severely with the biogeochemical cycle of carbon, by transferring in the atmosphere large amounts of this element that had been previously stocked in geological formations. This process feeds the anthropogenic greenhouse effect, generating dangerous consequences for the climate stability. On the contrary, burning fuels produced from biomass does not affect the natural carbon cycle, as the source the element comes from (i.e. plants) is not a geological formation and a much shorter time is required to absorb it from the atmosphere.

On the other hand the large development of biofuels has raised some critical issues about the sustainability of their production and use. This is especially true for first generation biofuels, whose productions are based on dedicated cultivations (i.e. bioenergy crops). In this regard one of the most debated issues is the competition between biofuels and food, since their productions can be based on the same feedstock (e.g. corn, sugarcane, wheat, soybean) (Harvey and Pilgrim, 2011). As argued by Ajanovic (2011), when a feedstock that can be used for food production is aimed at producing biofuels, the risk that occurs is the increase of food prices with negative consequences in terms of food security. The land availability is another crucial aspect to deal with, as it represents a limiting factor to the production of biofuel feedstocks (Fischer et al., 2009). The rising demand for biofuels can cause a conversion of land types such as forest or grassland to cropland for the production of required feedstocks. Beside the loss of biodiversity, another negative consequence of this dynamic is related to the phenomenon known as indirect land-use change (ILUC), that generates as result the undesired release of CO_2 emissions due to land-use change (Searchinger et al., 2008).

The production and use of biofuels is a complex matter, characterized by several controversial aspects that according to Tilman et al., (2009) can be summarized in "the food, energy and environment trilemma". In the light of such critical issues emerged around the development of biofuels, it is fundamental to investigate the feasibility and sustainability of producing this alternative energy source, especially with regard to the most advanced biofuels that do not affect food security and land availability. In this regard a relevant role can be played by biofuels based on crop residues and biowaste produced by agriculture and food industry.

In the last 20 years, various studies have investigated the sustainability of biofuels (Gopalakrishnan et al., 2009; Markeviius et al., 2010; Solomon, 2010). The most used methodologies are Energy analyses, Life Cycle Assessment (LCA), Carbon and Water Footprint and Emergy evaluation. An integrated approach that combines more than one method is fundamental to outline an environmental profile of biorefinery systems that is as complete as possible, especially to provide a robust support to the decision-making process and to the elaboration of policies about renewable energy sources. Among the others, emergy evaluation, defined as the solar energy directly and indirectly used to make a service or product, and emergy-related indicators have been widely used in this context (e.g. Bastianoni and Marchettini, 1996; Carraretto et al., 2004; Seghetta et al., 2014). The relevance of emergy relies on the fact that it is an environmental accounting method by means of which it is possible to evaluate the effort of the environment in providing resources, i.e. Nature's "labor" for re-producing something once it is consumed. Emergy evaluation is a systems approach that complements the evaluations of biofuel production systems, usually carried out from other points of view, with the information on their ability in converting basic input to the biosphere (solar energy) into actual products (Bastianoni and Marchettini, 1996). Another methodology usually adopted for investigating the sustainability of biofuel production systems is the life cycle assessment (e.g. Cherubini and Strømman, 2011). LCA is a tool for the analysis of the environmental burdens of products at all stages in their life cycle – from the extraction of the resources, through the production of materials, product parts and product itself, and the use of the product to the management of the waste after it is discarded, either by reuse, recycling or final disposal (in effect, therefore, 'from the cradle to the grave') (Guinée et al., 2001). The joint adoption of these two environmental accounting methods provide a whole and complementary picture about the sustainability of the systems under study, because emergy can estimate the work done by the environment in providing resources (i.e.

donor-side perspective), while LCA defines the aspects that generate negative impacts on the surrounding environment (i.e. user-side perspective). In the light of such considerations, the present research has been carried out with a focus on the integrated sustainability assessment of biorefinery systems by means of emergy and LCA.

The concept of biorefinery has been explored in order to provide a characterization of these energy production systems, with the aim to investigate how they works, which products they generate (e.g. energy vectors and biomaterials), which feedstocks can be used to develop such productions. Because of the controversial aspects related to biofuel feedstocks produced from energy-crops, alternative biomass resources have been investigated as potential feedstocks. The attention has been posed especially on bioresidues and biowaste produced by agriculture and food-processing industry. In this regard the evaluated case study had a specific focus on African productions, as the implementation of such systems represent an opportunity for developing countries that have a large availability of biomass resources.

1.1 Research questions

The specific aims of the present research can be summarized in few points, by identifying the related research questions.

First of all there are some methodological aspects to face when sustainability assessment of biofuel productions is performed. Depending on the generation of biofuels the whole production chain works in different ways, so the sustainability assessment of such systems cannot be carried out by using the same criteria, especially with regard to emergy. To this end the first research question is:

- *How does emergy methodology work for first, second and third generation biofuels?*

The present research has evaluated the biofuel production chains by exploring various alternative solutions in terms of feasible feedstocks to be used for feeding such biorefinery systems. Beside the economic aspects, that necessarily have to be considered to evaluate the actual feasibility of these productions, sustainability criteria have to be satisfied as well. In this regard an environmental accounting method like emergy can support the identification of the most feasible feedstocks, by quantifying the work done by the environment to provide such biomass resources, according to a donor-side perspective. Thus the second research question is:

- *Which are the most promising biomass feedstocks for producing biofuels, from a sustainability standpoint?*

Another fundamental phase to evaluate from a sustainability perspective is represented by the transformation process of biowaste and bioresidues into final useful products (e.g. energy vector, biomaterial, fertilizers, etc.). According to a user-side point of view, LCA method can provide a valid support to quantify potential impacts associated with biofuel production plants developed by exploiting different feedstocks. To this end the third research question can be formulated as follows:

- *Which is the biofuel production that generates the less level of environmental burdens?*

In order to diminish the impacts of the by-products in output from biorefineries, part of the research has regarded the evaluation of the synergy that can be established between industrial and ecological systems. The focus was on a case study relative to an industrial biodiesel production to be implemented in a developed country such as USA. The study explored the synergy that can be established between industrial and ecological systems, evaluating the ecosystems services provided by the latter as alternative to conventional solutions for treating plant emissions and waste production. To this end emergy method was adopted to investigate such a techno-ecological synergy, evaluating demand and supply of ecosystem services. This part of the study tried to respond to the following research question:

- *Is there a way to provide an aggregated measure of sustainability level of industrial symbiosis?*

MATERIALS AND METHODS

2. Biorefinery systems

The biorefinery concept has been developed because of the need of human society to reduce its dependency on fossil fuels and to face great challenge such as the supply of energy, food and other products in a sustainable way. While traditional oil-based refineries produce energy carriers and various chemical products by exploiting crude oil, biorefinery facilities produce fuels, chemicals, feeds and other products by integrating biotechnological conversion processes that are fed by biomass feedstocks. Biorefinery systems are implemented according to an approach aimed at maximizing the value of the biomass (i.e. optimizing the use of resources) and to minimize wastes, thereby maximizing benefits and profitability (WEF, 2010). This process fosters the reduction of GHG emissions that represents an urgent action to be taken in order to face climate change-related issues.

The key drivers of the adoption of biorefinery technology include (Gidamis et al., 2015):

- The economics of fossil-based products are deteriorating due to scarcity of conventional crude oil resources;
- The growing need for national energy security and geopolitical security;
- The public pressure for environmental sustainability is increasing due to an increasing environmental awareness;
- The rapid demographic growth will drive demand coupled with rising economic aspirations of developing countries.

It is broadly recognized that the implementation of white biotechnology represents a crucial step for the sustainable production of energy carriers, chemical and materials from biomass sources in order to allow a substantial reduction of environmental impacts derived from productions based on crude oil. In this regard the term biorefinery is particularly relevant not only because of the biological origin of feedstocks that are processed, but also because of the biological character of treatment and conversion processes that generate energy and materials (Kamm and Kamm, 2004).

Among the available bioconversion processes of biomass feedstocks, yeast-fermentation is the most common and usually adopted for producing liquid biofuels. As illustrated in Figure 1 the bioconversion stage comes after a pretreatment process that is required to obtain carbohydrates (i.e. sugars) to be processed for producing bioethanol and other products.

On the basis of biomass feedstocks the production system is based on, biorefineries are usually classified as (Kamm and Kamm, 2004):

- whole-crop biorefinery;
- green biorefinery;
- lignocellulose feedstock (LCF) biorefinery.

The first one uses raw material such as cereals or maize, the green biorefinery is based on biomass such as grass, clover and lucerne and the LCF biorefinery exploits cellulose-containing biomass.

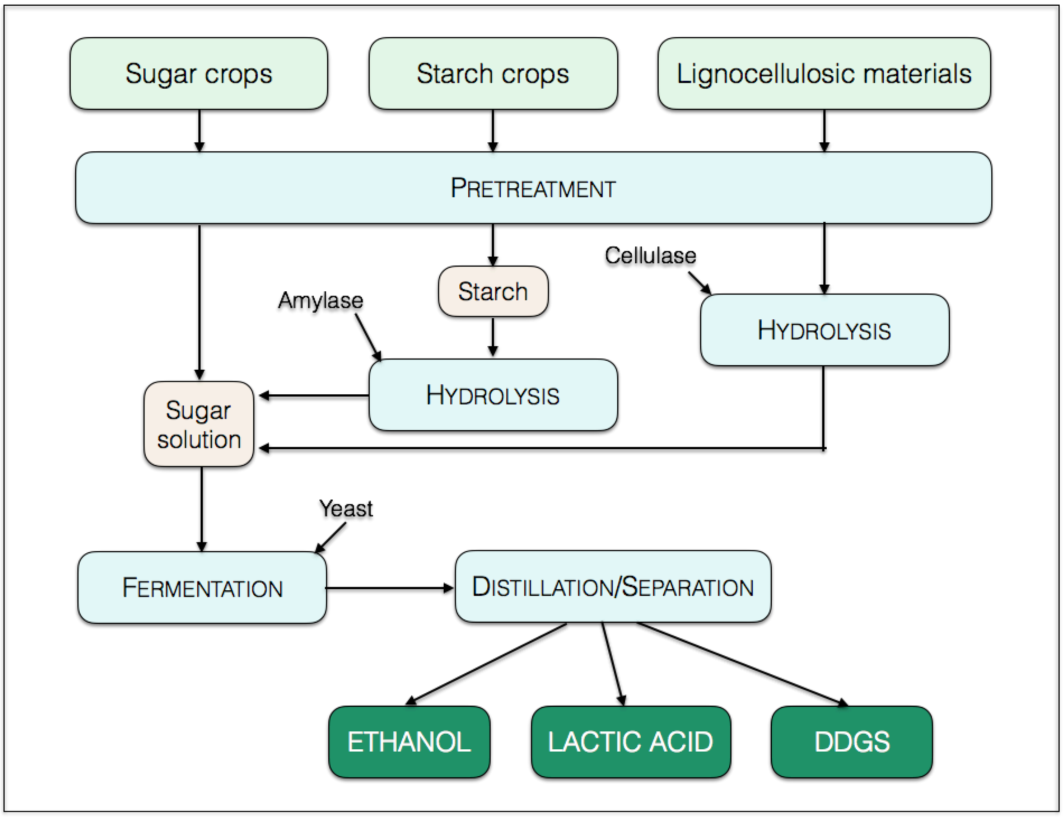


Figure 1. Example of biorefinery framework based on sugar, starch and lignocellulosic materials. The acronym DDGS stands for Dried Distillers Grains with Solubles.

2.1 Pretreatment stage

Pretreatment is the most critical phase of biofuels production as it is the process responsible for the conversion of biomass feedstocks into sugar monomers that are then involved in the fermentation process. Depending on what kind of material is processed, this stage is characterized by different steps. While traditional bioethanol producing microorganisms can easily access to sugar and starch material, some additional processes are needed for lignocellulosic feedstocks since they are rich of cellulose and hemicellulose, the main sources of six-carbon sugars such as glucose and five-carbon sugars such as xylose, respectively (Clark and Deswarte, 2008).

Pretreatment processes are generally classified as physical (i.e. mechanical), chemical and biological. All these methods have the specific aim to decrease the crystallinity of the sugar polymers (e.g. cellulose, hemicellulose) and to increase the porosity of the material. This first step is necessary to make biomass material accessible for the subsequent hydrolysis process (Kumar et al., 2009).

Mechanical processing, broadly adopted, is implemented with the purpose to reduce size of treated materials and it can run on different ways (e.g. milling, grinding, extrusion, etc.). Such a kind of method generate various benefits in the processing of biomass, as listed below:

- facilitation of handling;
- increase of surface area;
- decrease of crystallinity;
- reduction of the degree of polymerization;
- improvement of the efficiency of hydrolysis process.

2.2 Hydrolysis

The hydrolysis process, that follows the size reduction of biomass feedstock, is generally classified as enzymatic or acid hydrolysis and is aimed at obtaining a mixture of monomeric sugars (i.e. hydrolysate) that is the substrate to be processed in the fermentation stage. The enzymatic hydrolysis is used more than acid hydrolysis and it can be set differently according to the various biomass feedstocks that are processed. While starchy materials requires the use of amylase enzymes, cellulosic biomass need to be treated by using cellulase enzymes. There are three different protein units that compose the cellulase enzyme complex, called endocellulase, exocellulase and cellobiase (Clark and Deswarte, 2008). The first one is responsible for breaking the crystalline structure to generate shorter chain fragments, subsequently cellobiose is released from linear cellulose by means of the action of exocellulase and finally cellobiase works on cellobiose and splits off glucose to make the material suitable for fermentation.

2.3 Yeast fermentation process

The bioconversion of pretreated feedstocks runs starting from the sugar substrate obtained from fractionation and hydrolysis processes. This step can generally occur in two different ways, i.e. Simultaneous Saccharification and Fermentation (SSF) and Separate Hydrolysis and Fermentation (SHF) (Hari Krishna et al., 2001; Öhgren et al., 2007). In both cases the careful selection of microorganism represents the key point to effectively convert pretreated substrate into bioethanol and other value-added products. This is especially true with regard to lignocellulose containing feedstocks as they contain both C5 and C6 sugars and the pentose sugars are not easily metabolized by common yeast in the production of bioethanol.

3. Feedstocks

According to the classification of biofuels in first, second and third generation (IEA, 2008), it is possible to identify several types of feedstocks to be exploited for different productions, as shown in Table 1.

Table 1. Classification of biomass feedstocks according to the biofuel generations. Some potential feedstocks are reported as example of possible biomass sources to be exploited.

<table>
<tr><th>Biofuel generation</th><th colspan="2">Biomass group</th><th>Feedstock</th></tr>
<tr><td rowspan="12">1G</td><td colspan="2" rowspan="3">Sugar crop</td><td>Sugar cane</td></tr>
<tr><td>Sugar beet</td></tr>
<tr><td>Sweet sorghum</td></tr>
<tr><td rowspan="6">Starch crop</td><td rowspan="4">Grain</td><td>Wheat</td></tr>
<tr><td>Corn</td></tr>
<tr><td>Barley</td></tr>
<tr><td>Rey</td></tr>
<tr><td rowspan="2">Tuber</td><td>Sweet potato</td></tr>
<tr><td>Cassava</td></tr>
<tr><td colspan="2" rowspan="3">Oil crop</td><td>Soybean</td></tr>
<tr><td>Rapeseed</td></tr>
<tr><td>Sunflower</td></tr>
<tr><td rowspan="4">2G</td><td colspan="2">Waste</td><td>Biowaste/bioresidues</td></tr>
<tr><td rowspan="3">Lignocellulosic biomass</td><td rowspan="2">Dedicated cultivation</td><td>Miscanthus</td></tr>
<tr><td>Switchgrass</td></tr>
<tr><td>Residues</td><td>Agricultural residues</td></tr>
<tr><td>3G</td><td colspan="2">Aquatic biomass</td><td>Algae</td></tr>
</table>

Biomass feedstocks usually adopted for producing first generation biofuels derived from dedicated cultivations that consist of sugar, starch and oil crops. Among the sugar crops the most common used feedstocks for bioenergy purpose are sugar cane, sugar beet and sweet sorghum. Sugar cane (*Saccharum officinarum*) is a perennial grass that belongs to the grass family Poaceae, it is a tall grass that grows 3-6 m high with stems 20-45 mm in diameter (Willis and Bachman, 2016). Sugar cane is widely cultivated in the tropical regions for producing a high valued food such as sugar, both raw and refined. The development of biofuels production has brought the attention on this feedstock for producing bioethanol, which can be obtained from by-products of sugar production (e.g. sugar cane bagasse) or directly produced as main product of sugar cane processing (IEA, 2008).

Sugar beet (*Beta vulgaris*) is a biennial plant, part of the family Amaranthaceae, with a high concentration of sucrose in its roots. It is typically cultivated in temperate regions and among its several uses it is especially aimed at food and drink industries. In the light of the sugar content of its toots that can reach 20% by weight, it is exploited for first generation biofuel production.

Another fundamental feedstocks usually adopted for bioenergy purpose is sweet sorghum, a variety of sorghum (*Sorghum bicolor*), that is an annual plant whose grains are commonly used for feeding livestock in the Americas and Australia, while in the semi-arid tropics it represent an important food crop (Willis and Bachman, 2016). The sweet variety is also involved in the food industry for producing products such as sorghum syrup, in the light of the high sugar content that characterize this grass.

For what concerns starch crops there is a wide variety of feasible feedstocks that can be grouped into grains and tubers. The main advantage of exploiting starch-based feedstocks is about the possibility to convert easily starch in fermentable sugar, from which bioethanol is then produced. Among grains feedstocks, wheat (*Triticum aestivum*) is the most produced cereal crop after corn and rice. It is an annual grass that belongs to the family Poaceae, cultivated worldwide and within a vast altitude range. It represents a fundamental part of human diet as it is used as ingredient in several foods (e.g. breads, cakes, biscuits, etc.). It is also broadly exploited as biomass feedstock for bioenergy production, by using either grain or straw for conventional and advanced bioethanol, respectively.

Corn (*Zea mays*) represents another fundamental crop in terms of cereal production. It is a grain plant that reaches an average height of 3 m and it is cultivated worldwide, with a share of about 40% of total production that is placed in the United States (FAOSTAT, 2014). Corn is a staple food in many countries, it is broadly involved as ingredient in the food industry for various purposes and it has been adopted as feedstock for producing biofuels in the light of its high content of starch and sugar. Like for grain, corn can be used for bioenergy purpose by exploiting both cobs and stover.

Barley (*Hordeum vulgare*) is a plant that belongs to the grass family Poaceae, usually cultivated in temperate areas. It has many uses in food and drink industry as it represents an important ingredient for several food products and it is the basic fermentable substrate for producing beer and other distillate beverages (Willis and

Bachman, 2016). Because of its high starch content (i.e. 50-75%) it represents a potential feedstock for producing biofuels.

In contrast to the others grain crops, Rey (*Secale sereale*) is a grass that usually can grows in difficult soils. It is an annual plant whose cultivation is mainly aimed at producing fruits to be used as ingredient in food industry, especially for producing rye bread. Beside that, it is broadly used as animal fodder and it represents a feasible biomass feedstock for biofuel production, in the light of its starch content that is about 60% (Willis and Bachman, 2016).

For what concerns tubers, sweet potato (*Ipomoea batatas*) is one of most used feedstock for producing bioethanol because of the considerable level of starch content (i.e. 70%). It is a plant of the family Convolvulaceae with tuberous roots and it is commonly cultivated in tropic areas. Sweet potato is one of the most important root crops, broadly used in food industry in various ways.

Cassava (*Manihot esculenta*) is a plant of the family Euphorbiaceae, widely cultivated as annual crop in tropical regions and able to grow also in poor soils. It is a staple food in many developing countries as it is a paramount source of carbohydrates; it is the third largest source of food carbohydrates in the world (Fauquet et al., 1990) and it is used also in drink industry and food processing. Cassava has gradually become a feedstock to be exploited for biofuel production.

While starch and sugar crops feed biorefinery systems aimed at producing bioethanol, oil crops represent the basis for producing biodiesel and among them the most prominent are soybean, rapeseed and sunflower.

Soybean (*Glycine max*) is a leguminous plant of the family Fabaceae, whose cultivation produce edible beans widely used in food industry. One of the most important uses of soybean in these terms is about diary production, as it represents a valuable substitute for various food products. Soybean is also broadly used for livestock feeding, while soybean oil that is produced by processing soybean has many uses for food and industrial purposes.

Rapeseed (*Brassica napus*) is a plant that belongs to the family Brassicaceae, it grows up to 100 cm and produce bright-yellow flowers. With respect to soybean, rapeseed can have an oil content that is more than twice, but usually it has a lower protein level (Willis and Bachman, 2016). Among its most common uses, rapeseed is grown for the production of livestock fodder and for producing edible vegetable oils (i.e. canola oil). With regard to bioenergy sector rapeseed is a basic feedstock for biodiesel production.

Sunflower (*Helianthus annuus*) is an annual plant of the family of Compositae, which reaches up to 5 m high, with a well-developed taproot extending up to 3 m into the soil (Willis and Bachman, 2016). It is widely cultivated for its edible seeds and versatile oil, both involved in the food processing industries, while some by-products of such processing can be used for feeding animals. Among the industrial uses, sunflower oil is widely exploited in cosmetic sector and for producing biofuels.

Second generation biofuels are typically produced from non-food feedstocks that consist of lignocellulosic biomass coming from agriculture and forestry. These feedstocks can be generated by dedicated lignocellulosic crops such as miscanthus and switchgrass, or they can come from agricultural and food processing systems (discarded biomass).

Miscanthus (*Miscanthus giganteus*) is a perennial grass that belongs to the family Poaceae, typical of temperate climates. It is characterized by high photosynthetic efficiency and low water requirement, which make it able to accumulate biomass fastly (Willis and Bachman, 2016). Because of such characteristics miscanthus has been widely exploited for producing advanced biofuels.

Another potential non-food feedstock to be exploited for bioenergy purpose is switchgrass (*Panicum virgatum*), another perennial grass of family Poaceae that commonly grows in North America. This grass is characterized by deep roots and it can reaches 2.5 m high; it requires low quantity of water and fertilizer to develop and for this reason is particularly feasible for growing in marginal lands (Willis and Bachman, 2016). Among the various potential uses, switchgrass is widely used as forage for animals, especially cattle, and it is particularly good for soil conservation.

Agricultural residues represent another important source of lignocellulosic material for advanced biofuel production, especially because they are waste materials and do not compete with food crops for land. This source includes field residues such as straw, roots, leaves and other residues from fruit, vegetables, crop production and farming. Such materials contain mainly lignocellulosic components of cellulose, hemicellulose and lignin, while some of them have also significant contents of a wide range of inorganic elements.

On the other hand a fundamental source of potential feedstocks to be exploited for producing bioenergy vectors and other value-added products is represented by biowaste that according to Gustavsson et al. (2014) are defined as “animal and vegetal waste arising from households, commerce and the food manufacturing industry. The food manufacturing industry includes the whole value chain hence farming and animal husbandry sectors are included”.

The implementation of biorefinery systems based on both bioresidues and biowaste, as described above, represents an opportunity to overcome the main shortcomings of conventional biofuels, avoiding competition for land and all environmental and social issues relative to the production of bioenergy based on dedicate cultivation (i.e. food crops).

Algae and aquatic biomass are potential feedstocks to be exploited for producing third generation biofuels (i.e. the most advanced ones). Algae can produce greater amounts of biomass and lipids per unit of surface area than terrestrial biomass, without content of lignocellulose. Cultivation of algae can occur on marginal land, by avoiding competition with food or other crop that is typical of conventional biofuels. Algae can be grown in shallow lagoons, in raceway ponds on marginal land or in closed ponds by using sunlight for energy and CO_2 as a carbon source. Recently cultivations of algae are under study in the seas of northern Europe to produce biomass for energy and materials purposes while reducing the excess of nutrients in the sea (e.g. Seghetta et al., 2016a, 2016b). Along with biofuel production, algae are promising also because of their versatility and suitability for wastewater treatments and other industrial (FAO, 2010; Rocca et al., 2015).

4. Case study

The transformation of biomass into various products has seen much development and today there is a range of opportunities for upgrading bio-based materials products such as biofuels, chemicals, food, feed and fertilizers. Beside the development of technologies and know-how on the processing of biomass, it is fundamental to identify the feasible feedstocks to be processed and on the basis of which to implement biorefinery systems. In this regard a fundamental role can be played by those feedstocks that do not required dedicated energy crops to be produced, in order to avoid all negative side effects related to environmental issues (e.g. fuel vs. food, ILUC effects, etc.). Bioresidues and biowaste produced by agricultural productions and food industries represent viable biomass to be exploited to support such biotechnological conversion processes. In fact biorefinery systems based on these biomass feedstocks are able to provide energy, food, biochemical, fertilizers and other biomaterials which human society needs of, without compromising ecosystem services and natural capital provided by the biosphere.

The exploitation of such types of resource can give a fundamental contribution to the development of bioeconomy sector, especially in developing countries where there is a large amount of bio-based waste. Africa, for example is a continent with enormous natural resources in the form of biomass. For African countries and people to benefit from the emerging bioeconomy sector, innovative ways are needed to exploit the biomass available from agricultural processes and other production systems (Nzila et al., 2010; Okello et al., 2013; Thomsen et al., 2014).

In the light of such considerations, the case study explored within the present work regarded the potential development of sustainable biotechnological processes (i.e. biorefinery systems) fed by biowaste and bioresidues produced by agriculture and industrial food processing in some African countries (i.e. Egypt, Ghana, Kenya, Morocco and South Africa; see Figure 2).

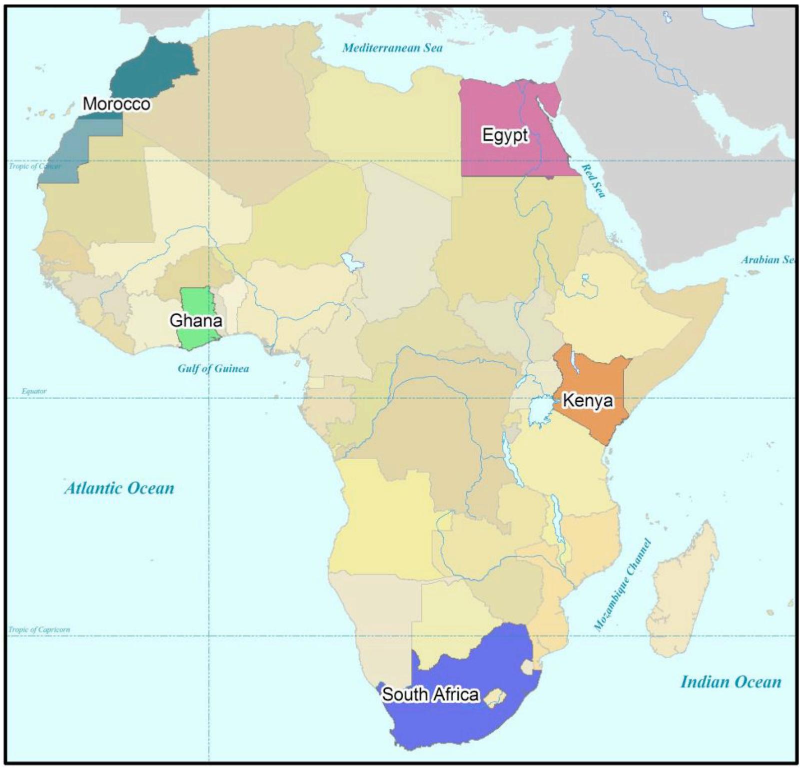


Figure 2. African countries considered in the present case study.

According to Gustavsson et al. (2014), bio-resources that have an economic or other value are usually classified as bioresidues, while those ones without (or with only a nominal) economic or other value can be considered biowastes. Most of the wastes produced by African countries are bio-based and their management represents an issue to be faced and an opportunity to explore. The application of biorefinery concept in such a context has a great potential to make these countries developing since it provides them the opportunity to turn a problem into an opportunity by exploiting underutilized biomass as energy feedstock.

4.1 Biowaste in Africa

According to a life cycle approach it is possible to identify potential biowaste and bioresidues streams in the various life phases of bio-based products such as biomass production, processing, use and end of life. Both biowaste and residues from agriculture and food industry represent a significant portion of waste in the African continent. According to Gustavsson et al. (2011) a large amount of food waste is released by food industry sector, due to some financial and technical limitations that severely affect developing countries. This is especially true for what concerns harvesting techniques, infrastructure, poor storage and cooling facilities in difficult climatic conditions, packaging and marketing systems. Just to give an example, some typical African food wastes are generated by fruit and crop production such as banana, cassava and sweet potatoes that are starch-rich products (Gustavsson et al., 2011), whose production yields are shown in Table 2 for the evaluated countries. On the other hand, agriculture is responsible for a considerable amount of biowaste that consist of residuals such as straw, leaves, roots and stover. Such types of residues are characterized by lignocellulosic material, particularly rich of cellulose, hemicellulose and lignin. In some cases, especially with regard to straw, they also present a significant content of inorganic elements (e.g. potassium). Another important source of biowaste is represented by manure produced by animal farming, which can provide a limited and essential plant nutrient such as phosphorus to be used for the production of biofertilizers.

Table 2. Example of some agricultural product yields (in t) in Egypt, Morocco, Kenya, Ghana and South Africa (FAOSTAT, 2014).

Product \ Country	**Egypt**	**Morocco**	**Kenya**	**Ghana**	**South Africa**
Banana	1,144,717	302,469	1,398,154	84,240	387,703
Cassava			858,461	16,524,000	
Olives	558,610	1,191,520			
Sorghum	776,000	4,800	177,553	259,000	150,920
Rice	6,000,000	33,050	112,263	604,000	3,010
Sunflower seeds	25,000	27,370	14,000		832,000

The chemical characterization of biowaste and bioresidues provides the needed information for planning the use of different sources of biomass feedstock for the dedicated biotechnological production chains. In this regard a fair classification of African biowaste generated by agriculture and food-processing industry is based on the identification of two groups of biomass (Gustavsson et al., 2014):

- Sugar based feedstocks
- Nutrient based feedstocks

The first type of feedstocks is characterized by high contents of carbohydrates such as starch and sugar, thus it is a viable source for producing energy carriers (i.e. biofuels), chemicals and food/feed. The elevated content of inorganic elements and lignocellulosic material that characterizes the nutrient based biowaste, instead, makes these feedstocks a potential source for the production of biofertilizers (i.e. plants nutrient), in co-production with biogas. In the present study the sustainability assessment was performed focusing the analysis on selected sugar-rich and/or nutrient-rich feedstock for each country (Gustavsson et al., 2014) (see Table 3).

Table 3. Summary of selected potential feedstocks. Sugar-rich feedstocks are addressed to bioethanol (plus other value-added material) production; nutrient-rich feedstocks are instead aimed at biogas and fertilizer production.

Sugar-rich feedstock	Nutrient-rich feedstock	Country
Corn residues	-	Egypt
Cassava processing - peelings	Cocoa plantation	Ghana
Pineapple processing residues	Vegetable market residues (cabbage)	Kenya
Olive oil processing residues	Cattle manure	Morocco
Rejected bananas	Soybean processing residues	South Africa

For a complete characterization of potential sugar and nutrient rich feedstocks the present study refer to, it is possible to consult the *Catalogue of biowaste and bioresidues in Africa* (Gustavsson et al., 2014).

4.2 Technologies for converting biowaste into value added products

According to the different sets of identified biowaste (i.e. sugar and nutrient rich feedstocks), the sustainability assessment carried out in the present work was focused on the potential development of two different biotechnological options:

- Sugar based platform;
- Processing of nutrient rich feedstocks.

While the first production chain is mostly aimed at producing bioethanol, lactic acid and amino acid, the main outputs of the latter are biogas and biofertilizers. In order to implement such technological routes on a full scale it is necessary to take into account some aspects related to the access to water, sewage, space, know-how and energy in the form of electricity or heat.

4.2.1 Sugar platform

The sugar-based platform (see Figure 3) includes a pretreatment of the feedstock and a bioconversion stage. The pretreatment can include for example a wet-fractionation stage together with enzymatic hydrolysis (Hazri et al., 2014; Hou et al., 2014; Lawther et al., 2014; Rashamuse et al., 2014). The second stage is the bioconversion of pretreated feedstock for converting carbohydrates (i.e. sugars) to bioethanol with co-production of protein for feed (Dried Distillers Grains with Solubles - DDGS) and amino acids. Another option is converting hemicellulose sugars into lactic acids or other high value amino acids with the support of selected and modified bacterial strains (Xiaoru Hou et al., 2014; Jensen et al., 2014; Jensen and Hansen, 2013; Utkan et al., 2013).

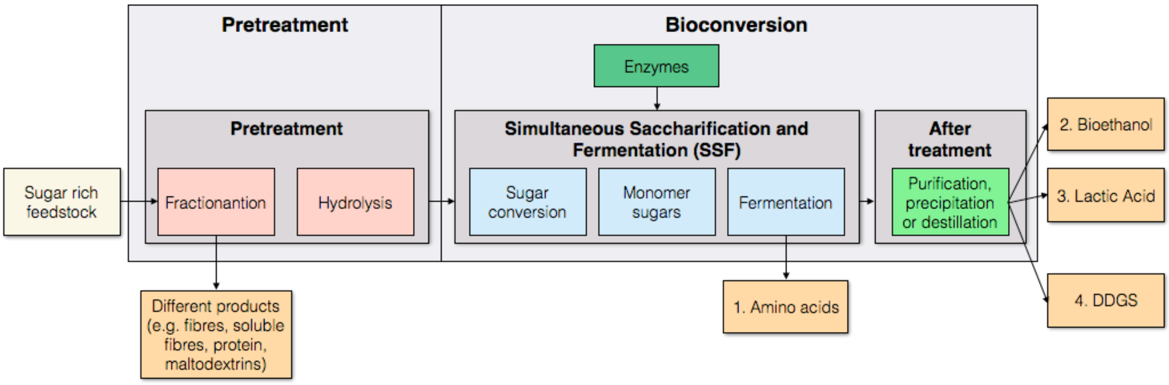


Figure 3. Example of Simultaneous Saccharification and Fermentation (SSF).

Pre-treatment of sugar rich feedstock

The technologies for pretreatment process this work refers to are the further development and application of technology that today are available for other similar feedstocks (e.g. wheat bran, oat bran). With regard to African countries this kind of technology could be adopted by companies already producing the oatmeal or similar that may be interested to also upgrade the by-product (Gidamis et al., 2015). Generally the equipment has to be used throughout, thus it can be designed in such a way that it can use different feedstocks depending on seasonal availability. In this regard, Table 4 shows five sugar rich feedstocks and their availability throughout the year, selected for sustainability evaluation.

Table 4. Availability of some selected sugar rich feedstocks.

Feedstock	Quantity (tons/year)	Seasonal availability	Country	Reference
Corn farming biowaste	5,000,000	Aug-Sept	Egypt	Amal and El Tablawy, 2013
Cassava peels	3,802,080	Nov-Dec	Ghana	Bayitse et al., 2013
Pineapple peels	75,000	Jan-Dec	Kenya	Sila and Namu, 2013
Olive pomace	367,500	July-Sept	Morocco	Bartali and Belmakki, 2013
Rejected bananas	24,798	Jan-March	South Africa	Sila and Namu, 2013

Pretreatment process usually occurs in heated stainless steel tanks, where products are separated from the bran (e.g. fibers, soluble fibers, protein, maltodextrins). As it already happens in food industry, there is a combination of decanters and separators that makes this process working. Among the different options currently exist, wet milling is the pretreatment process considered in the present work (Gidamis et al., 2015).

In the light of the geographical context such processing plants are expected to be implemented (i.e. African continent), there are some crucial aspects that it is fundamental to handle:

- Drying capacity: drying is necessary as the process is wet and is the main contributory cost of the whole process (up to 85% of the production cost is linked to the drying).
- Access to safe electricity and steam: with regard to the previous point, electricity and steam supply are core components to make the process working.
- Clean water: there is a need for clean water for the use in the process. A local filtration scheme should work, since water gets sterilized in the process. The water used in the steam generator would require a high level of purity.
- Skilled labor: some skilled labor will be required in order to operate the plant. The technology is similar to what is found in food and feed production and person with mechanical or process engineering know-how are needed.

Bioconversion of the pre-treated sugar rich feedstock

This bioconversion process is about the transformation of pretreated sugar rich biomass into to value added products. The potential products can be obtained by implementing such kind of technology are:

- Ethanol (liquid) – bulk chemical
- Lactic acid (liquid) – bulk chemical
- Lysine (amino acid, powder form) – bulk for feed

These different products can be potentially obtained by using the same equipment, while microorganisms have to be selected specifically and added to the process for producing different types of outputs. Both ethanol and lactic acid are produced by means of anaerobic process, while lysine is the output of aerobic process.

The bioconversion of pretreated biomass occurs in the form of a batch process, thus the substrate is kept in a tank where all the fermentation and microbe processes take place. Tanks are filled, then the processes takes place and after that emptied for post-treatment. The tanks are then cleaned and filled again.

As already argued for the pretreatment stage, there are some crucial points to take into consideration when we face with bioconversion of feedstocks (Gidamis et al., 2015):

- Secure supply of water: as the processes considered are based on having the processes taking place in liquids, there is need to have a secure supply of water. The water should be potable as a rule of thumb, since heavy metals would make the microbes less active and hence reduce the speed of the processes.
- Feedstock/water mass ratio: approximately 10-15% of the fermentation broth is biomass, i.e. roughly 85% water is needed. This means that 5-7 times the mass of the final product (lactic acid or ethanol) is required as water.
- Electricity security: in the case of ethanol production energy is required for the distillation process. Generally for all processes there is a need of electricity inputs for activities such as pumping, stirring, airing, etc.
- Steam supply: steam is typically used in the processes for various purposes (e.g. cleaning, heating the substrates, etc.). A steam generator would be needed at the site and this would require very clean water.
- Cooling: the processes are exothermic so in some cases some cooling is needed rather than heating. About 30-32°C is the starting temperature and 37°C is for some processes the optimal one.
- Microbes: they have a key role in achieving the expected results. Microbes are generated at the plant and they are able to grow again and again from the same source.
- Good and functional buildings: there is a need of good and functional buildings for storing of substrates, growing the microbes, generating steam, etc.
- Wastes: some wastewater is generated, but that can be handled in ordinary sewage systems. Some other solid wastes can occurs but the volumes are small.
- Labor: labor input depends of the level of automation. Running these type of plants is typically done in three shifts. The required labor input has to be from both skilled and unskilled labor.

4.2.2 Processing of nutrient rich feedstocks

The processing of nutrient rich feedstocks is the second technology option hypothesized. The focus here is about to optimize production of high value organic fertilizer in combination with energy carriers such as biogas.

As showed in Figure 4, the transformation system includes two sub-systems that are the biogas production chain and the composting process. Both these sub-systems can be seen in isolation to each other. The effluent from the anaerobic processing has improved qualities as a soil conditioner and fertilizer with respect to what is in input to the digester. The optimized compost would also be possible to operate in isolation to the anaerobic processing stage (for insight please see Hashim et al., 2014, 2013).

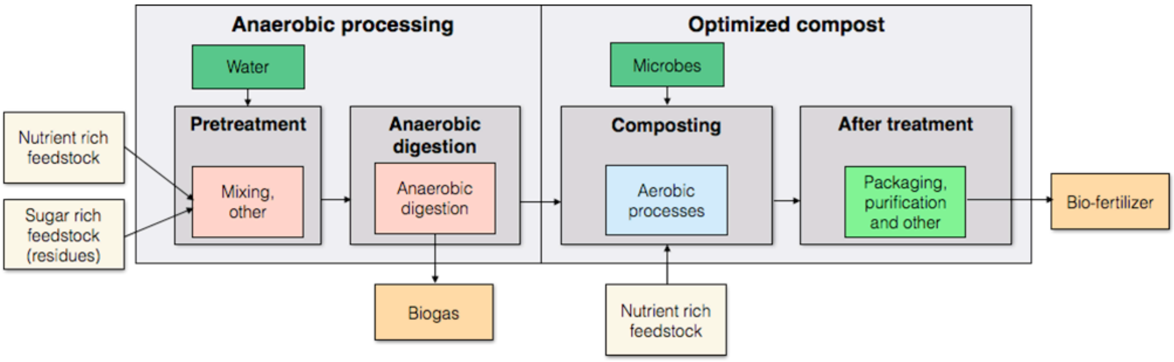


Figure 4. Anaerobic digestion in combination of composting to produce biofertilizer and biogas.

Anaerobic processing of biowaste

There are different technologies for anaerobic digestion of bio-based materials. Most of the biogas digesters in Africa today are household based technologies. In Morocco there are examples of sites where electricity is generated from biogas (Afilal et al., 2010); these systems are found in sewage treatment plants and also from landfill gas. The electricity generated is typically not fed into the power grid but used locally.

According to the scale of operation, there are three different technology systems to be taken into consideration (Gidamis et al., 2015):

- Small scale co-digestion: biowaste can be pretreated by means of chopping, mixing, etc. The digester has a basic design, heating is not required and there is no after-treatment of biogas.
- Medium scale co-digestion: the digester has to be designed according to optimum operational parameters (e.g. heating, stirring etc.). Management of how to make best use of the effluent is required (see for example Bayitse et al., 2014; Sithole and Tawona, 2013).

- Large scale co-digestion: optimized system that includes pre-treatment, optimization of process parameters and possibly also upgrade of gas. This also includes management of the effluent.

Among the described options, the small-scale digester can represents a valuable and economically feasible technology within the context of rural areas in African countries. Like for the sugar rich feedstocks it is helpful to know the amount of biowastes and bioresidues available throughout the year in order to plan correctly the supply of bioconversion plants. In Table 5 some selected nutrient rich feedstocks are listed with information about their availability on a national scale.

Table 5. Availability of some selected nutrient rich feedstocks.

Feedstock	Quantity (tons/year)	Seasonal availability	Country	Reference
Cocoa empty pods	903,646	Sept-Mar	Ghana	Bayitse et al., 2013
Cabbage waste	235,463	Jan-Dec	Kenya	Sila and Namu, 2013
Cattle manure	14,605,000	Jan-Dec	Morocco	Bartali and Belmakki, 2013
Soybean residues	305,895	Mar-June	South Africa	Gidamis et al., 2015

Optimized composting

The operation of optimized composting is started with the formation of composting heaps by blending the shredded raw materials with the carbon source and nitrogen source to get the desired carbon-to-nitrogen (C:N) ratio. The ideal initial C:N ratio should range from 30:1 to 40:1. It is fundamental to define the proper size and shape of the composting heap in order to allow air to flow throughout the heap while maintaining temperature in the proper range.

To have an optimized process that works properly it is fundamental to consider some crucial aspects (Gidamis et al., 2015):

- Moisture content, oxygen supply (aeration) and temperature: the moisture level should be maintained between 60% to 70% and the temperature between 55°C to 70°C. The level of oxygen content should be more than 8% for an aerobic activity to be maintained. Concerning the temperature it is worth to note that the process in the compost is exothermic and the temperature inside the heap should not be below 60°C.
- Water supply: in order to regulate temperature and moisture, water is added.

- Microbes: adding microbes to the process is what makes the composting process “optimized”. The microbes have to be cultivated under controlled conditions using a starter culture.

5. Emergy

Emergy evaluation was developed by H.T. Odum in the 1980s and it is an environmental accounting method based on thermodynamic principles (Odum, 1996). It quantifies the relationships between human-made systems and the biosphere and is used to assess environmental sustainability of processes and systems. Emergy is defined as the available solar energy (i.e. exergy) previously used, directly and indirectly, to make a service or product (Odum, 1996). "The unit of solar emergy is the solar emergy joule (sej), to distinguish it from the regular joule (J) and point out a different quality assessment based on a donor-side point of view" (Odum and Odum, 2006); sej means solar emergy Joule (and not just solar energy Joule) since the other two independent sources of energy that fuel all the processes on the biosphere (gravitational and the heat from the internal of the Earth) are converted into solar equivalents (Odum, 1996). Emergy is not a state function since it depends on the pathway of the process, in fact it can be considered as an "energy memory" that is the memory of all solar energy is needed to support a system, taking into account the work has been previously done by environment to produce a good.

Emergy evaluation assigns a value to products and services by converting them into equivalents of a single form of energy, solar energy, that is used as the common denominator and through which different types of resources, either energy or matter, can be measured and compared to each other. Emergy of different products is assessed multiplying mass or energy quantities by a transformation coefficient, called *Unit Emergy Value* (UEV). UEV is the solar emergy required, directly or indirectly, to make 1 unit (usually J or g) of a product. In the first case the intensive expression of emergy is also known as *transformity*, while in the second it is called *specific emergy*. By definition, the solar emergy *Em* of a product or process is:

$$Em = \sum_{i=1}^{n} E_i \, UEV_i \qquad (1)$$

where E_i is the actual energy content of the *i*th independent input flow to the process and UEV_i is the unit emergy value (in this case the transformity) of the *i*th input flow.

By means of UEV it is possible to measure the (in)efficiency of systems in transforming past and present solar energy into final products (Bastianoni and Marchettini, 1996; Odum, 1996). This is especially significant when similar products are compared, since a lower UEV indicates that natural resources are used in a more efficient way.

As we will see below there are some exceptions to the summability of the emergy “carried” by different inputs. According to Odum (1996) emergy deals with splits and co-products in different ways. Splits have the same UEV, since they originate from the same energy flow, and the emergy assigned to them is proportional to their respective energy flows. On the contrary, co-products have different UEVs, as they are flows of different types, while the emergy assigned to them is by definition equal to the total emergy needed to support the co-product production process. If co-products re-unite their emergy should not be summed (this would be double accounting), since exactly the same emergy produced both outputs.

According to Brown and Herendeen (1996), emergy algebra can be described with four rules:

1. All source emergy of a process is assigned to process output.
2. Co-products of a process have the total emergy assigned to each pathway (no allocation).
3. When a pathway splits, emergy is assigned to each ‘leg’ of the split according to the percentage of total energy flow on the pathway.
4. Emergy cannot be counted twice in a system: (a) emergy in feedback loops cannot be double counted; (b) co-products, when reunited, cannot add up to a sum greater than the source emergy from which they were derived.

Set theory can be used to illustrate emergy and its rules (Bastianoni et al., 2011; Morandi et al., 2014, 2013). It reduces the necessity of “detailing” an emergy algebra, since the property of union of sets encompasses all the rules of emergy. According to Bastianoni et al. (2011) emergy can be represented as the set of solar exergy that is directly and indirectly necessary to make a good or service. This means that every input can be considered as a set, while the process where inputs converge can be represented with the operation of union. The total emergy of the product, *Em*, is given by:

$$Em = \bigcup_i Em_i = \bigcup_i E_i UEV_i \tag{2}$$

where Em_i is the emergy of the *i*th input, E_i is the set that includes the amount of energy of the *i*th input and UEV_i is the corresponding unit emergy value. This implies that the emergy of inputs is only summed when (or for the part for which) the inputs are independent of each other.

Together with emergy, a specific language called energy system diagrams was developed in order to describe material and energy flows. These diagrams use specific symbols to represent the pathway of energy through a process system (see Figure 5).

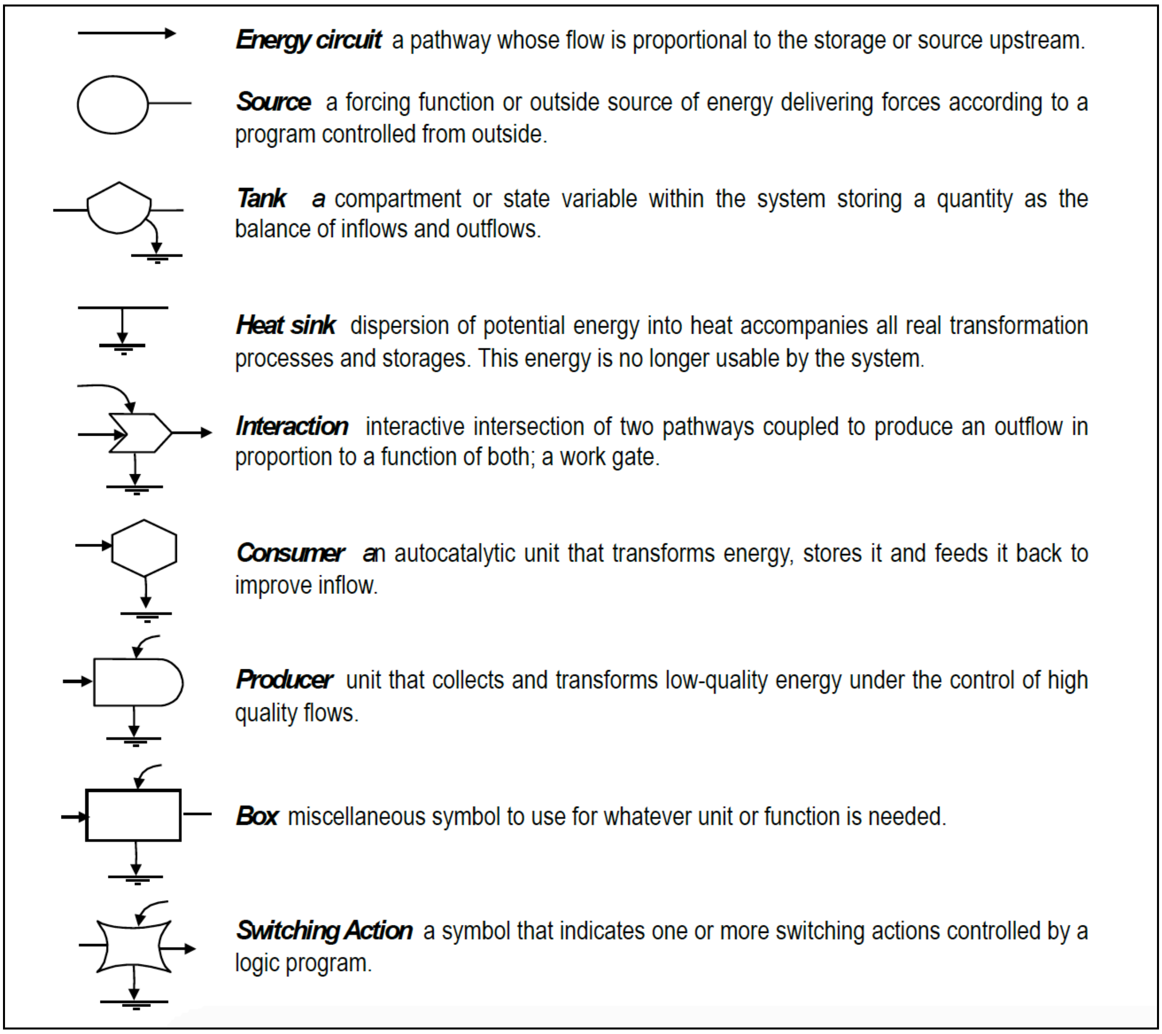
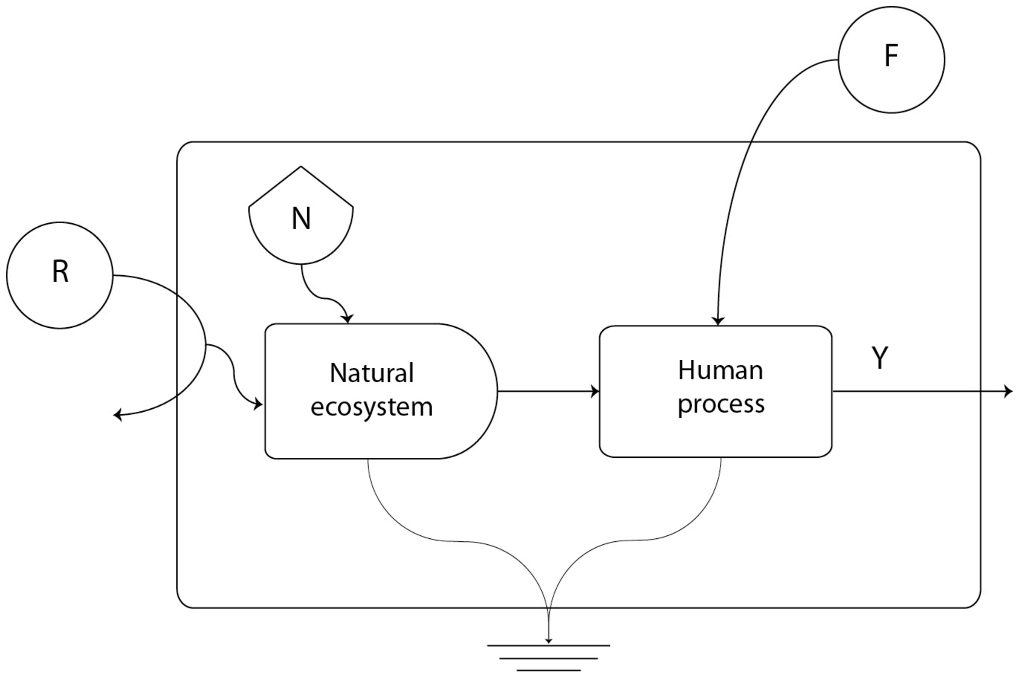


Figure 5. Energy system symbols (Odum, 1973).

According to Odum (1996) and based on their provenance and regeneration times, resource flows can be distinguished as: a) emergy flow related to local renewable resource (R); b) emergy flow related to local non renewable resource (N); c) emergy flow related to good and service purchased outside the system under study (F). Beside UEV, other emergy-related indicators are usually used to characterize emergy results, on the basis of such different emergy flows, as showed in Figure 6. Usually the adopted indicators are: percentage of renewable inputs (%R), Environmental Loading Ratio (ELR), Emergy Investment Ratio (EIR) and Emergy Yield Ratio (EYR)



Y = R+N+F
ELR = (N+F)/R
EIR = F/(N+R)
EYR = Y/F = (R+N+F)/F

Figure 6. Emergy-based indicators illustrated through an energy system diagram.

RESULTS AND DISCUSSION

6. Guidelines for Emergy Evaluation of first, second and third generation biofuels

A peculiarity of emergy evaluation that stems from its definition is the way it treats co-production: no allocation is made since all the emergy necessary for the production system is needed for all the products (for insights into this problem, see Brown and Herendeen, 1996; Bastianoni and Marchettini 2000; Bastianoni et al., 2011). This aspect is particularly relevant to the conclusions drawn from emergy evaluation.

A fundamental part of this work focused on providing guidelines on how to carry out emergy evaluation of biofuel production systems and how to interpret the results correctly, according to the first research question of the present study. The indications that can come from emergy evaluations are different among first, second and third generation biofuels. It is fundamental to clarify how to approach these different systems in order to avoid misunderstandings about the actual meaning of emergy results of biofuel production systems.

6.1 Literature review

Most emergy-based studies available in literature regard first-generation biofuels. Overall they stress the criticality of the production systems from a sustainability viewpoint. After performing emergy evaluation of bioethanol production from wheat in a Chinese province, Dong et al. (2008) highlighted the unsustainability of the process in that context. Bastianoni and Marchettini (1996) previously reached the same conclusion for different case studies of bioethanol from sugarcane in Florida, Brazil and Louisiana and from grapes in Italy. Pereira and Ortega (2010) studied a large-scale system for ethanol production from sugarcane in Brazil and demonstrated low renewability of the system due to major environmental impacts as well as consumption of natural resources. Another case study of Brazilian sugarcane ethanol was evaluated by Agostinho and Siche (2014), whose results confirmed low level of renewability of the biofuel. Lu et al. (2012) carried out emergy evaluation of rice-ethanol production in Japan and the results show that it is not ecologically feasible to use ethanol to replace gasoline, despite the advantage of reduced emission of polluting gases. Another study on the emergy of rice-to-ethanol production in Japan was done by (Liu et al. (2012) who found that the process was unsustainable and nonrenewable in the long run due to the large amount of purchased resources that drive it, like for fuel production from petroleum that they analyzed by way of comparison. Cassava is an alternative feedstock for producing ethanol, as explored by Yang et al. (2011) with a Chinese case study. Authors stated that the dependency of the production on input emergy purchased from outside the system needs to be dramatically reduced in order to have a more sustainable process.

Regarding biodiesel, Carraretto et al. (2004) showed that fuel produced from soybean feedstock is less efficient than fossil fuel, in terms of emergy. Cavalett and Ortega (2010) obtained similar results analyzing biodiesel production from soybean in Brazil. In this case study the fraction of fuel that can be considered renewable is less than one-third. By comparing some oleaginous crops cultivated in Brazil, Takahashi and Ortega (2010) found that rapeseed crop is the most sustainable one with a share of about 40% of renewable energy consumed. Sunflower is another feedstock that can be used to produce biodiesel, as explored by Spinelli et al. (2013) for a pilot production chain in the Province of Siena (Italy). They found that biodiesel from sunflower is not totally renewable and that its production system is less effective than that of fossil fuels in converting basic input into actual products. Ren et al. (2013) compared soybean-, rapeseed-, sunflower-, jatropha- and palm-based biodiesel production. They concluded that none of the five options can be considered sustainable in the long term. Nimmanterdwong et al. (2015) made another comparison of seven different biodiesel production systems. The systems were based on palm oil: three of them were real case studies while the others were hypothetical proposed systems. Since high portions of imported and non-renewable resources characterized all of these systems, it was not possible to consider them sustainable. Another case study based on palm oil was conducted by Goh and Lee (2010) who analyzed the option of directing 8% of Malaysian palm oil crop to the production of biofuel.

Ulgiati (2001) performed an economic and energy assessment of a case study of ethanol production from maize, located in Italy. The emergy evaluation confirmed the unsustainability of the biofuel option on a large scale. The study proposed clustering biofuel production with other agro-industrial processes so as to exploit byproducts as feedstock. This is in line with the approach proposed by Tiezzi et al. (1991), according to which the integration of agro-industrial systems can be a good solution for simultaneous sustainable production of food and energy (Bergquist et al., 2012). For this purpose, biorefineries are a valuable alternative to the current oil refineries, since they transform biomass and raw materials into biofuels and biochemicals (Cherubini, 2010).

The need for sustainable alternative solutions has aroused the general interest of stakeholders and researchers in second-generation biofuels. These advanced biofuels overcome the critical issue of competition for land with food production (Harvey and Pilgrim, 2011; Valentine et al., 2012).

In this regard Coppola et al. (2009) explored 24 bioethanol production scenarios with first- and second-generation conversion technologies based on wheat grain with and without wheat straw, respectively. Second-generation bioethanol proved to have lower efficiency due to a low yield of final product, but it also had lower environmental load, thanks to limited use of non-renewable resources.

Non-food crops on marginal land can be a viable way to produce second-generation biofuels. Fahd et al. (2012) evaluated a case study in southern Italy, where *Brassica carinata* was grown as dedicated non-food crop. Comparison of a cropping-for-energy option with a biorefinery perspective favoured the latter due to several added-value products resulting from the transformation processes.

Ju and Chen (2011) evaluated production of biodiesel from a non-grain feedstock (i.e. *Jatropha curcas* L.), making a comparison with two case studies of first generation biofuels. They found lower efficiency of biodiesel produced from *Jatropha curcas* in converting inputs to the biosphere, with respect to the reference studies. Another biofuel production based on cellulosic sources was evaluated by Felix and Tilley (2009), who highlighted the low level of sustainability of production based on switchgrass, *Panicum virgatum*, due to the large amount of non-renewable and purchased inputs.

Agostinho and Ortega (2013) analyzed the energy-environmental performance of a biorefinery scenario in Brazil that produced ethanol from cellulose. It was compared with another large-scale system that produced bioethanol from sugarcane and an *Integrated system of Food, Energy and Environmental Services* (IFEES). Among the large-scale systems the biorefinery option had better emergy efficiency, while the small-scale system, i.e. IFEES, had the best performance from an energy-environmental viewpoint.

Patrizi et al. (2015) used emergy to evaluate the proposal of a biorefinery system in the Province of Siena (Italy), fed by residual heat and material flows from local productions (i.e. straw). Since the biorefinery would be part of an existing system (i.e. electricity production from geothermal heat), the study focused on the physical investment required to implement the biofuel production system. This study introduced the concept of *Unit Emergy Investment* (UEI - the emergy input to an existing system required to produce further outputs). The results showed the site-specific feasibility of bioethanol production by a biorefinery coupled with local resource optimization.

With regard to third generation biofuels, Bastianoni et al. (2008) evaluated the production of biodiesel from two species of macroalgae collected in an Italian lagoon. The relative sustainability of the system was lower than biodiesel produced from sunflower. To make the production from macroalgae sustainable, the oil extraction method needed improvement. Seghetta et al. (2014) carried out another study on the feasibility of macroalgae as feedstock for the production of bioethanol from two eutrophic water bodies. In this case the implementation of biorefineries integrated with macroalgae harvesting could also provide a solution for the environmental problem of eutrophic water bodies. The percentage of renewable emergy involved in bioethanol production was higher than for other feedstocks used in biofuel production. This underlines that more efficient technologies are needed to produce biofuels in sustainable way, because under current conditions, production systems using macroalgae are less efficient in the utilization of resources than the less competitive alternative biofuels.

Productions of biofuel based on microalgae present the same shortcomings about the efficiency of current technologies. Da Cruz and Do Nascimento (2012) claim that such types of production are still less competitive from a sustainability viewpoint against first generation biofuels (e.g. ethanol from corn or grapes).

An alternative approach based on fast pyrolysis of naturally produced water hyacinth was assessed by Buller et al. (2015), who found lower dependence on fossil fuel resources, machinery and fertilizer with respect to other biofuels like soybean biodiesel and sugarcane ethanol.

6.2 Guidelines for emergy evaluation of different kinds of biofuels

Here we investigate the different ways to deal with biofuel production systems in terms of emergy, highlighting the crucial points for the three generations.

6.2.1 First-generation biofuels

A generic system that produces first-generation biofuels consists of two main stages that are agricultural production and the biorefinery plant. The crop is totally devoted to the production of energy and is therefore the main input of the biorefinery where biomass is converted into biofuel. Figure 7 shows an example of first-generation bioethanol production in energy system language.

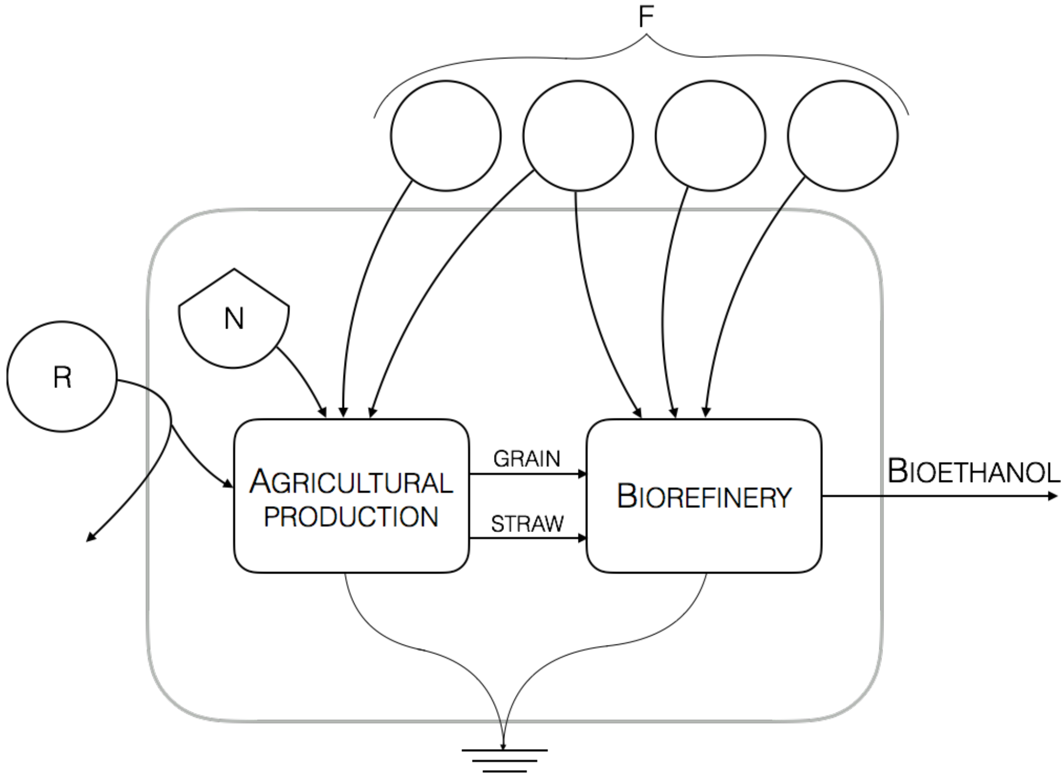


Figure 7. Energy system diagram of a first-generation bioethanol plant based on wheat feedstock. The biorefinery inputs are the main product and (sometimes) by-products of grain cultivation. *R* is the emergy flow from local renewables resources; *N* is the emergy flow embodied in local non-renewable resources; *F* is the emergy flow from resources purchased outside the system.

For first-generation biofuels, production systems are generally constructed for the specific purpose of producing energy, so all emergy driving the process goes into the product, i.e. the biofuel. This means that from a methodological point of view the evaluation can be carried out by the basic rules of emergy algebra, without need of further in-depth analysis. In other words, the evaluation is the same as for any other kind of single-output production system. For instance, the UEV of biofuel is simply calculated by dividing the total emergy that supports the system, i.e. the emergy of inputs, by the available energy of the output.

The relative sustainability of first-generation biofuels can be assessed by counting all the emergy required to support the production system and we can for example compare the emergy needed for one joule of fuel and the renewability of the emergy supporting the production system. There are graphic tools that provide visualization of emergy results in a clear and effective way. According to Giannetti et al. (2006) by means of emergy based ternary diagrams it is possible to better understand "the actual contribution of given inputs and the global sustainability of production processes". As alternative, to summarize the results of emergy evaluations, simultaneously showing quantitative and qualitative aspects, a polar diagram with the UEVs (in sej/J) on the radius and percentage renewability on the angle (between 0 and 180°) can be used (see Saladini et al., 2016). The results of some of the papers on first generation biofuels mentioned above are represented in Figure 8 using the polar representation.

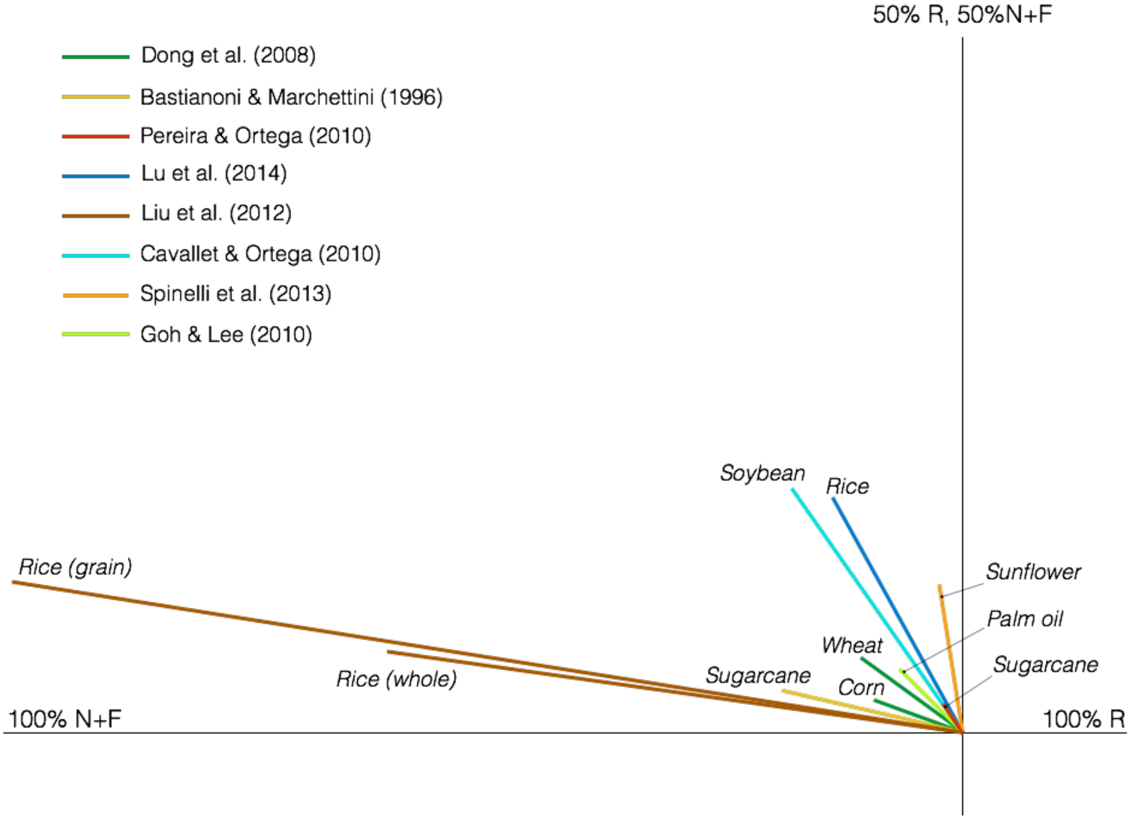


Figure 8. Summary of some UEVs of first generation biofuels, from the studies cited in section 6.1. Each line represents a biofuel (the feedstocks are indicated); a given color is used for biofuels evaluated in the same study. The absence of lines in the right part of the graph is fortuitous indicates that the renewable portion of emergy (R) was always below 50%.

6.2.2 Second-generation biofuels

Some biofuels classified as second-generation, namely those that originate from the main product of a production system (e.g. *Brassica carinata* on marginal land reported in Fahd et al., 2012) are actually first generation in terms of emergy, since they rely on feedstocks that are specifically produced for energy. Other second-generation biofuels, unlike first-generation ones, are produced using a by-product of agricultural production (e.g. straw). These biofuels are usually produced in the context of an agro-industrial system that works as an integrated process. Figure 9 shows such a system consisting of agricultural production and a biorefinery plant. The useful outputs of the integrated system are the crop (e.g. grain) and the biofuel.

According to emergy algebra, all emergy that drives the agro-industrial system is assigned to both outputs, since they are co-products. This is a crucial aspect of emergy analysis, since the biorefinery subsystem is powered by residues of the agricultural process, i.e. a by-product of the main output of the agricultural system. In this case the crop is not used for energy purposes (as in first generation), so the emergy that supports the whole system has to be interpreted considering the fact that we have several simultaneous outputs.

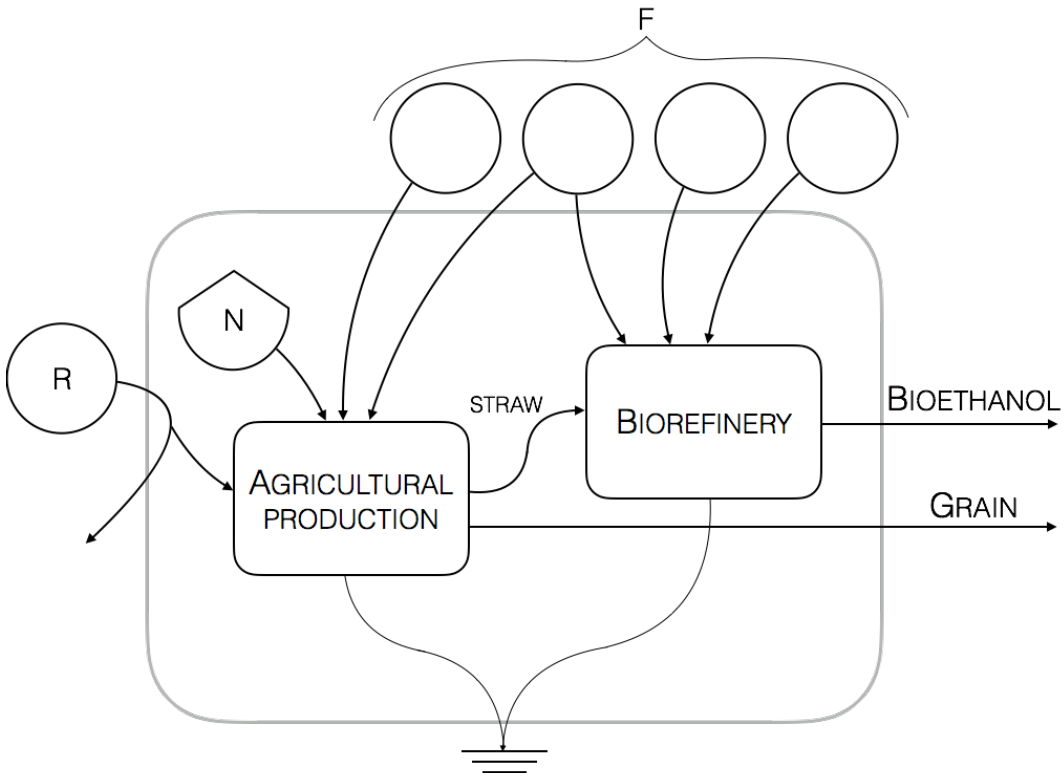


Figure 9. Energy system diagram of second-generation bioethanol from residues of grain production. The biorefinery input is a by-product of grain cultivation (straw) and the imported inputs required for its functioning.

Below we list three aspects to consider with particular attention when conducting emergy evaluation on second-generation biofuels.

1. *Evaluation of overall system*: the total emergy flow of the agro-industrial system, considered as a whole, is the emergy input to agricultural production and the biorefinery plant. This parameter, along with emergy-related indicators, is useful for evaluating the sustainability of the whole system, but it does not give meaningful information about the biorefinery plant product, i.e. the biofuel. This is

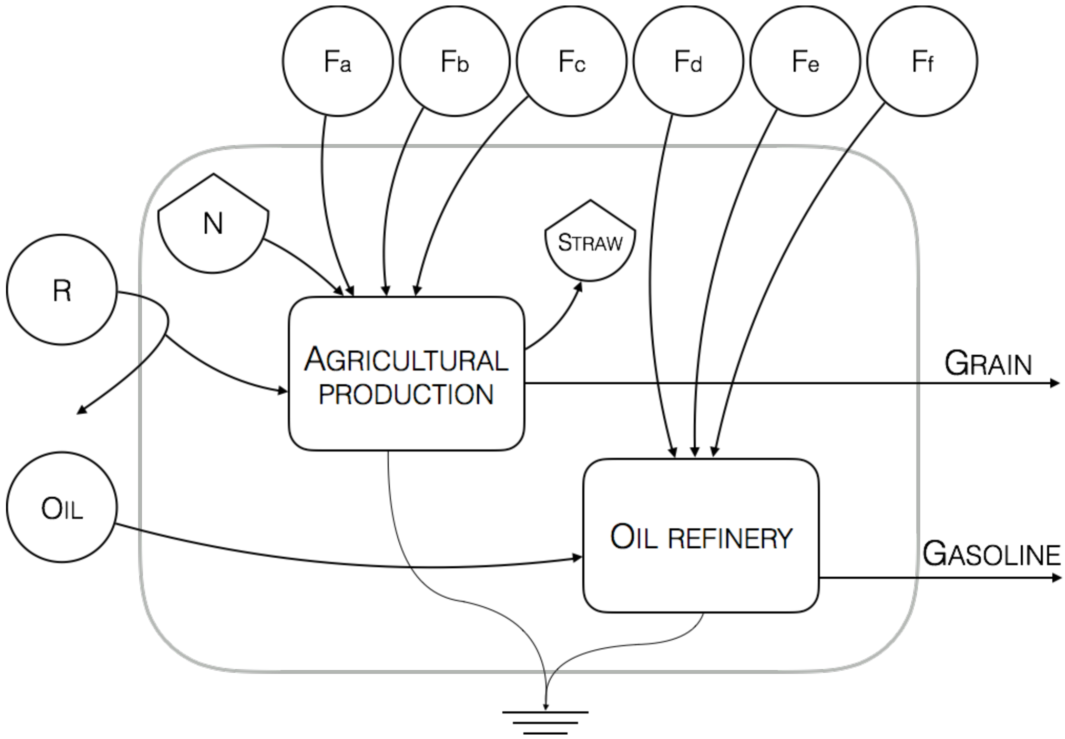
because agro-industrial systems produce simultaneously energy carrier as well as food.

2. *Emergy of the biofuel considered in isolation*: since all the emergy supporting the agricultural system has to be assigned to the outputs, it is correct to assign the emergy of all inputs to the residues. This is passed on to the industrial process (biorefinery) and as a result the emergy of the biofuel is all the emergy supporting both the agricultural system and the biorefinery. While appropriate from a methodological viewpoint, the results cannot be used for comparison with other fuels (fossil fuels or first-generation biofuels) since the production system is also producing another output, i.e. the crop. So by this approach we cannot compare ethanol from straw, for instance, with ethanol from sugarcane or other dedicated agricultural systems.
3. *Emergy investment*: according to Patrizi et al. (2015), emergy investment is defined as the emergy input to an existing system required to (upgrade by-products and) obtain further output(s). In the specific case of an agro-industrial system that produces both food and energy, emergy investment is equal to the sum of: a) emergy of labor, fuels and machinery required to collect residues from the field and transport them to the plant; b) emergy of all inputs needed to produce biofuel in the biorefinery plant. The upstream emergy related to the agricultural phase is not counted, because the focus is on what is added to an existing system in order to obtain value-added products. The index defined in this context is *Unit Emergy Investment* (UEI), that is the emergy investment required per unit product. This can be compared with UEVs of biofuels analyzed in other studies by the usual emergy approach.

Emergy investment is the additional input upon which the production of a new or additional output (in this case, biofuel) is ultimately based. The emergy investment required to implement a biorefinery can be compared with the emergy saved that would be otherwise needed to support a conventional oil refinery for fuel production (see Figure 10a-b). In this sense we can appreciate the difference in sustainability between business-as-usual and bio-based fuel production, since the main goal of producing biofuels is to substitute fossil fuels. Thus the approach proposed by Patrizi et al. (Patrizi et al., 2015) is especially useful for: i) comparing the emergy investment required to implement the biorefinery and the emergy saved due to substitution of fossil fuel with the bio-based equivalent; ii) comparing the UEI for the production of biofuels and the UEVs of fossil fuels.

Figure 10 helps clarify the rationale of this approach. Figure 4a shows two separate systems producing fuel and grain. Figure 10b shows an integrated system: the first part is the same as the agricultural part of Figure 10a, whereas the other inputs represent the collection of residues, transport of residues to the biorefinery and the inputs necessary for the establishment and operation of the biorefinery plant. For correct comparison, fuel production output in Figure 10a has to be equal (in energy terms) to the output obtained by treatment of the residues in the biorefinery.

a



b

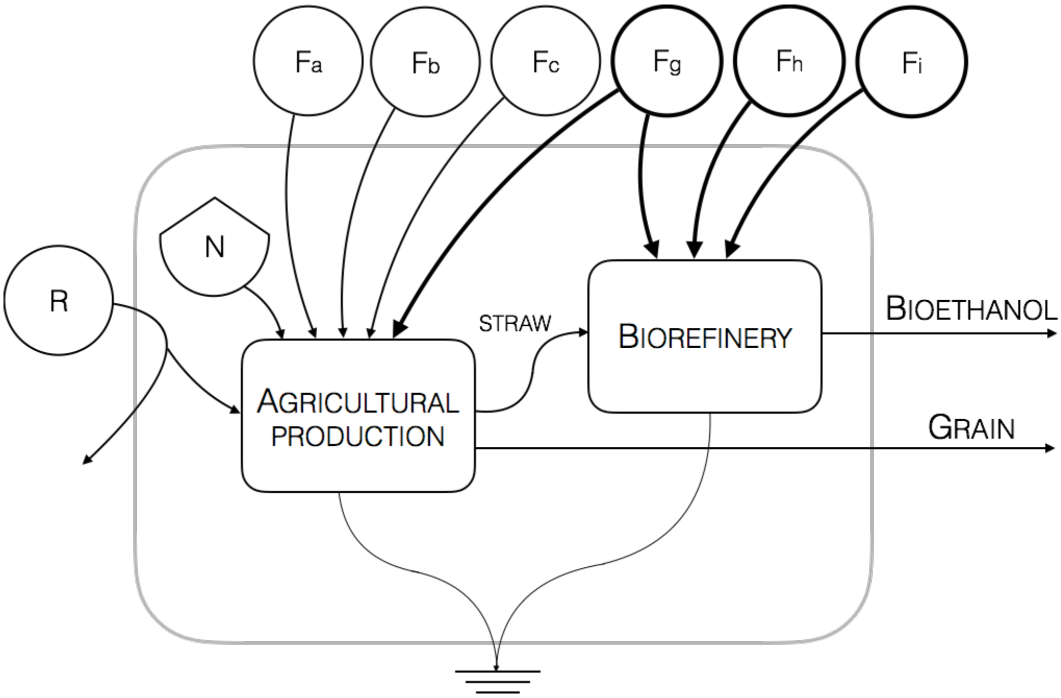


Figure 10a-b. Comparison of energy system diagrams of fuel (a) and biofuel production (b). The bold circles and arrows in figure *b* refer to inputs that could be counted as emergy investment. Figure *a* shows two independent production systems: a wheat cultivation and a traditional oil refinery.

6.2.3 Third-generation biofuels

According to the IEA definition (IEA, 2008), third-generation biofuels are bio-based fuels produced from aquatic feedstock (usually algae). As showed in Figure 11, systems that produce this type of biofuel consist of two main phases; the first is the natural growth or cultivation of aquatic biomass, and the second includes all operations from harvesting of feedstock to production of biofuels. The single-output process implemented for producing third-generation biofuels is usually based on multiple purposes, i.e. energy and water remediation, for example. This entails several considerations for emergy evaluation on these systems.

a. The UEV (in sej/J) of biofuel is calculated as usual, dividing the emergy needed to support the whole system by the energy content of the output.

b. Where a biorefinery is implemented to exploit an aquatic biomass, harvested in any case to combat eutrophication (Bastianoni et al., 2008; Seghetta et al., 2014), it makes sense to evaluate the emergy investment (Patrizi et al., 2015). As already explained for second generation biofuels, the emergy investment is the set of inputs that need to be added to an existing system, i.e. those involved in the transformation of algae into energy, without considering the upstream inputs associated with the growth and harvesting of algae.

c. With regard to biofuel production based on cultivated algae, it is worth highlighting the importance of the second purpose of biofuel production, i.e. water remediation and protection of aquatic ecosystems. In fact, when eutrophication occurs, the aquatic plant biomass (e.g. macroalgae) grows in an uncontrolled way, with harmful consequences for the aquatic ecosystem due to excessive consumption of oxygen when the biomass decomposes. In this case it is also possible to evaluate the "emergy saved" by the ecosystem service of water purification by algae: they take up nutrients during their growth, avoiding eutrophication and associated environmental problems. The "emergy saved" is related to the cost that would be otherwise due to remove nutrients from the aquatic ecosystem by other technologies.

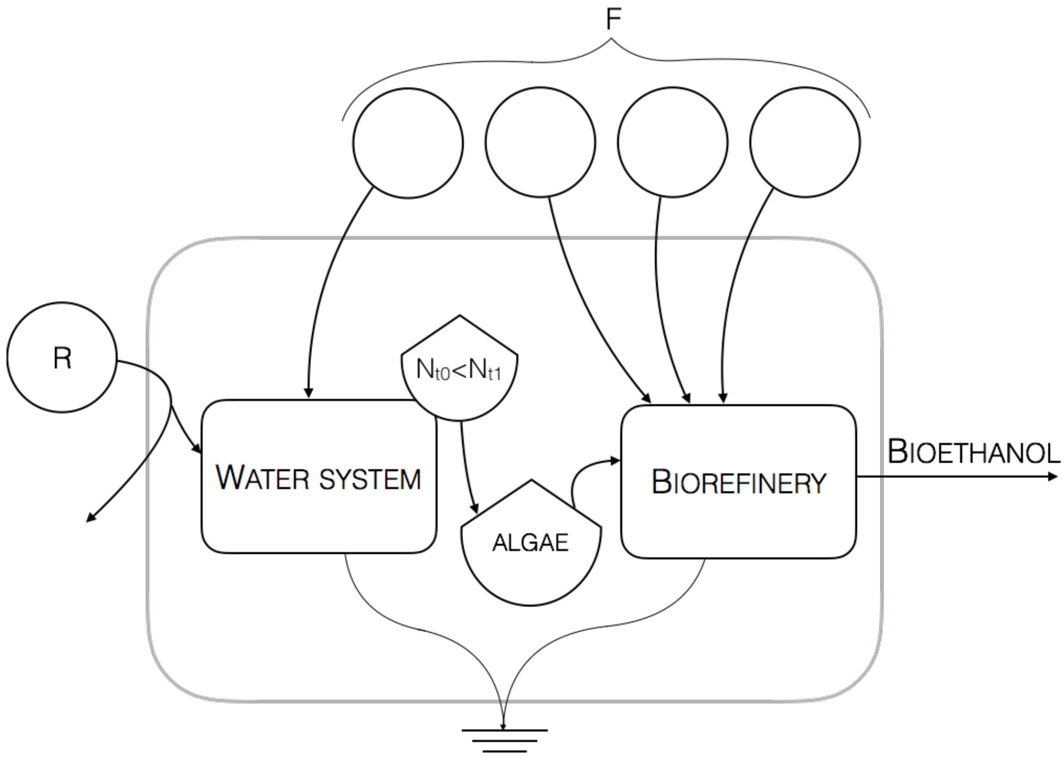


Figure 11. Energy system diagram of third-generation bioethanol from algae feedstock (*N* is nitrogen). $N_{t0}<N_{t1}$ means that the nitrogen decreases due to the algal uptake. The same can be said for other nutrients (e.g. P, K) and contaminants (e.g. Cd, Cu).

6.3 Discussion

As recently claimed by Amaral et al. (2016) more research is needed in order to make emergy a "management tool readily usable at a strategic and/or operational level". On this subject the present study aims to support researchers as well as not-specialists that want to deal with emergy evaluation of biofuels, by clarifying the actual meaning of the obtained results according to the generation of biofuel that analyses refer to. As consequence, such guidelines can provide a helpful support to the decision-making process, especially when comparison among similar products has to be handled. In this regard, some efforts have been recently provided with the aim to design model of biofuel supply network based on the optimization of the emergy sustainability index (ESI) (Ren et al., 2015). Such a type of model provides a coarse indication of the actual level of sustainability of biofuel productions, because of some methodological shortcomings characterizing ESI (Bastianoni et al., 2007). Other emergy-based indicators are needed to comprehensively evaluate the sustainability of biofuel production and this work is intended to support such types of evaluations.

7. Emergy evaluation of selected biowastes as feedstocks for biofuel and biomaterial production in five African countries

The transformation of biomass into various products has seen much development and today there is a range of opportunities for upgrading bio-based materials to products such as medical chemicals, food, feed, biofuels and fertilizers. To this end it is important to identify the possible bio-resources to which adding value, by means of new transformation processes aimed at producing biofuels and biomaterials. As argued by the second research question, this part of the research was focused on the sustainability assessment by means of emergy of a set of potential feedstocks for the production of biofuels and other value-added products in Egypt, Ghana, Kenya, Morocco and South Africa. These feedstocks are mainly residues from agriculture and industrial food processing. The aim was to determine whether African countries could benefit from exploiting underutilized biomass as energy feedstock.

7.1 Selected feedstocks and related production systems

As shown in Table 3 (see section 4.1), the sustainability assessment was performed focusing the analysis on selected sugar-rich and/or nutrient-rich feedstock for each country.

Where possible, traditional and commercial farming systems for the same feedstock were compared:

- Traditional farming system (tf): defined here as small-scale cultivation for the local market or subsistence, characterized by low-input of matter and energy;
- Commercial farming system (cf): defined here as large-scale intensive cultivation aimed at a wider market.

The systems selected are representative of average or usual kinds of production (Gustavsson et al., 2014).

Selected feedstock from Egypt

Corn residues consisting of corn stover i.e. leaves, stalks and husks left in the field after harvesting, was selected as a sugar-rich (cellulose) feedstock. The stover to grain mass ratio was estimated at about 0.9:1 fresh weight (Pordesimo et al., 2004). The system analyzed is commercial cultivation of 142 ha at Ismailia Research Station.

Selected feedstock from Ghana

Cassava-processing residue in the form of peelings is a sugar-rich (starch) feedstock. A traditional cultivation was compared with a commercial system (both in Nkwanta South district). The farm under traditional cultivation has an area of 2 ha and produces 23 t per cultivation cycle (10 months) and the commercial farm has an area of 10 ha and produces 250 t of cassava.

Residue from a cocoa plantation, i.e. the empty cocoa pods left after the harvest, is the selected nutrient-rich feedstock. We analyzed a traditional cultivation at Akim Tafo, which produces 2 t y^{-1} of cocoa beans and the same quantity of cocoa pods (bean to pod mass ratio 1:1) in an area of 5 ha.

Selected feedstocks from Kenya

We selected peels from pineapple processing as a sugar-rich feedstock. The commercial pineapple farm is at Mangu, measures 1 ha and produces 30 t per cultivation cycle (24 months), that give 15 t of peels.

We also selected the nutrient-rich feedstock cabbage (discarded leaves) from the vegetable market wastes. The system concerns the market company in Molo, which buys vegetables from farmers within a radius of 60 km. One traditional and one commercial cabbage farm were analyzed. The amount of cabbage waste collected at the vegetable market is about 5% of the harvested yield.

Selected feedstocks from Morocco

Pomace from olive oil production was selected as a sugar-rich feedstock in Morocco. The traditional cultivation system is a 5 ha olive grove in the region of El Hajeb, representative of small Moroccan olive producers. An annual olive harvest of 3.5 t is processed in an oil press at Dkhissa and yields 451 kg of oil and 3.05 t of pomace. The commercial cultivation is near Meknes. The olive grove covers 16.5 ha and produces 49.5 t of olives that yield 8.2 t of oil and 41.3 t of pomace.

The nutrient-rich feedstock selected for Morocco was cattle manure. Two cattle breeding systems were analyzed: free-grazing (fg) and intensive raising based on forage “zero-grazing” (zg). The former is a farm with 8 cows that produces 24,000 L y^{-1} of milk and generates 72 t y^{-1} of manure. The zero-grazing system has 36 cows producing 252,000 L y^{-1} of milk and 432 t of manure.

Selected feedstocks from South Africa

Bananas rejected in the field is the sugar-rich feedstock we selected in South Africa. The traditional plantation is at Tshakhuma (Limpopo province), measures 1 ha and produces 25 t of bananas per cultivation cycle (16 months). The commercial system is at Levubu, covers 40 ha and produces 1,600 t per cycle. Rejected bananas are 5-10% of total production.

The nutrient-rich feedstock selected for South Africa is soybean waste, namely what remains of the mother plant after threshing and removal of the beans. This commercial system is at Marriannhill; it has an area of 15 ha and yields 105 t of beans per cultivation cycle (4 months).

7.2 Emergy evaluation of African biowaste

The selected feedstocks were chosen for their potential for transformation into biofuels and biomaterials, i.e. bioethanol and fertilizers, respectively. It was therefore necessary to evaluate them on a common basis to enable comparison in terms of emergy of both types of residues. Glucan content was assumed to reflect the sugar content of feedstocks, being the sum of starch and cellulose, while the ash content was used as indicator of nutrient content (Gustavsson et al., 2014). Given these values for both types of residues, we calculated their UEVs, as explained below:

Sugar-rich feedstocks

sej/g of glucan = (sej/g) / (g of glucan/g)

Nutrient-rich feedstocks

sej/g of ash = (sej/g) / (g of ash/g)

where g (without index) is the weight of dried biomass of the selected crop.

For each country, the UEV of human labor was calculated from emergy per capita reported in the National Environmental Accounting Database (NEAD) compiled by the Center for Environmental Policy of the University of Florida (NEAD, 2008). Due to the particular context this study refers to (i.e. developing countries), we decided to do not include emergy input from human work in calculating the percentage of renewable emergy input. This is because the renewability proportion of human labor in principle should be calculated according to the renewable emergy inputs that support the country in which the workers live. Especially for what concern the traditional farming systems, this value does not reflect the actual renewable emergy we can attribute to labor input, since we are dealing with small-scale cultivations that represent subsistence farming for those workers. For consistency we have applied the same approach to all production systems we have evaluated. Emergy evaluation considered an emergy baseline of 9.26E+24 sej y^{-1} (Campbell, 2000). The emergy baseline is given by the sum of the main biosphere inputs and represents the reference according to which all UEVs are calculated.

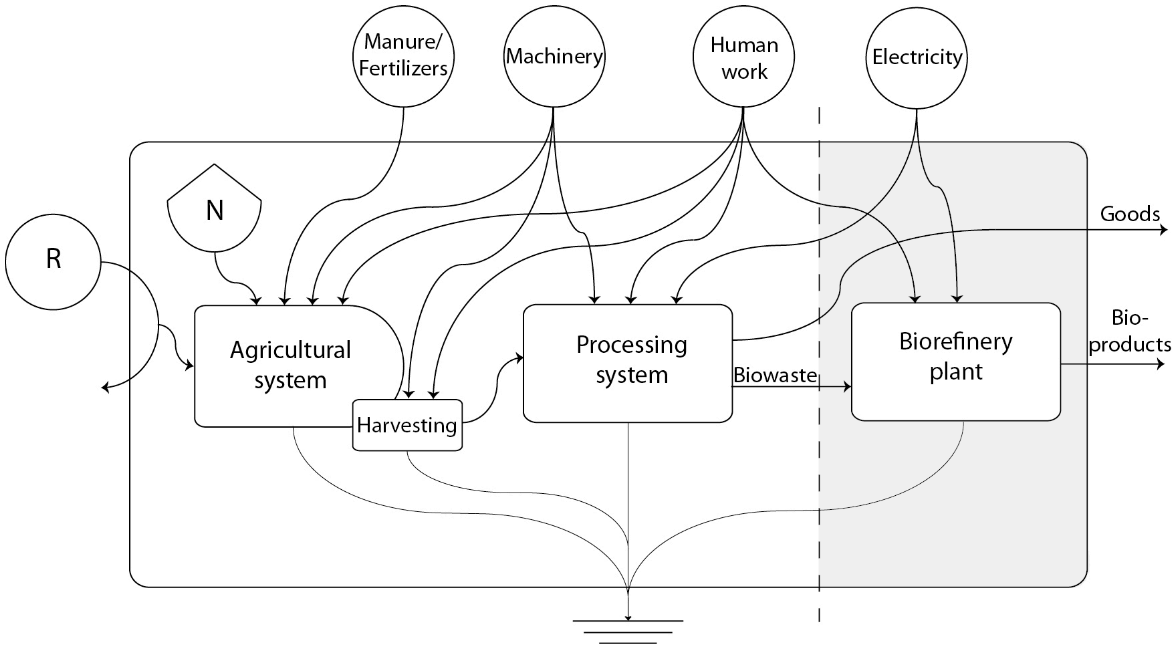


Figure 12. Energy system diagram of integrated agro-industrial production of goods and bio-products. Our study focused on the first part of the system (white section on left) that produces the main goods and related residues, keeping in mind the destination of the residues, i.e. the biorefinery plant (gray area).

7.2.1 Emergy of nutrient-rich feedstocks

For traditional and commercial cabbage growing, the efficiency with which past and present solar energy was transformed into final products is higher for the latter. This trend is in line with those of other production systems assessed in this study. Specifically the UEV of cabbage waste from commercial cultivation collected at the vegetable market is 1.16E+08 sej g^{-1} (see Table 6) and that one from the traditional system is more than double. Emergy indices show that traditional cultivation has less impact on the environment (ELR=2.18 vs. 5.65) and is less dependent on inputs purchased outside the system (EIR=1.95 vs. 5.17).

The other emergy tables for all residues can be consulted in the appendix.

Table 6. Emergy evaluation of commercial cultivation of cabbage (Kenya).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV, sej $unit^{-1}$	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Cabbage cultivation								
1	Solar radiation		6.28E+13	J	1.00	Odum, 1996	6.28+13	R

2	Rain		9.75E+09	g	8.48E+04	Campbell et al., 2005	8.26E+14	R
3	Wind		1.36E+11	J	1.43E+03	Campbell et al., 2005	1.95E+14	R
4	Geothermal heat		2.68E+10	J	6.00E+03	Campbell et al., 2005	1.61E+14	R
5	Net topsoil loss		6.89E+08	J	1.12E+05	Cohen et al., 2006	7.72E+13	N
6	Tractor	Iron/steel	1.17E+05	g	3.38E+09	Cabezas et al., 2010	3.97E+14	F
		Tyre	5.22E+04	g	4.22E+09	Buranakarn, 1998	2.20E+14	F
7	Fuel	Diesel	1.45E+05	g	2.83E+09	Bastianoni et al., 2009	4.10E+14	F
8	Tools	Steel	2.21E+04	g	3.38E+09	Cabezas et al., 2010	7.45E+13	F
		Wood	2.45E+03	g	1.72E+09	Cabezas et al., 2010	4.21E+12	F
9	Fertilizer	N	1.20E+05	g	3.73E+09	Cabezas et al., 2010	4.48E+14	F
		P	5.24E+04	g	3.83E+09	Cabezas et al., 2010	2.01E+14	F
		K	9.96E+04	g	1.08E+09	Cabezas et al., 2010	1.08E+14	F
10	Pesticide		2.40E+05	g	1.45E+10	Cabezas et al., 2010	3.48E+15	F
11	Human work		1.33E+03	h	2.74E+11	This study	3.63E+14	
Output								
12	Cabbage		6.25E+09	J	1.08E+06	This study	6.77E+15	
			6.00E+07	g	1.13E+08	This study	6.77E+15	
Transport to market								
13	Transport		3.00E+09	g km	5.38E+04	Pulselli et al., 2008	1.61E+14	F
Vegetable market								
14	Cabbage (waste)		6.25E+09	J	1.11E+06	This study	6.93E+15	
			6.00E+07	g	1.15E+08	This study	6.93E+15	

[a] R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table 7 summarizes the main results for nutrient-rich feedstocks. The first column indicates production and associated residues identified as potential feedstock. UEVs are reported in the second column. The other emergy indices are reported in columns four to seven and are for overall production systems.

Table 7. Summary of UEVs and emergy-based indicators for nutrient-rich feedstocks and related production systems. The selected residues are in bold.

Feedstock	UEV, sej unit^{-1}	Unit	% R	ELR=(N+F)/R	EIR=F/(R+N)	EYR=Em/F	Type of system
Milk	7.21E+08	g	92%	0.08	0.08	12.89	Free-grazing
Manure	2.40E+08	g					
Milk	1.99E+09	g	48%	1.09	1.09	1.92	Zero-grazing
Manure	1.16E+09	g					
Cocoa beans	4.23E+05	J	77%	0.30	0.27	4.66	Traditional
	4.67E+09	g					
Cocoa pods	4.67E+09	g					
Cabbage	2.64E+06	J	31%	2.18	1.95	1.51	Traditional
	2.75E+08	g					
Cabbage (waste)	2.64E+06	J					
	2.75E+08	g					
Cabbage	1.08E+06	J	15%	5.65	5.17	1.19	Commercial
	1.13E+08	g					
Cabbage (waste)	1.11E+06	J					
	1.16E+08	g					
Soybean	2.36E+05	J	19%	4.26	3.52	1.28	Commercial

	5.93E+08	g
Soybean residues	1.19E+09	g

Regarding manure production, the free-grazing system relies mainly on human work (almost 86% of total emergy), while the calculated emergy of the more intensive system is primarily influenced by purchased forage (98%). The results of emergy evaluation show two completely different systems. The zero-grazing cattle farm is totally based on purchased inputs, especially on forage to feed the cows. The percentage of renewability depends totally on forage input (48%). On the other hand the free-grazing system is characterized by 92% renewability of inputs and consequently low environmental impact (ELR=0.08 vs. 1.09). These results are affected by the fact that we did not consider human work in calculating emergy indicators. The manure input required for some of the cultivations analyzed in this study considered the UEV and percentage renewability of manure from the Moroccan free-grazing system.

Regarding the cocoa plantation, the traditional system is supported by low-input flows of matter and energy as shown by the emergy-based indicators: 77% of the total emergy supporting the system is from renewable resources and the impact on ecosystems is low (ELR=0.30).

With regard to the soybean feedstock, renewable inputs of the commercial production system analyzed are 19% of total emergy. The other indices suggested that production depends largely on purchased resources and therefore has high environmental impact (ELR=4.26, EIR=3.52, EYR=1.28).

7.2.2 Emergy of sugar-rich feedstocks

Table 8 shows the details of emergy evaluation for traditional production of olive oil (the other residues production phases can be consulted in the appendix). Comparison of commercial and traditional olive oil production gave UEVs for olive oil that are 9.70E+09 sej g^{-1} and 1.92E+10 sej g^{-1}, respectively. This result is closely linked to the lower yield of traditional olive cultivation and oil production in comparison with commercial production. The other emergy-based indices show that traditional production of olive oil relies on more renewable inputs (85% of the total) and has lower environmental impact (ELR=0.21 vs. 0.70). The commercial system is more able to exploit local resources than the traditional one (EYR=6.69 vs. 2.48).

Table 8. Emergy evaluation of traditional production of olive oil (Morocco).

#	Item	Detail	Input [a], Unit ha^{-1} y^{-1}	Unit	UEV, sej $unit^{-1}$	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[b]
Olives cultivation								
1	Solar radiation		5.52E+13	J	1.00	Odum, 1996	5.52E+13	R
2	Rain		3.91E+09	g	8.48E+04	Campbell et al., 2005	3.31E+14	R
3	Wind		1.57E+11	J	1.43E+03	Campbell et al., 2005	2.25E+14	R
4	Geothermal heat		2.36E+10	J	6.00E+03	Campbell et al., 2005	1.42E+14	R
5	Net topsoil loss		2.91E+08	J	1.12E+05	Cohen et al., 2006	3.27E+13	N
6	Herbicides		2.88E+03	g	8.66E+09	Brandt-Williams, 2002	2.49E+13	F
7	Motorized sprayer	HDPE	5.76E+02	g	5.17E+09	Cabezas et al., 2010	2.98E+12	F
		Steel	3.84E+02	g	3.38E+09	Cabezas et al., 2010	1.30E+12	F
8	Fuel	Gasoline	2.66E+04	g	2.92E+09	Bastianoni et al., 2009	7.78E+13	F
9	Manure		3.00E+06	g	2.40E+08	This study	7.17E+14	92% R, 8%F
10	Secateurs	Steel	2.02E+02	g	3.38E+09	Cabezas et al., 2010	6.81E+11	F
		HDPE	5.04E+01	g	5.17E+09	Cabezas et al., 2010	2.61E+11	F
11	Canes	Wood	8.00E+02	g	1.72E+09	Cabezas et al., 2010	1.38E+12	F
12	Bags	LDPE	8.00E+01	g	5.17E+09	Cabezas et al., 2010	4.14E+11	F
13	Human work		2.94E+02	h	1.14E+12	This study	3.34E+14	
Output								
14	Olives		1.20E+09	J	1.38E+06	This study	1.67E+15	
			7.00E+05	g	2.38E+09	This study	1.67E+15	
Transport to olive press								
15	Transport		1.40E+07	g km	5.38E+04	Pulselli et al., 2008	7.53E+11	F
Olive oil production								
16	Water		2.80E-01	m^3	1.57E+12	Chen and Chen, 2009	4.39E+11	N
17	Electricity		1.27E+08	J	2.90E+05	NEAD, 2008	3.68E+13	F
18	Human work		2.52E+01	h	1.14E+12	This study	2.86E+13	
Outputs								
19	Olive oil		9.02E+04	g	1.92E+10	This study	1.73E+15	
20	Olive pomace		6.10E+05	g	2.84E+09	This study	1.73E+15	

[a] See appendix for calculation of input values.
[b] R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table 9 shows the main results of emergy evaluation of the different sugar-rich biomass. The first column indicates the residue identified as potential feedstock and the main product. The UEV of each is reported in the second column. The other emergy indices for whole production systems are reported in columns four to seven.

Table 9. Summary of UEVs and emergy-based indicators of sugar-rich feedstocks and related production systems. The selected residues are in bold type.

Feedstock	UEV, sej $unit^{-1}$	Unit	% R	ELR=(N+F)/R	EIR=F/(R+N)	EYR=Em/F	Type of system
Corn	6.86E+05	J					
	7.38E+08	g	48%	1.09	1.09	1.92	Commercial
Corn stover	8.20E+08	g					

Olives	1.38E+06	J	83%	0.21	0.18	6.69	Traditional
	2.38E+09	g					
Olive oil	1.92E+10	g					
Olive pomace	2.84E+09	g					
Olives	9.09E+05	J	59%	0.70	0.67	2.48	Commercial
	1.56E+09	g					
Olive oil	9.70E+09	g					
Olive pomace	1.92E+09	g					
Cassava	4.69E+04	J	92%	0.08	0.05	20.40	Traditional
	1.30E+08	g					
Peeled cassava	2.45E+08	g					
Cassava peels	6.62E+08	g					
Cassava	1.05E+04	J	71%	0.41	0.37	3.68	Commercial
	7.21E+07	g					
Peeled cassava	1.55E+08	g					
Cassava peels	4.19E+08	g					
Pineapple	1.20E+06	J	55%	0.82	0.78	2.29	Traditional
	3.36E+08	g					
Pineapple juice	1.07E+09	g					
Pineapple peels	7.78E+07	g					
Rejected bananas	1.47E+06	J	10%	8.80	8.19	1.12	Traditional
	1.58E+09	g					
Rejected bananas	1.84E+05	J	3%	32.71	25.75	1.04	Commercial
	8.27E+08	g					

Emergy evaluation of traditional corn cultivation shows that almost half the total emergy comes from renewable inputs (48%). The indices ELR and EIR have the same value (1.09), since no local non-renewable inputs are used; EYR is 1.92.

In comparing traditional and commercial cassava production we found that both systems are based mainly on renewable resources (92% and 71% of total emergy, respectively). They also have a low impact on natural ecosystems and rely mainly on local resources, as shown by the emergy-based indices in Table 9.

A comparison of the UEVs of products highlights that the commercial production is more efficient than the traditional one from an emergy viewpoint. For the latter, the UEV of cassava peels, i.e. the selected feedstock, is 6.62E+08 sej g^{-1}, for the former is 4.19E+08 sej g^{-1}.

In analyzing the traditional system of cultivation and processing of pineapples, we found that the main emergy contribution came from the cultivation phase (almost 88%). The system as a whole relies on renewable resources for 55% of total emergy. The system also has a low environmental loading ratio and low exploitation of purchased inputs (ELR=0.82 and EIR=0.78).

In comparing traditional and commercial banana production, emergy-based indices show that both systems are mainly based on nonrenewable resources, though the traditional cultivation system shows better sustainability performance (see Table 9). Also in this case the UEV of bananas from commercial cultivation (8.27E+08 sej g^{-1}) is lower than that of the traditional product (1.58E+09 sej g^{-1}). This result is again related to the difference in harvesting yields of the two systems. The manner of managing the two systems is quite similar, while for other crops there is a more evident difference between traditional and commercial systems.

7.3 Comparison of feedstock UEVs and renewability

To compare the potential of different residues for transformation into value-added products, their UEVs based on glucan and ash content were calculated starting from their specific emergies.

Figures 13 and 14 show the results for the two residues groups. The colored segments indicate the different feedstocks. Segment lengths are proportional to UEV (in sej g^{-1} of glucan or sej g^{-1} of ash) and slopes indicate the percentage renewability of the total emergy supporting the production system, from 100% (right end of horizontal axis) to 0% renewability (left end). A system with 50% renewability will fall on the vertical axis. In this way it is possible to have an emergy snapshot of the feedstock and its production system (Saladini et al., 2016).

Agricultural systems in which manure is an input (fertilizer) were evaluated, also considering an alternative scenario in which the emergy of this input was set equal to zero. This is because manure can be considered a co-product of dairy farms, the main product of which is milk, and accounting this input could overestimate the total emergy needed to support the agricultural system. According to emergy algebra, the total emergy flow sustaining the dairy system is assigned to both milk and manure, since they are co-products, and including the emergy of manure (in analysis of an agricultural system) somehow implies that the output is not only the agricultural product, but also milk (or meat). The results of alternative scenarios are represented in the diagrams with dotted lines in the same color. In this regard it is interesting to note that the UEVs calculated for the second scenario are always lower than those calculated for the first (dotted segments are shorter than continuous ones) since we have removed one input that is often a major one. We also see that the percentage of renewable inputs supporting these production systems decreases (dotted segments are rotated counterclockwise with respect to continuous ones). This trend is explained by the fact that manure is an important input for the production system and also has high percentage renewability (92%), according to our analysis.

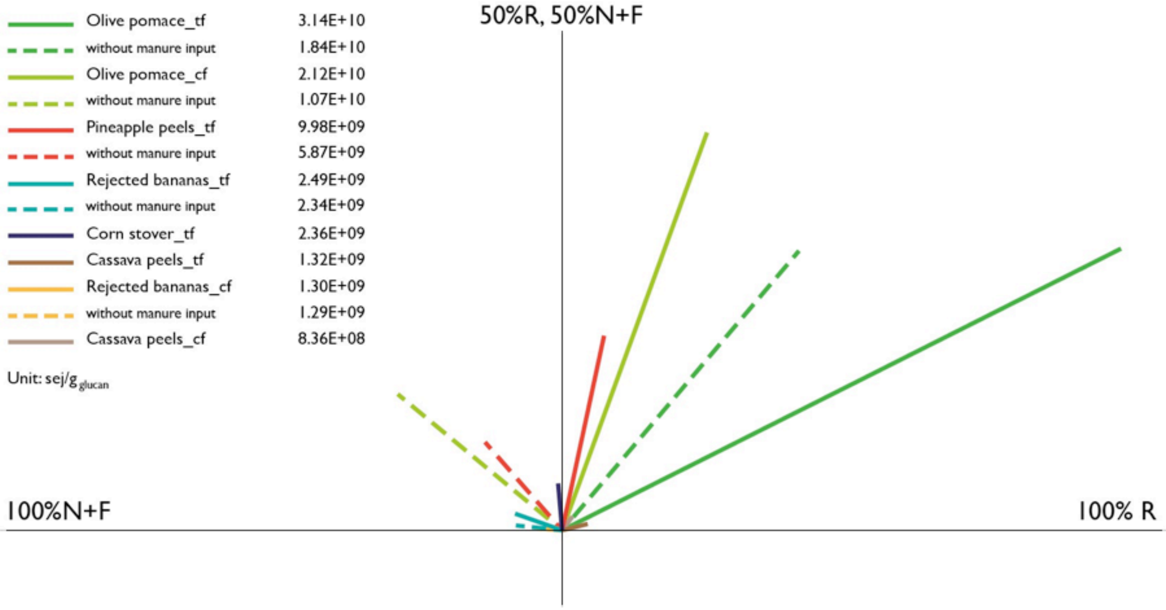


Figure 13. Summary of UEVs (expressed in sej/g of glucan) calculated for the sugar-rich feedstocks on the basis of glucan content, and related percentage renewability. *Banana (rejected)-cf* have %R=3%.

With regard to sugar-rich feedstocks, UEVs based on glucan content suggest that *olive pomace* from the traditional system is less efficient in transforming the past and present solar energy needed for the production system into glucans. This is mainly due to the fact that it has the lowest glucan content of all the sugar-rich feedstock analyzed. On the contrary, the lowest UEVs, i.e. highest efficiencies, are reported for *cassava peels*, especially in the case of commercial cultivation; the high sugar content and low production intensity are responsible for this good result.

The theoretical yield of ethanol was estimated on the basis of feedstock glucan content. According to the theoretical glucan to glucose (1.11 g of glucose/g of glucan) and glucose to ethanol conversion factors (0.51 g of ethanol /g of glucose) (Liu et al., 2014) we estimated an ethanol yield of about 57%, dry weight basis (i.e. we considered the glucan content of dried biomass). For example, from the amount of *cassava peels* left over from the traditional production system (6.2 t) it would be possible to obtain 1.76 t of ethanol.

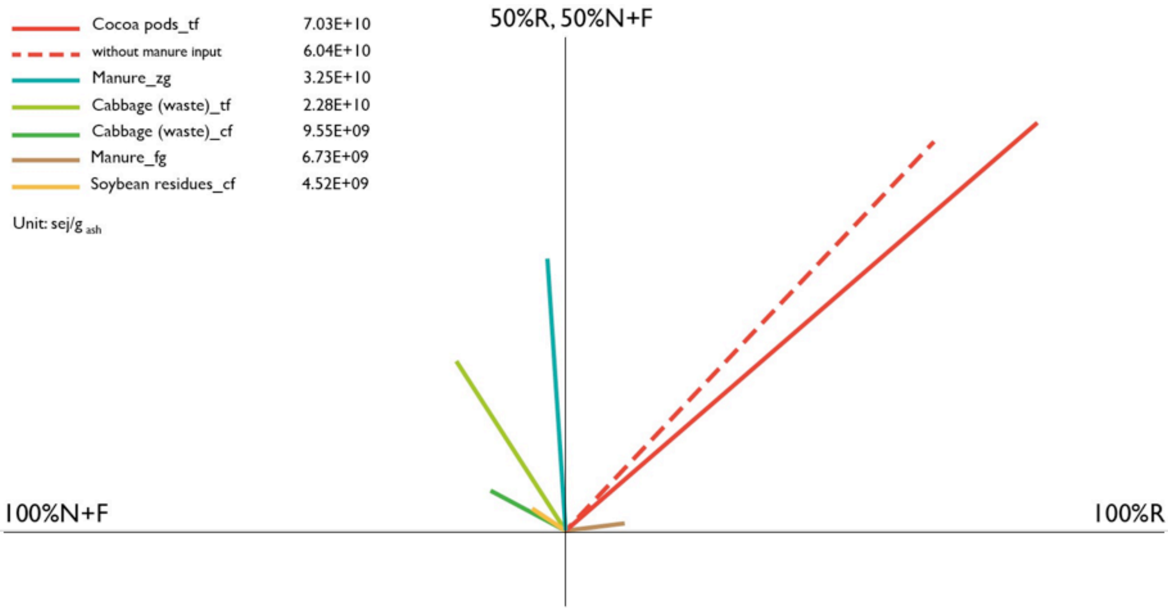


Figure 14. Summary of UEVs calculated for nutrient-rich feedstocks on the basis of ash content, and related percentage renewability.

Among the nutrient-rich feedstocks, the lowest UEVs were obtained for *soybean residues* and *cattle manure* from the free-grazing system. Especially in the case of manure, the high ash content with respect to the other feedstocks and the low-intensity farm inputs presumably influenced the outcome. Instead soybean residues showed relatively good efficiency but low renewability of inputs. The worst efficiency was obtained for *cocoa pods*. This is due to their high specific emergy as a feedstock and their low ash content, despite good renewability.

8. Biorefinery systems based on biowaste: a comparative LCA

According to the biorefinery concept evaluated in the present study, the production phase of biowaste and bioresidues mainly consists of agricultural production and food processing industry. Starting from these sources of biomass feedstocks, the biorefinery systems have to be implemented by developing production plants capable to convert biodegradable fraction of such inputs into useful energy carriers and value-added products, by means of sustainable biotechnological processes. Currently the sustainability assessment by means of LCA of biorefineries based on evaluated sugar and nutrient rich feedstocks can be carried out just partially, because of the lack of available data. The present work has been done in the context of an international scientific project, involving many other partners. Such evaluation necessarily relies on the results produced by the others analysts by providing the needed data for the implementation of a complete sustainability assessment. As the other scientific partners have not published their results yet, it is not possible to use such information to perform a LCA of biofuel production plants. In the meanwhile this evaluation has been performed according to data found in literature, as a preliminary analysis to be accomplished in a complete way as soon as primary data from the partners are available. In this regard the focus has been posed on the technology route characterized by the use of sugar-rich feedstocks for implementing a hypothetical bioethanol production based on sugar platform. In order to explore the variety of biowaste and bioresidues classified as sugar-rich, a comparison between biofuel productions based on lignocellulosic feedstock (i.e. corn stover) and starch rich feedstock (i.e. cassava peels) was performed.

8.1 LCA literature review

Several LCA-based studies of bioethanol productions have been recently carried out, with a particular focus on systems that produce lignocellulosic ethanol, in the light of their potential for mitigating climate change. As argued by Borrion et al. (2012), most of them investigated issues related to climate change potential and energy consumption, providing results that can vary significantly form one study to another. This is especially due to the complexity of such systems that makes LCA studies strongly dependent on multiple factors such as the definition of system boundaries, functional unit and most of all the allocation approach that is adopted. Morales et al. (2015) confirmed the difficulty to compare results from different life cycle assessments of lignocellulosic bioethanol, in the light of different methodological approaches used by analysts. Nevertheless they observed that several studies showed lower impacts for several categories (e.g. GHG emissions and ozone layer depletion) and positive energy balance with respect to conventional fuels (i.e. gasoline) and first generation bioethanol. According to Singh et al. (2010) LCA approach is fundamental for a proper implementation of biofuel production strategies, as it is able to estimate potential environmental impacts on both regional and global scale. They highlighted the importance of facing challenges such as system boundary, functional unit and allocation approach in order to carry out LCA of bioethanol productions in a proper way. There are also some technical aspects that can influence the variety of outcomes obtained by performing LCA of bioenergy systems (Cherubini et al., 2009). Among the others, the combination of feedstocks that feed the production, the implemented technological routes and the type of produced biofuel play a pivotal role in determining energy balance and GHG emissions of bioethanol productions, from a life cycle perspective. According to Cherubini and Ulgiati (2010), biorefinery systems based on lignocellulosic residues (i.e. corn stover and wheat straw) are able to face different challenges at the same time, by mitigating negative environmental effects related to the exploitation of non renewable energy sources and providing a proper management of bioresidues. As argued by von Blottnitz and Curran (2007), many studies highlight that even if bioethanol productions contribute positively in reducing resources use and mitigating global warming effects, some criticalities emerged with regard to impact categories such as acidification, human toxicity and ecological toxicity.

Some others LCA studies have been carried out with regard to bioethanol productions based on alternative feedstocks such as cassava, especially in China (Leng et al., 2008). This feedstock was evaluated by Ou et al. (2009) as one of the potential source for implementing biofuel production pathways, by comparing it with other five feedstocks from a LCA perspective, with regard to energy consumption and GHG emissions issues. Cassava as biomass source for bioethanol production was found to be one of the feedstocks that give a fundamental contribution to the energy-saving purpose. Yu and Tao (2009) explored the feasibility of producing cassava-based biofuel in a Chinese province and their results confirmed the energy-saving effect generated by production of this biofuels that was found to have a positive net energy value. In contrast Papong and Malakul (2010) performing a LCA of bioethanol produced from cassava feedstock in Thailand found a negative net energy value that show a net energy loss, while with regard to the potential environmental impacts they found that the transformation phase is the main responsible due to the use of coal as main energy source to make the plant work. Another case study that regarded Thailand was investigated by Silalertruksa and Gheewala (2009), with a LCA carried out on some existing bioethanol plants. They obtained different results according to various factors (e.g. cultivation practices, transportation means, operation practices, technology of ethanol conversion, etc.).

With regard to corn-based bioethanol Pieragostini et al. (2014) performed a LCA on a production chain in Argentina, finding that the cultivation phase play a pivotal role in term of environmental impacts. In this regard Xue et al. (2014) evaluated different agriculture management practices to improve the environmental performance of corn-based bioethanol. LCA in this case highlighted that no till against conventional tillage can contribute to the improvement of environmental performance of such bioethanol production for both global warming and eutrophication potentials. Recently, Zhao et al. (2016) investigated the technology advancement of bioethanol conversion based on corn stover in the Chinese context, by means of LCA approach. The study showed positive results if compared to convectional fuels, especially with regard to reduction of GHG emissions and energy saving. Bioethanol produced from the same feedstock and some other biomass resources was evaluated by Muñoz et al. (2014). According to the obtained results they stated that such fuel can be considered a preferable option especially for what concern GHG emissions.

Several studies carried out by using LCA methodology for assessing bioethanol productions, stressed the relevance of allocation methods adopted to perform the analysis. Murphy and Kendall (2013) argued that the allocation method has to be selected according to the aim of the study. By exploring the bioethanol production based on corn feedstock (i.e. grain and stover) they found that the economic allocation approach attribute the lowest impact to corn stover (i.e. bioresidues). By evaluating a corn stover-based ethanol production, Luo et al. (2009) highlighted that the allocation method is crucial for LCA results that vary also depending on the considered impact categories. For example, this case study stressed that bioethanol option defined an increase of GWP with respect to gasoline by adopting the economic allocation, while the opposite is obtained if mass/energy allocation is used. Kim and Dale (2002) evaluated an ethanol production based on corn feedstock to explore the allocation procedure. They argued that the adoption of systems expansion approach represent a valuable option to eliminate the allocation procedure in LCA studies of such biofuel productions.

8.2 Life Cycle Assessment (method)

LCA is defined as "the compilation and the evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). Thus, LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle – from the extraction of the resources, through the production of material, product parts and product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal (in effect, therefore, 'from the cradle to the grave') (Guinée et al., 2001).

The environmental burden covers all types of impact upon the environment, including extraction of different types of resources, emission of hazardous substances and different type of land use (Guinée et al., 2001). Through this approach it is possible to identify processes that generate the main environmental burdens in order to hypothesize scenarios to improve or mitigate the produced impacts.

As shown in Figure 15, in a LCA there are four main phases (ISO, 2006):

1. Goal definition and scoping: it is the preliminary phase in which aims, field of application, functional unit (FU), boundaries of the system under study and assumptions are defined. The functional unit describes the primary function(s) fulfilled by a product system, and indicates how much of this function is to be considered in the intended LCA study. It will be used as a basis for selecting one or more alternative product systems that might provide these function(s) (Guinée et al., 2001).
2. Life Cycle Inventory, LCI: in this stage the life cycle of the process or activity is studied. The main goal of the LCI is to understand how the system works and which material and energy flows are involved to support the process. It is then possible to draw up an inventory of all input and output flows that characterized the system through the collection of primary data.
3. Life Cycle Impact Assessment, LCIA: starting from results of the LCI, the environmental potential impacts are evaluated. In this phase data about the consumption of resources and the produced emissions by the system under study are associated to specific impact categories. The main steps of a LCIA are: a) classification/characterization; b) normalization; c) weighting.
4. Life cycle interpretation: this is the final stage of a LCA. It is characterized by the proposals to reduce the environmental impacts produced by processes and

activities under study. It is an iterative procedure of revision about analyzed system.

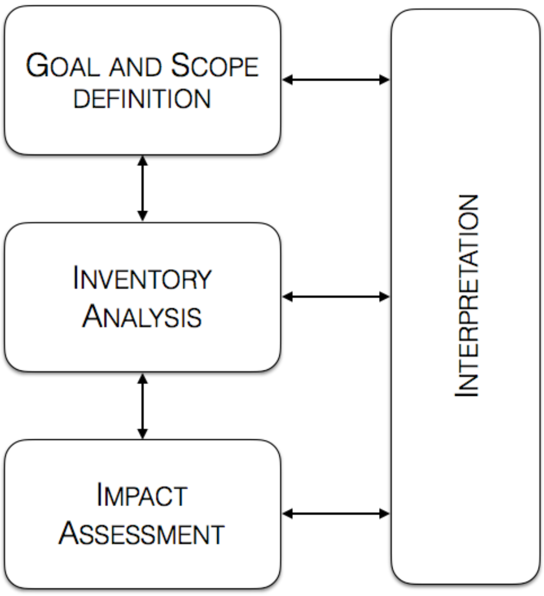


Figure 15. The LCA framework (ISO, 2006)

8.3 LCA case study

There are some key methodological issues to deal with when LCA studies of biorefinery systems are performed. One of this is the allocation of potential impacts related to the production of biomass feedstocks. As shown in the present work, agricultural productions and food industry represent important sources of biowaste and bioresidues to be exploited as potential feedstocks for feeding biorefineries. According to Ahlgren et al. (2015) zero environmental burdens should be allocated to the production of biowaste feedstocks, as they are recycled material and the related potential impacts should not be included in the life cycle inventory of biorefinery systems. In the light of such considerations, the present LCA of hypothetical biofuel productions based on biowaste feedstocks was focused on system boundaries that consider production chains from the post cultivation phase, with the transportation of feedstock, to the biorefinery plant producing bioethanol as main output (see Figure 16).

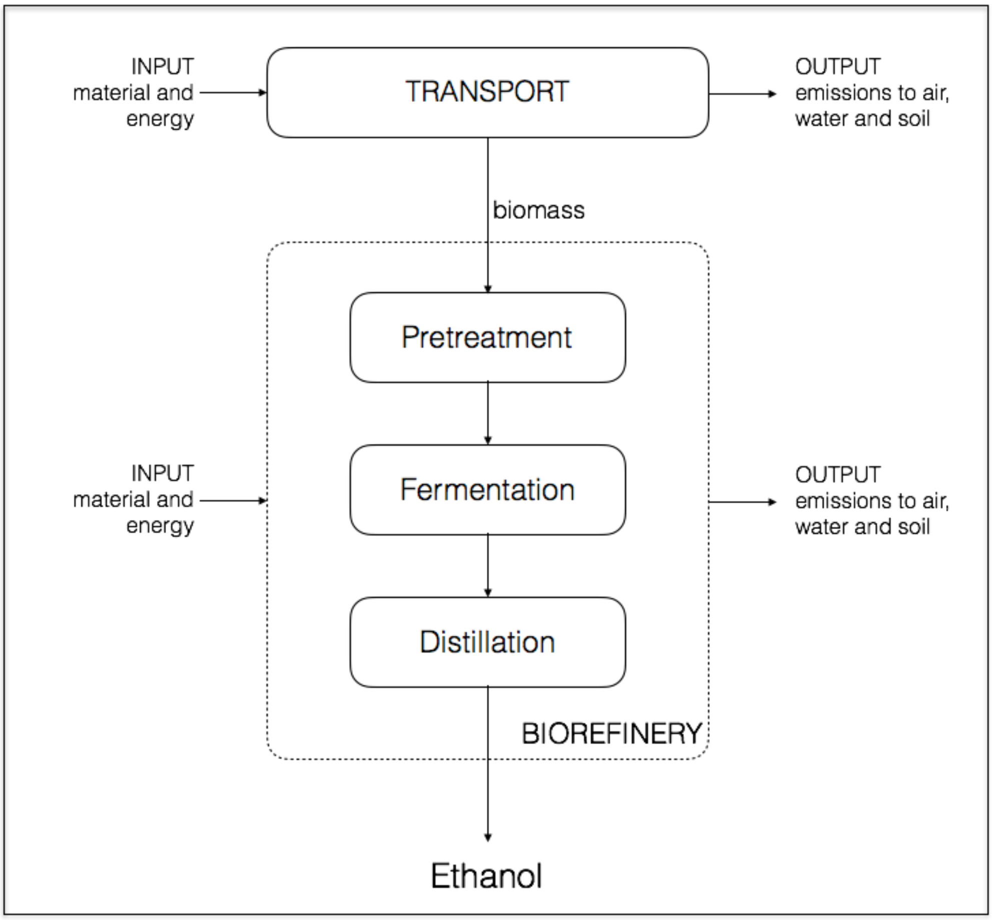


Figure 16. Life cycle flowchart of biofuel productions based on sugar-rich feedstocks.

The evaluated bioethanol productions referred to two case studies about biorefinery systems based on feedstocks such as corn stover (Jensen and Thyo, 2007) and cassava peels (Le et al., 2013). Both inventories were built up according to data collected from reference studies, referring to the same output of production plants, i.e. bioethanol. In this regard a common functional unit (FU) was identified in order to perform a LCA that makes it possible to compare results obtained form the two different case studies. The FU was 1 ton of bioethanol obtained processing corn stover or cassava peels and the inventories of bioethanol productions were built up by accounting for data that referred to material and energy inputs necessary to produce this quantity of biofuel.

8.4 The methodology for assessing impacts and the software

The characterization method used in this study was the CML-IA, the updated version of CML 2 Baseline Method 2000 (Guinée et al., 2001) that was developed by the Institute of Environmental Sciences of Leiden University (Holland). This method has a midpoint approach (i.e. problem oriented approach), according to which the indicators of impact categories are classified in an intermediate position between the results of LCI and the level defined as endpoint that is characterized by the quantification of potential effects produced by impacts (PRe', 2016). Below are listed the selected impact categories for this study, among the eleven given by the methodology (PRe', 2016):

- Acidification Potential (AP): it takes into account the produced impacts on soil, air, water, organisms and ecosystems. The unit is the kg SO_2 equivalents per kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale. This impact category is based on the model developed by (Huijbregts et al., 2003)
- Eutrophication Potential (EP): it includes all impacts due to excessive levels of macro- nutrients in the environment caused by emissions of nutrients to air, water and soil. Also known as Nutrification potential (NP), it is based on the stoichiometric procedure of Heijungs (Heijungs et al., 1992), and expressed as kg PO_4^{3-} equivalents per kg emission. The time span is eternity, and the geographical scale varies between local and continental scale.
- Global Warming Potential (GWP100): this impact category has been upgraded according to the IPCC method of 2013 (IPCC, 2013). It is expressed in kg CO_2 equivalents per kg emission, the time span is 100 years and the geographical scale is the global one.

In this study the LCA was performed by means of the software SimaPro 8 (Goedkoop et al., 2016) that was developed by the Dutch enterprise PRé Consultant. It is a flexible tool that is used all over the world and thanks to which it is possible to analyze results in an interactive way. It includes several databases with thousands of processes and materials.

8.5 Inventory analysis

As described in Figure 16 both bioethanol production chains included a first phase that consists of the transportation of feedstock from the biowaste production site (i.e. cultivation field, food processing plant) to the biorefinery plant and a second step represented by the conversion process of biomass into final product (i.e. bioethanol). Table 10 summarizes input data that support such production system with regard to the exploitation of lignocellulosic feedstock (i.e. corn stover). All input data referred to the main product of biorefinery system, namely 1 ton of bioethanol, and they were collected from the case study analyzed by Jensen and Thyo (2007). This study provided also direct emissions to air and water that have been included in the elaborated inventory. The LCI was developed according to the secondary data available in the Ecoinvent v3 database (Ecoinvent, 2014).

Table 10. Life cycle inventory profile for the production of 1 t of bioethanol based on corn stover feedstock.

CORN STOVER PROCESSING		Item	Unit	Quantity	Primary data	Secondary data
Transport	to plant		kg km	212766	Assumption	
Input	Feedstock	CORN STOVER	kg	4255	This study	
	Enzymes	Enzymes (cellulase)	kg	4.7	Jensen & Thyo, 2007	-
	Additives	H_2SO_4 (sulphuric acid)	kg	31.1	Jensen & Thyo, 2007	Ecoinvent database, 2014
		H_3PO_4 (phosphorous acid)	kg	7.2	Jensen & Thyo, 2007	Ecoinvent database, 2014
		NaOH (sodium hydroxide)	kg	4.7	Jensen & Thyo, 2007	Ecoinvent database, 2014
		NH_3OH (ammonia water)	kg	14.9	Jensen & Thyo, 2007	Ecoinvent database, 2014
		Urea	kg	7.2	Jensen & Thyo, 2007	Ecoinvent database, 2014
		$CaCl_2$ (calcium cloride)	kg	1.5	Jensen & Thyo, 2007	Ecoinvent database, 2014
	Water	Water	kg	34.0	Jensen & Thyo, 2007	Ecoinvent database, 2014
	Energy	Electricity	MWh	0.766	Jensen & Thyo, 2007	Ecoinvent database, 2014
		Steam	MWh	4.85	Jensen & Thyo, 2007	Ecoinvent database, 2014
		Cooling	MWh	4.766	Jensen & Thyo, 2007	Ecoinvent database, 2014
	Fuel	Propane	kWh	25.06	Jensen & Thyo, 2007	Ecoinvent database, 2014
	Plant	Concrete	kg	20.18	Patrizi et al. 2013	Ecoinvent database, 2014
		Reinforcing steel	kg	11.35	Patrizi et al. 2013	Ecoinvent database, 2014
Output	Product	Ethanol	kg	1000		
	Air emissions	CO_2	kg	961.70	Jensen & Thyo, 2007	
		TOC	kg	0.04	Jensen & Thyo, 2007	
		CO	kg	0.09	Jensen & Thyo, 2007	
		NOx	kg	0.09	Jensen & Thyo, 2007	
	Wastewater	COD	kg	36.77	Jensen & Thyo, 2007	
		BOD5	kg	7.36	Jensen & Thyo, 2007	
		N-total	kg	2.47	Jensen & Thyo, 2007	
		P-total	kg	0.09	Jensen & Thyo, 2007	

Also with regard to the evaluation of biorefinery fed by cassava peels (i.e. starch-rich feedstock), the system boundaries included the transportation of biomass from the food processing plant, where feedstock is produced, to the biorefinery plant and the conversion process itself into final product (see Table 11). For the sake of consistency also for this case study the modeled data referred to 1 ton of bioethanol produced from the selected feedstock and they were collected from the LCA study performed by

Le et al. (2013). Unlike the inventory elaborated for biorefinery plant fed by corn stover, this one did not included direct emissions to air and water, as they were not available. LCI of bioethanol based on cassava peels was developed by using the secondary data provided by the Ecoinvent v3 database (Ecoinvent, 2014) as well.

For both production chains under study the transportation of feedstock from the biomass production site to the transformation plant was assumed to cover a distance of 50 km (Gidamis et al., 2015) by using a truck (7.5 t).

Table 11. Life cycle inventory profile for the production of 1 t of bioethanol based on cassava peels feedstock.

CASSAVA PEELS PROCESSING		Item	Unit	Quantity	Primary data	Secondary data
Transport	to plant		kg km	176200	Assumption	
Input	Feedstock	CASSAVA PEELS	kg	3524	This study	
	Enzymes	Enzymes	kg	1.27	Le et al. 2013	-
	Additives	NaOH	kg	3.80	Le et al. 2013	Ecoinvent database, 2014
		Urea	kg	3.80	Le et al. 2013	Ecoinvent database, 2014
		DAP	kg	3.80	Le et al. 2013	Ecoinvent database, 2014
	Energy	Electricity	kWh	355.70	Le et al. 2013	Ecoinvent database, 2014
	Fuel	Coal	kg	759.49	Le et al. 2013	Ecoinvent database, 2014
	Plant	Concrete	kg	20.18	Patrizi et al. 2013	Ecoinvent database, 2014
		Reinforcing steel	kg	11.35	Patrizi et al. 2013	Ecoinvent database, 2014
Output	Product	Ethanol	kg	1000		

8.6 Impacts assessment

With the support of software SimaPro the LCA of bioethanol production based on corn stover was performed, producing results that are summarized in Table 12. For both GWP100 and AP impact categories most of the environmental burdens were due to used energy (i.e. electricity and steam), with a share of 65% and 90%, respectively. Direct emissions to air and water represented another considerable impact with regard to GWP100 (30%), while they were the mains responsible for results obtained for EP indicator, with a contribution of 43% of the total impacts, followed by potential burdens produced by material construction of plant (29%) and energy (23%).

Table 12. Environmental impact indicators for biorefinery system based on corn stover feedstock.

Impact category	Unit	Total	Transport	Additives	Plant	Energy	Fuel	Emissions
Global warming (GWP100)	kg CO_2 eq	3170.56	42.55	56.85	39.38	2063.43	6.66	961.70
Acidification (AP)	kg SO_2 eq	10.28	0.18	0.67	0.15	9.22	0.02	0.05
Eutrophication (EP)	kg PO_4^{3-} eq	4.99	0.13	0.16	1.42	1.13	0.02	2.13

With regard to bioethanol production fed by cassava peels, the analysis produced results reported in Table 13. For all impact categories evaluated a paramount part of potential impacts has to be attributed to the use of coal as fuel for making plant work. For GWP100 it contributed with 72%, for AP we have a value of 54%, while for EP it was responsible for the 33% of total environmental burden. For the same category another fundamental input was the plant (i.e. construction material) with a percentage of 40%, while for GWP100 and AP another significant input was energy (i.e. electricity) that supported the process (19% and 28%, respectively).

Table 13. Environmental impact indicators for biorefinery system based on cassava peels feedstock.

Impact category	Unit	Total	Transport	Additives	Plant	Energy	Fuel
Global warming (GWP100)	kg CO_2 eq	1559.30	87.24	15.55	39.38	298.54	1118.59
Acidification (AP)	kg SO_2 eq	3.53	0.36	0.11	0.15	1.00	1.92
Eutrophication (EP)	kg PO_4^{3-} eq	3.57	0.32	0.05	1.42	0.60	1.18

In order to make a comparison between the evaluated biorefinery systems that was as consistent as possible, direct emissions accounted for bioethanol produced from corn stover have not been considered. As shown in Figure 17, with regard to the GWP100 the production system based on corn stover produces a potential environmental impact that is higher than the biorefinery fed by cassava peels. In this regard a pivotal role is played by energy input that is responsible for a quantity of emissions equal to 2063.43 kg CO_2 eq.

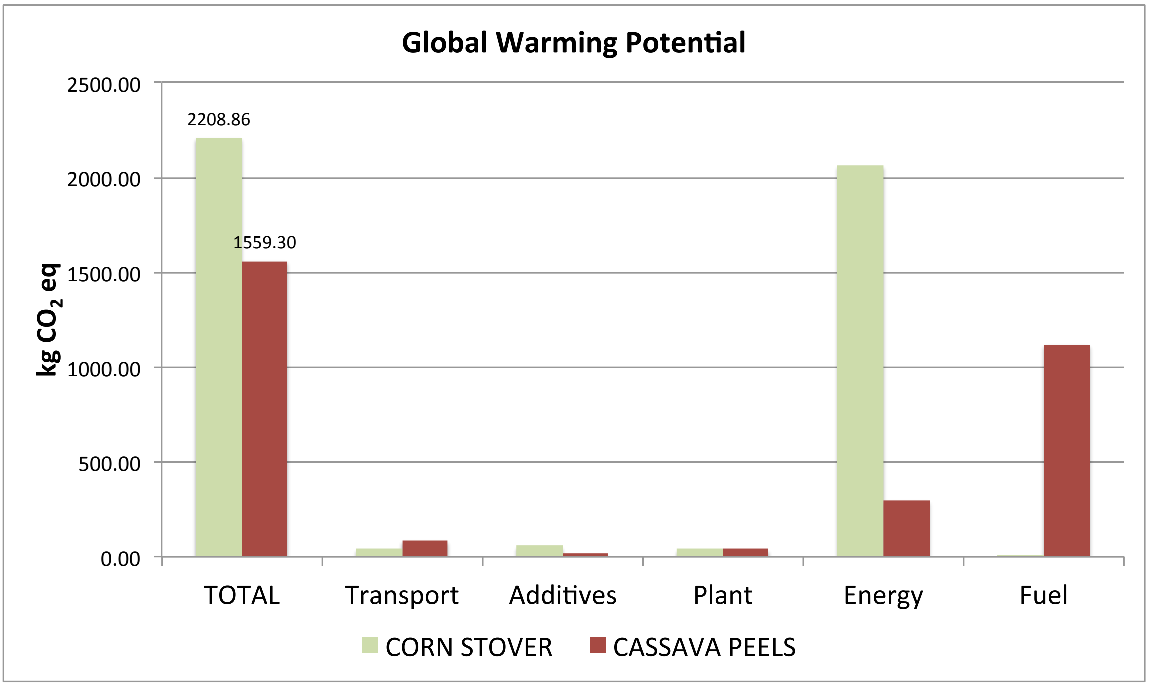


Figure 17. Results for the indicator GWP100, comparing bioethanol productions from corn stover (green) and cassava peels (red).

A similar trend can be observed with regard to AP category, as we have a higher level of impacts generated by lignocellulosic-based biorefinery against the starch-based one. As already stressed for the other impact category, also for AP a considerable weight of environmental burdens has to be attributed to the energy input.

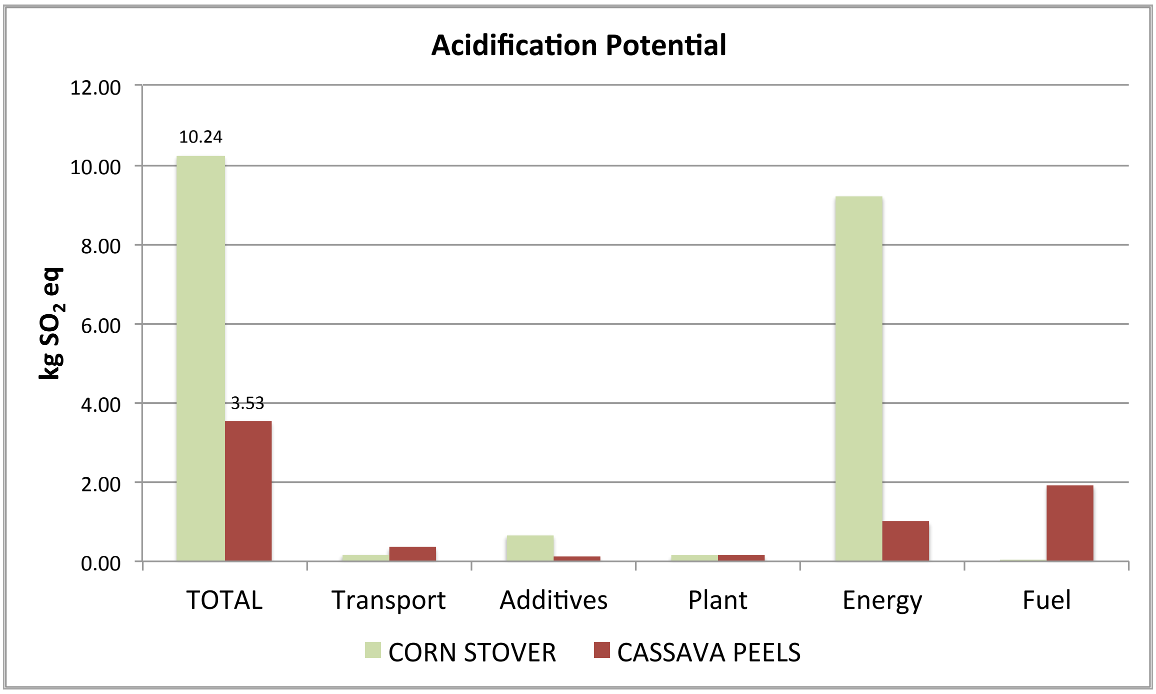


Figure 18. Results for the indicator Acidification potential, comparing bioethanol productions from corn stover (green) and cassava peels (red).

For what concerns EP category, the impact assessments produced different results with respect to the other two evaluated impact categories. In fact for EP category, biorefinery based on cassava peels produced higher impacts than the other fed by corn stover, even if the difference between total environmental burdens was not considerable (3.57 kg PO_4^{3-} and 2.86 kg PO_4^{3-}, respectively). In this case the highest impacts for both productions were attributed to the construction material of biorefinery plants (i.e. concrete and reinforcing steel).

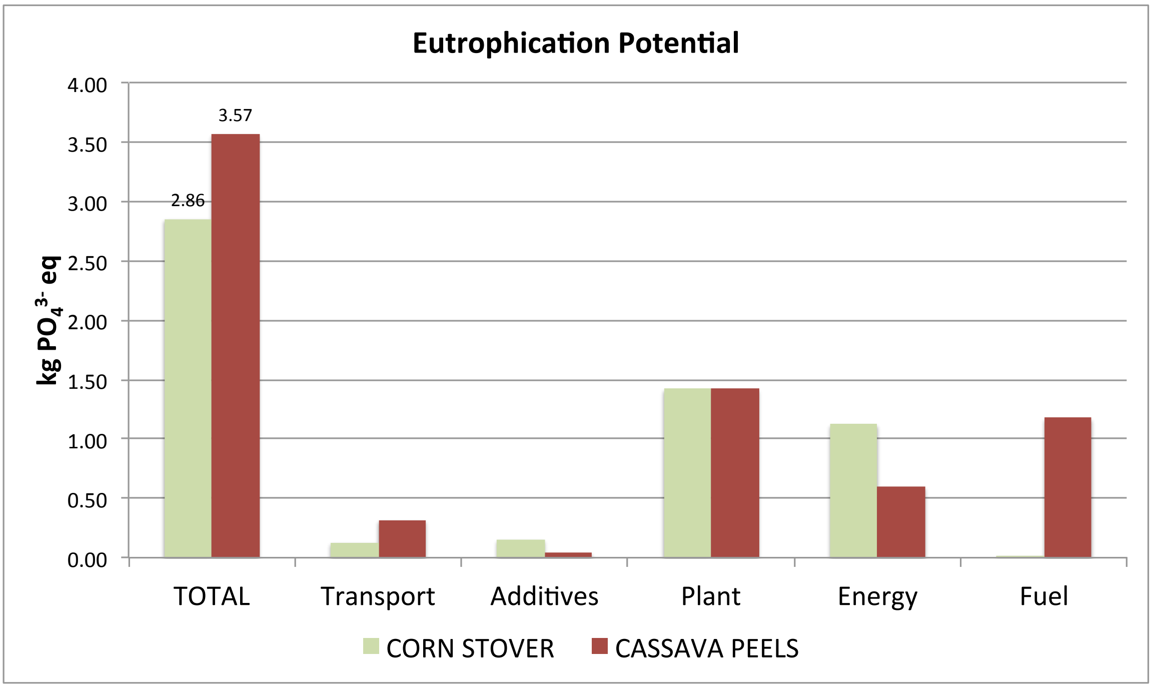


Figure 19. Results for the indicator Eutrophication potential, comparing bioethanol productions from corn stover (green) and cassava peels (red).

9. Synergies between industry and nature evaluated by means of emergy

Several efforts are developing methods to evaluate in a proper manner the fundamental role of ecological systems in sustaining humanity. Among the others, the first and best-known attempt was done by Costanza et al. (1997), who highlighted the relevance of the ecosystem services from a monetary standpoint, at a global scale. This approach has drawn attention to the value of the ecosystem services by using a language easy to understand (i.e. the economic one). The growing concern about issues such as the degradation of ecosystem services (MA, 2005), the operation of human being beyond the so-called “safe operating space” (Rockström et al., 2009; Steffen et al., 2015) and the overexploitation of natural resources that exceeds the natural regenerative capacity of the biosphere (Borucke et al., 2013), have made clear the necessity to include ecosystem services in sustainability assessments of human activities. This awareness has resulted in the development and implementation of tools capable of investigating and capturing the work done by Nature, both from economic and physical viewpoints. While the former is particularly useful to bring the debate around ecosystem services in the mainstream economic analyses, the latter is fundamental to provide clear information about exploitation of natural capital and services that it generates. In this regard, one of the most recently developed approaches that aims to physically quantify the sustainability level of systems is the Techno-Ecological Synergy (TES) framework (Bakshi et al., 2015). This framework is an effort toward addressing “the urgent need to consider the status of ecosystem services in engineering decisions”, by quantifying the demand as well as the supply of ecosystem services, in terms of emissions and resource use on one hand, and provided benefits on the other one. Specifically, the TES approach assesses and designs synergistic networks of technological and ecological systems at multiple spatial scales, from local to global. A unique feature of TES is that it quantifies for the demand imposed on ecosystem services by human activities, and considers the capacity of relevant ecosystems to supply these services. This information is used to define absolute sustainability metrics based on quantifying the difference between the supply and demand. A positive value of this metric means that the system is operating within the capacity of the ecosystem to supply the selected ecosystem good or service. This approach is different from most methods used for assessing and designing technological systems, since most existing methods only quantify the demand for ecosystem services and aim to reduce it by reducing environmental impact. A practical outcome is that TES encourages reduction of impact by modifying technologies, as done by existing methods, but also considers (and often supports) restoration and protection of ecosystems, unlike most existing methods.

The potential economic and environmental benefits of assessing and establishing techno-ecological synergies between industrial processes and surrounding ecosystems has been demonstrated by application to a biodiesel manufacturing site (Gopalakrishnan et al., 2016), but this work also highlights the practical challenges in extending this approach to the diverse array of ecosystem services. This previous work focuses on air quality regulation and water quality regulation ecosystem services, which are only two of the 23 services identified by the Millennium Ecosystem Assessment (MA, 2005). Even then, there are over a half dozen emissions that need to be compared. Some form of aggregation is needed if the promise of assessing and designing techno-ecological synergies is to be realized. In this regard emergy is an aggregation method that is broadly adopted to investigate the effort of ecological systems in providing resources to human activities. As argued by Bastianoni and Marchettini (1996) emergy is particularly useful to evaluate systems that combine natural and man-made resources, since it provides a common basis upon which they can be assessed (i.e. the solar equivalent energy).

The relationship between ecosystem services and emergy has been already explored by Coscieme et al. (2011), whose work stresses the contribution of emergy methodology in supporting the usual ecosystem services valuation (ESV) based on economic terms. From a similar perspective, Pulselli et al. (2011) evaluated the linkage between the emergy inputs to and the ecosystems services provided by ecological systems, by adopting a grey-black box scheme. According to this approach the state and the structure of the ecosystem are not considered and the focus is only on the role of inputs and outputs. Among the others, one of the main advantages of such a way to assess ecosystem services is the common physical basis provided by emergy for the evaluation of the services themselves. In this regard Campbell and Tilley (2014) have recently evaluated the ecosystem services of forests by means of environmental accounting with the aim to investigate the relation between biophysical and economic methods for assessing environment.

Application of the TES framework by adopting the emergy perspective can help better understand the interaction between the technological approach that is usually adopted in engineering design and the alternative one that includes implementation of ecological solutions. In this regard the purpose of the present research was to evaluate how the TES framework can benefit by using the emergy approach. Specifically, this study aimed to, i) compare technological and ecological solutions for achieving the same goal in a biorefinery context; ii) quantify both demand and supply of ecosystem services, as proposed by TES framework, in emergy terms to calculate aggregated metrics. The suggested approach was explored at the process scale, through an application to a biodiesel production plant located in the US (see Gopalakrishnan et al., 2016), where air quality regulation and carbon sequestration services provided by a forest and water purification service provided by a constructed wetland were respectively evaluated as alternative options to the technological ones that are usually adopted for treating air pollutants and wastewater. These alternatives aim to go beyond regulations toward net-zero or net-positive impact.

9.1 Techno-Ecological Synergy (TES) and emergy

The TES framework is based on the promise of developing mutually beneficial relationships between technological and ecological systems at multiple spatial scales. The linkage is analyzed by quantifying the demand of ecological services required by human activities and the capacity of nature to supply the same kind of services. The demand *D* of ecosystem services by technological systems can be determined by estimating the amount of natural resources that are consumed and the emissions that are produced. On the other hand, the supply *S* is evaluated on the basis of the beneficial effects that the provision of ecosystem services generates, by offering resources and absorbing emissions and waste flows. The comparison between the demand and the supply of ecosystem services makes it possible to define the metric *V* capable to estimate the level of sustainability that characterize the *i*-th system, at the *j*-th scale and for the *k*-th ecosystem service (Bakshi et al., 2015):

$$V_{i,j,k} = (S_{i,j,k} - D_{i,j,k})/D_{i,j,k} \tag{3}$$

$i = 1, \ldots, I; \quad j = 1, \ldots, J; \quad k = 1, \ldots, K$

Negative values of V describe an unsustainable condition of systems, while the positive ones are associated with a situation that can be defined to be absolutely sustainable. In other words by means of the TES approach it is possible to "account for whether a human activity is within the regenerative capacity of the biosphere at the spatial scales impacted by the activity" (Bakshi et al., 2015).

Ecosystem services are usually defined as benefits provided by the environment to humanity and emergy is a methodology that can support the evaluation of such kinds of benefit from a physical standpoint. According to the approach proposed by this study, emergy is adopted to improve the TES framework based on the comparison between demand and supply of ecosystem services and in doing that it makes it possible to evaluate different ecosystem services on the same common basis and thus to integrate emergy measure of demand and supply of the services themselves in order to assess different ecological solutions simultaneously.

Specifically air quality regulation and carbon sequestration services have been evaluated by using UEVs provided by Campbell and Tilley (2014), while estimation of demand and supply about water provision service have been done according to Ingwersen (2010) and Odum et al. (2000) (appendix gives insight about estimation of demand and supply based on emergy).

9.2 Biodiesel production plant

The emergy-based TES framework was tested by an application to a case study of a biodiesel manufacturing plant located in the US, close to Cincinnati (Ohio) (see Gopalakrishnan et al., 2016). The plant has a production capacity of 16.7 t of biodiesel per year, it relies on soybean feedstock and its main energy inputs (i.e. electricity and heat) are provided by a combined heat and power (CHP) unit that is fed by coal. The plant is responsible for the emissions of several air pollutants (i.e. CO_2, SO_2, NO_2, O_3 and PM10), especially due to the coal burned by CHP unit, and it releases about 1,500 m^3 per year of wastewater, generated by the several phases of the process requiring water as input. The operating time of the plant has been assumed to be 20 years.

In order to mitigate and reduce the environmental impacts caused by air pollutants and wastewater, two alternative scenarios were hypothesized (see Figure 20): the first case (*scenario A - technological option*) consisted of a usual techno-centric approach based on the use of additional equipment in order to treat air pollutants and wastewater. Specifically this scenario included the use of an absorption system of CO_2 based on monoethanol-amine (MEA), a flue gas desulfurization (FGD) unit to treat SO_2, a selective catalytic reduction (SCR) unit for NO_2 and baghouse filter system for treating PM10. For the treatment of wastewater the technological option was based on an anaerobic baffled reactor (ABR).

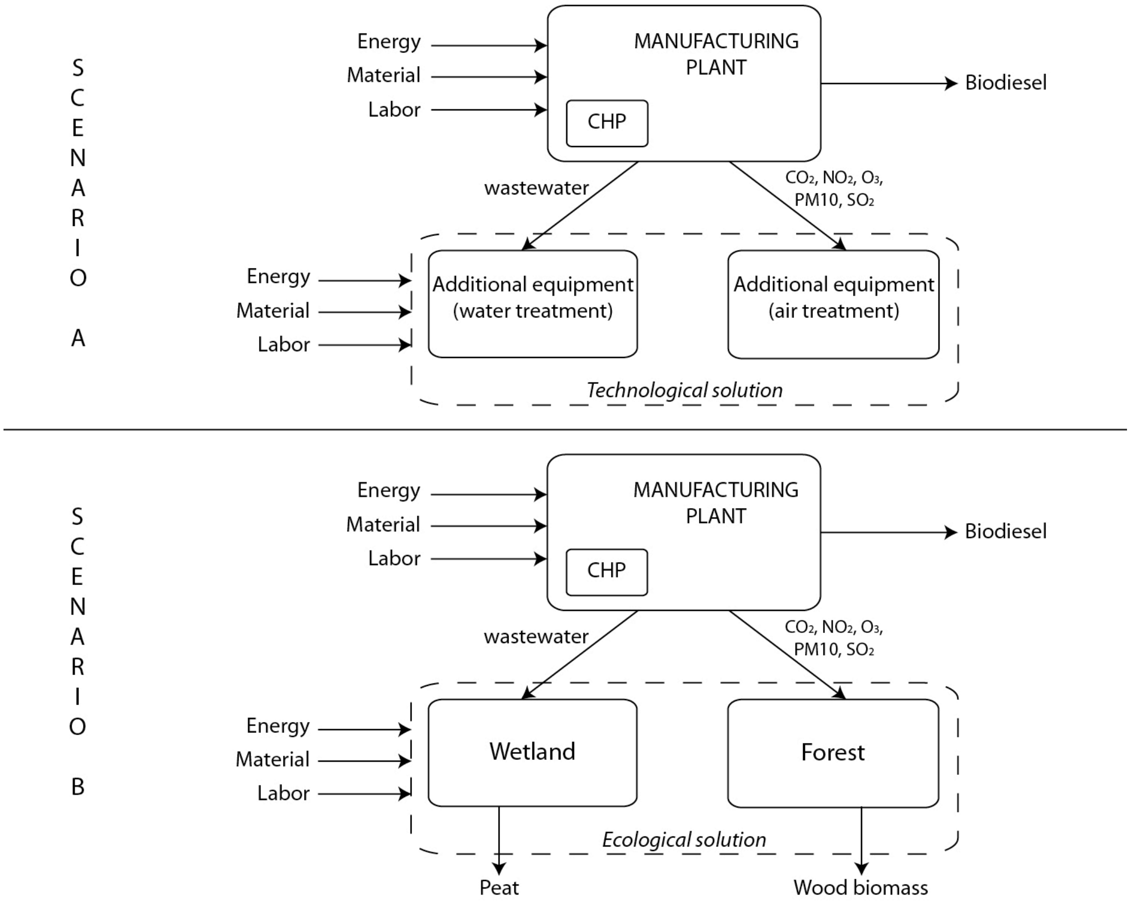


Figure 20. Flowcharts of the two alternative solutions evaluated in the present study. *Scenario A* consists of the adoption of techno-centric option to treat wastewater and air pollutants, while *Scenario B* considers integration of wetland and forest to the biodiesel plant for the same purpose.

The other evaluated case (*scenario B - ecological option*) was based on the integration of the manufacturing plant with ecological systems capable of treating air pollutants and wastewater, according to the techno-ecological synergy approach (Bakshi et al., 2015). Particularly, this study considered the establishment of a forest (10.5 hectares) for carbon sequestration and air pollutants absorption and a constructed wetland (0.5 hectare) for treating wastewater (see Figure 21). Both ecosystems were supposed to be developed close to the biodiesel plant, over available and underused land area. The forest was considered to include three native tree species: american elm (*Ulmusamericana*), white oak (*Quercus alba*) and eastern helmock (*Tsugacanadensis*). The wetland was considered to be a horizontal subsurface flow (SSF) one that receives an inflow of 4 m^3 of wastewater per day.

Emergy evaluation of biodiesel production plant (i.e. base case) was carried out to quantify past and present solar energy that is needed for biodiesel production. The following step of the study was to evaluate the emergy investment (Patrizi et al., 2015) that the technological option (i.e. scenario A) and the ecological one (i.e. scenario B) require in order to meet the goal of reducing air pollution emissions and treating wastewater. Both solutions were assessed and then compared with regard to the same plant output of 16.7 t of biodiesel per year, and to the same capacity of wastewater treatment and air pollutants absorption.

The second phase of the analysis was focused on quantifying and comparing the demand as well as the supply of ecosystem services from emergy perspective, in order to provide the TES sustainability metric *V* given in Equation (3) but expressed in emergy terms. Emissions of air pollutants and consumption of water resource by biodiesel plant represented the demand for ecosystem services that were considered in this study. Both of these demands were evaluated on annual basis as well as the supply of ecosystem services that stands for the capacity of ecosystems to provide carbon sequestration, air quality regulation and water provisioning. Specifically the annual supply of such natural services were analyzed according to four different timeframe scenarios: 10th, 15th, 20th and 50th year (Gopalakrishnan et al., 2016).

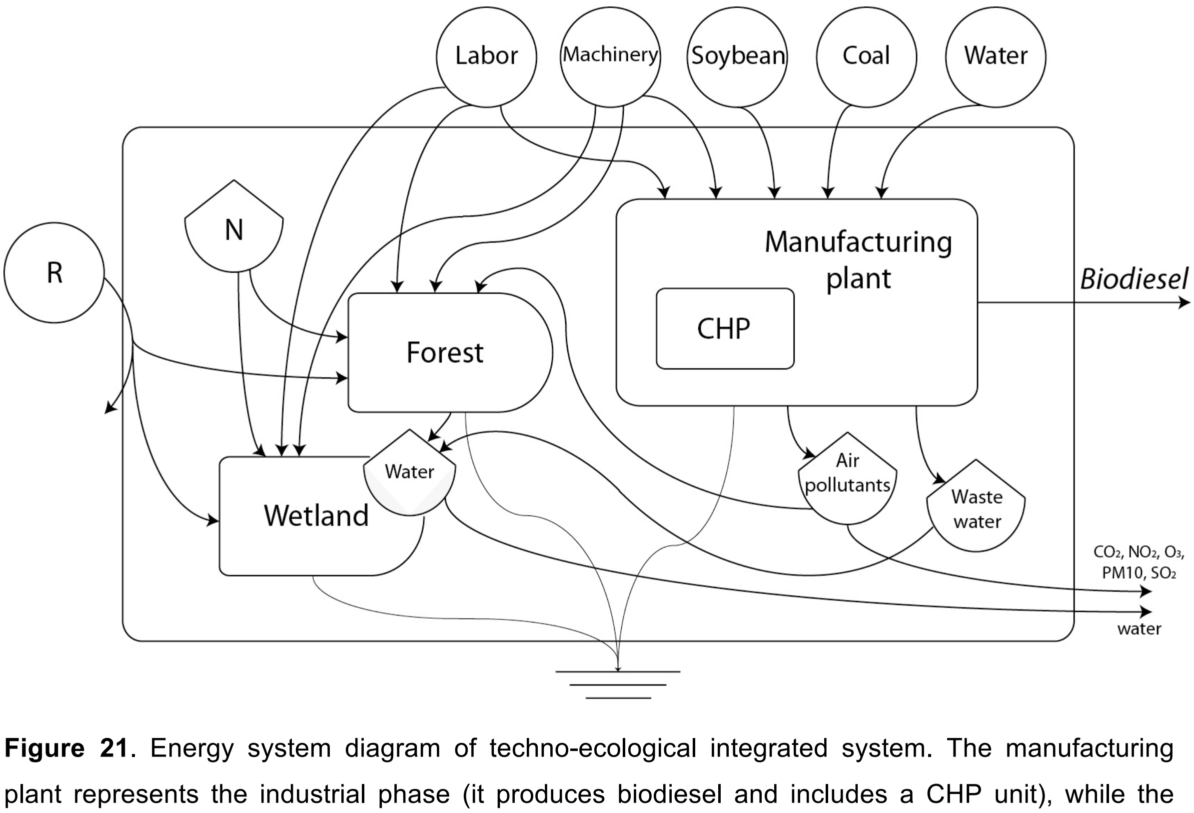


Figure 21. Energy system diagram of techno-ecological integrated system. The manufacturing plant represents the industrial phase (it produces biodiesel and includes a CHP unit), while the ecological part consists of wetland and forest ecosystems that received and respectively treat and absorb wastewater and air pollutants.

9.3 Emergy of techno-centric and ecological alternative solutions

Emergy evaluation of biodiesel production plant combined with technological and ecological options was performed and its outcomes are summarized in Table 14.

According to Pulselli et al. (2011), the relation between emergy input to and generated services from ecosystems was explored by means of a grey-black box approach. The actual state of ecosystems was not included in the evaluation, but they were assumed to be characterized by standard healthy condition, knowing that services provided by ecological systems for the same emergy input can vary according to the actual state of the ecosystems themselves (Coscieme et al., 2013; Pulselli et al., 2011).

Table 14. Emergy evaluation of the biodiesel production plant (i.e. base case), combined with the alternative technological and ecological options, respectively *scenario A* and *scenario B*. Inputs to biodiesel plants are common for both scenario A and B. Notes to this table can be consulted in the appendix.

#	Item	Details	Input, Unit y^{-1}	Unit	UEV, sej $unit^{-1}$	Reference UEV	Emergy, sej y^{-1}	Type
Biodiesel plant (base case)								
1	Cement		2.50E+08	g	1.78E+09	Pulselli et al., 2008	4.44E+17	F
2	Reinforcing steel		7.52E+06	g	3.38E+09	Cabezas et al., 2010	2.54E+16	F
3	Soybean		7.47E+10	g	5.93E+08	Saladini et al., 2016	4.43E+19	19% R; 81%F
4	Electricity	from CHP	1.96E+13	J	2.73E+05	This study	5.35E+18	F
5	Steam	from CHP	2.06E+10	g	3.13E+08	This study	6.44E+18	F
6	Process water	underground	2.11E+08	g	5.48E+05	Ingwersen, 2010	1.16E+14	F
7	Human labor		8.76E+03	h	8.01E+12	This study	7.02E+16	2.4% R; 97.6% F
Outputs								
8	Biodiesel		1.68E+10	g	3.06E+09		5.13E+19	
			6.57E+14	J	7.80E+04			
9	Air emissions	NO_2	1.69E+06	g				
		SO_2	9.29E+05	g				
		PM10	3.73E+06	g				
		CO_2	5.36E+08	g				
		O_3	3.05E+06	g				
10	Waste water		1.52E+03	m^3				
Scenario A (techno-centric option)								
Additional equipment-water treatment								
11	Cement	ABR unit	1.16E+05	g	1.78E+09	Pulselli et al., 2008	2.07E+14	F
12	Reinforcing steel	ABR unit	1.69E+03	g	3.38E+09	Cabezas et al., 2010	5.73E+12	F
13	Pump	steel	4.50E+03	g	3.38E+09	Cabezas et al., 2010	1.52E+13	F

Additional equipment-air treatment								
14	Electricity	from CHP	3.82E+11	J	2.73E+05	This study	1.04E+17	F
15	Process water	underground	9.91E+08	g	5.48E+05	Ingwersen, 2010	5.43E+14	F
16	Titanium dioxide	SCR unit	3.02E+06	g	1.33E+10	Zhang et al., 2011	4.02E+16	F
17	Ammonia	SCR unit	1.82E+02	g	2.22E+09	Brandt-Williams, 2002	4.03E+11	F
18	Lime	FDG unit	2.13E+06	g	9.81E+08	Cabezas et al., 2010	2.09E+15	F
19	Fabric filter	felt	6.98E+03	g	3.09E+09	Cabezas et al., 2010	2.16E+13	F
20	MEA	monoethanol-amine	2.74E+08	g	1.57E+09	Odum, 1996	4.31E+17	F
Outputs								
21	Biodiesel		1.68E+10	g	3.09E+09		5.18E+19	
			6.57E+14	J	7.88E+04			
22	Air emissions	NO_2	0.00E+00	g				
		SO_2	0.00E+00	g				
		PM10	0.00E+00	g				
		CO_2	4.37E+08	g				
		O_3	3.05E+06	g				
23	Treated water		1.52E+03	m^3	1.50E+11		2.28E+14*	
Scenario B (ecological option)								
Wetland								
24	Solar radiation		1.91E+13	J	1.00E+00	Odum, 1996	1.91E+13	R
25	Rainfall		4.83E+09	g	8.48E+04	Odum et al., 2000	4.09E+14	R
26	Wind		1.25E+11	J	1.43E+03	Odum et al., 2000	1.79E+14	R
27	Geothermal heat		5.62E+09	J	6.00E+03	Odum, 2000	3.37E+13	R
28	Topsoil loss		3.60E+08	J	7.26E+04	Campbell et al., 2005	2.61E+13	N
29	Liner	HDPE	1.09E+06	g	5.17E+09	Cabezas et al., 2010	5.64E+15	F
30	Gravel		5.01E+07	g	1.31E+09	Campbell et al., 2005	6.56E+16	F
31	Pipes	PVC	3.74E+04	g	5.77E+09	Pulselli et al., 2007	2.16E+14	F
32	Tractor	steel	8.81E+01	g	3.38E+09	Cabezas et al., 2010	2.98E+11	F
		tyre-rubber	9.79E+00	g	4.42E+09	Buranakarn, 1998	4.33E+10	F
33	Fuel	diesel	2.28E+03	g	2.83E+09	Bastianoni et al., 2009	6.46E+12	F
34	Labor		4.82E+01	h	8.01E+12	This study	3.86E+14	2.4% R; 97.6% F
Forest								
35	Solar radiation		4.50E+14	J	1.00E+00	Odum, 1996	4.50E+14	R
36	Rainfall		1.14E+11	g	8.48E+04	Odum et al., 2000	9.63E+15	R
37	Wind		2.95E+12	J	1.43E+03	Odum et al., 2000	4.22E+15	R
38	Geothermal heat		1.32E+11	J	6.00E+03	Odum, 2000	7.93E+14	R
39	Topsoil loss		8.47E+09	J	7.26E+04	Campbell et al., 2005	6.15E+14	N

40	Tractor	steel	2.07E+03	g	3.38E+09	Cabezas et al., 2010	7.01E+12	F
		tyre-rubber	2.30E+02	g	4.42E+09	Buranakarn, 1998	1.02E+12	F
41	Fuel	diesel	5.37E+04	g	2.83E+09	Bastianoni et al., 2009	1.52E+14	F
42	Labor		1.57E+02	h	8.01E+12	This study	1.26E+15	2.4% R; 97.6% F
Outputs								
43	Biodiesel		1.68E+10	g	3.06E+09		5.13E+19	
			6.57E+14	J	7.81E+04			
44	Air emissions	NO_2	0.00E+00	g				
		SO_2	0.00E+00	g				
		PM10	0.00E+00	g				
		CO_2	4.37E+08	g				
		O_3	0.00E+00	g				
45	Treated water	wetland	1.52E+03	m^3	4.77E+13		7.23E+16*	
46	Peat	wetland	3.74E+06	g	1.93E+10			
			3.38E+10	J	2.14E+06			
47	Wood biomass	forest	3.99E+07	g	3.12E+08		1.25E+16	

* Emergy flows values reported in the rows 23 and 45 have been obtained by summing up the related inputs necessary to implement the two alternative solutions (respectively rows 14-20 and 25, 27-34).

The most evident result from emergy evaluation is that for both solutions evaluated in the present study the amount of emergy that is required for their implementation is negligible, if compared to the emergy flow that supports the manufacturing plant (i.e. less than 2% for both). Having said that, according to the calculated emergy-based indicators we can see that the impact on the environment produced by scenarios A and B are practically equal (ELR= 5.16 vs. 5.12) as well as their capability to exploit local resources (EYR= 1.19 vs. 1.20). The emergy indicator about the percentage of renewable resources confirms that the performances of ecological and technological scenarios are very close (i.e. 16.4% and 16.2%, respectively).

A deeper analysis about how these different solutions actually perform can be carried out by splitting the different environmental issues and thus comparing emergy investment that is required to establish additional equipment (scenario A) and forest ecosystem (scenario B) to sequester CO_2 and removed air pollutants and on the other hand the emergy investment that is needed to implement anaerobic baffled reactor (scenario A) and wetland ecosystem (scenario B) for treating wastewater.

As shown in Figure 22, the technological approach for treating wastewater generated by biodiesel plant needs less emergy against the ecological option (2.28E+14 sej y^{-1} and 7.23E+16 sej y^{-1}, respectively; see Table 14, rows 23 and 45). In this regard the main input that contributes 91% of the total emergy investment in scenario B is gravel, needed to develop the SSF wetland. Arias and Brown (2009) confirm that gravel is one of the inputs that usually play a major role in the emergy value of constructed wetlands, even though at the end of life of the constructed wetland gravel can be available in exactly the same form and with the same mass as at the beginning. In this regard, the emergy flow that supports the implementation of wetland would decrease to 6.72E+15 sej y^{-1} if we do not consider the emergy input of gravel. About scenario A, the ABR unit is a solution characterized by low-input of material and energy flows, whose related emergy is mainly due to construction materials that are needed to build up the tank that collects wastewater.

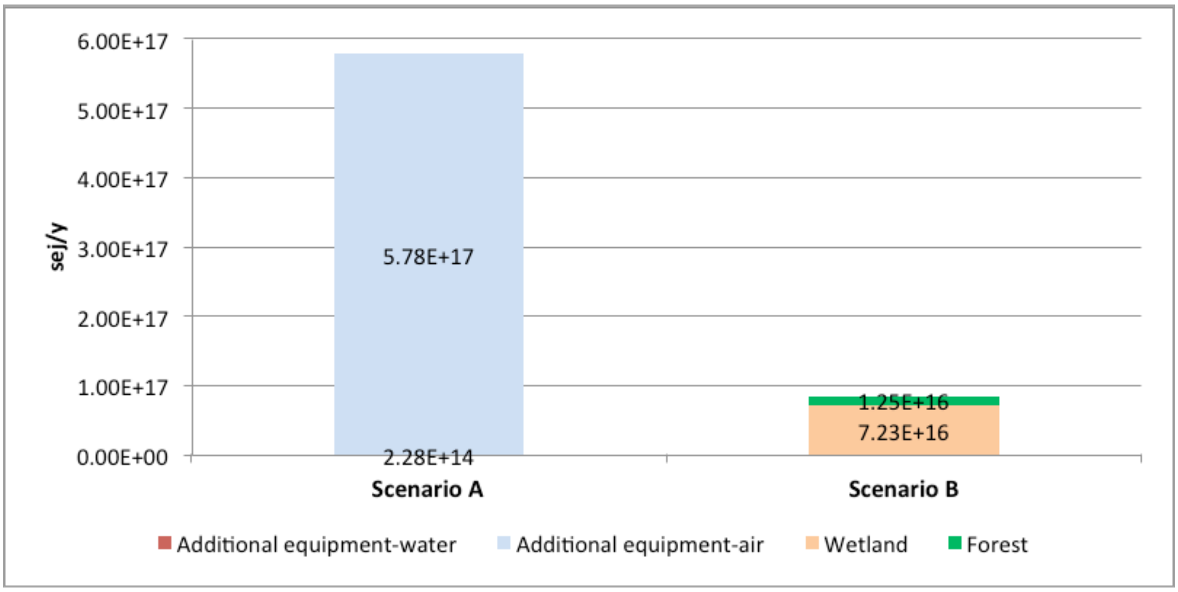


Figure 22. Emergy investments for scenarios A and B. The bars relative to technological and ecological options are split according to the different solutions provided to face the considered environmental issues (i.e. release of wastewater and air pollution emissions).

On the other hand the emergy flow that supports the implementation of additional equipment for capturing air pollutants, according to the scenario A, is largely higher than emergy related to the establishment and maintenance of forest for the same task (5.78E+17 sej y^{-1} and 1.25E+16 sej y^{-1}, respectively). Here the main contribution from the emergy viewpoint is driven by MEA input to the CO_2 absorption system, which accounts for almost 75% of the total emergy investment required by the implementation of additional equipment for treating air pollutants. Note that even without the CO_2 removal technology, the emergy needed to remove the other pollutants by conventional technological means is higher than what is needed by the forest.

The presented results are focused on the services provided by ecosystems, considered as alternative solution to the usual techno-centric approach adopted in the engineering design. Beyond these specific services that both approaches can provide, what ecosystems actually do is to provide multiple services to human beings and most of all they also generate material outputs that can be used as products. For instance, with regard to forest there is a production of wood biomass that according to this study has a UEV equal to 3.12E+08 sej g^{-1}, while constructed wetland produces peat whose calculated UEV is 7.96E+06 sej J^{-1}. This aspect clearly outlines the higher flexibility and versatility of ecosystems in providing services as well as products against analogous technological systems that are usually implemented in engineering design. Finally, it is worth outlining that whether such natural ecosystems already exist close to manufacturing plants, the development of techno-ecological synergy would be based on the work that Nature does for free. In other words the emergy investment that is usually needed to guarantee the treatment of wastewater and air pollutants by means of technological solution, would be exactly the emergy saved thanks to the support provided by ecosystems.

9.4 Comparison of ecosystem services demand and supply by means of emergy

The evaluated biodiesel plant requires an amount of water whose emergy flow is equal to 8.16E+14 sej y^{-1} (i.e. demand). Most of this resource is withdrawn from underground water reserve (6.59E+14 sej y^{-1}), while another fraction comes from the river near the plant (1.58E+14 sej y^{-1}). The potential supply of water within the boundaries of the production system was estimated according to two different types of sources: the rainfall that would be potentially collected by the roof of plant, and the underground water that is recharged by the action of forest trees that drive the water infiltration process, avoiding runoff phenomena. In this regard, within the considered temporal horizon of 20 years the estimated demand of water is not satisfied, since the potential annual supply at that time has an emergy flow equal to 2.79E+14 sej y^{-1}. Calculation of the TES sustainability (V) metric using Equation (3) based on these emergy flows gives a negative value (-0.66), that describes a situation of local unsustainability regarding the water provisioning service (details about calculation of the V metric can be found in the appendix).

This scenario can be improved if the wastewater that reaches the wetland is reused for feeding the plant, once it has been purified. In this way the demand for water from outside the system is dramatically reduced and the emergy flow drops to 1.97E+14 sej

y^{-1}, even though an emergy investment for supplementary equipment is required in order to recharge water upstream (i.e. 1.52E+13 sej y^{-1}) (see appendix).

With regard to the forest, the analysis was focused on carbon sequestration and air quality regulation services. The demand and supply of these services were both evaluated in emergy terms and then compared on annual basis to explore whether the forest unit is able to cover the demand generated by biodiesel plant, that is assumed to be constant, within the operating time of 20 years. For the air quality regulation service, the *V* metric calculated by accounting for all air pollutants except CO_2 is equal to 0.19, as the supply of such a kind of service is higher than the demand by 3.63E+16 sej y^{-1}. On the contrary, for the carbon sequestration service the demand generated by the manufacturing system exceeds the capacity of forest by 4.05E+16 sej y^{-1}, defining a condition of local unsustainability as consequence (V= -0.82) (see Tables A13 and A14 in the appendix). If the trees were 50 years old, then the metrics are 0.94 and -0.2 for air quality regulation and carbon sequestration, respectively.

As stressed by the present study, the fundamental contribution of emergy to the TES framework is represented by the common physical basis that it provides and upon which ecosystem services can be evaluated. For instance, according to the usual TES approach, the air quality regulation service is assessed for each single air pollutant by comparing demand and supply (Gopalakrishnan et al., 2016), but a comprehensive evaluation of the service itself is not provided. Since several pollutants can be evaluated on emergy terms and thus expressed in the same unit (i.e. sej) it is possible to evaluate both demand and supply for the air quality regulation service by aggregating the several emergy flows related to the respective pollutants. According to this approach, emergy makes it possible to accomplish other levels of aggregation of results for ecosystem services assessment. For instance we can define the overall measure about multiple services that can be provided by a single ecosystem (e.g. carbon sequestration and air quality regulation services with regard to forests). As highlighted by the present case study, the *V* metric with regard to ecosystem services provided by the forest is equal to -0.02 (see appendix); this means that the supply of the evaluated services provided by forest overshoots the demand required by the plant. This result is dramatically improved if we consider the scenario based on the supply of ecosystem services at the year 50^{th}, since the calculated *V* index raises to a value equal to 0.71. Calculation for both services together shows the dominance of the air quality regulation service over carbon sequestration due to the relative emissions in this example.

As shown in Figure 23, where the three ecosystem services evaluated in the present case study are presented, beside the comparison between demand and supply for a single ecosystem services on the basis of emergy, such an approach allows us to compare different ecosystem services for demand and supply as well. Moreover, it enables calculation of the overall emergy values for the total demand and supply as 2.41E+17 sej y^{-1} and 2.37E+17 sej y^{-1}, respectively.

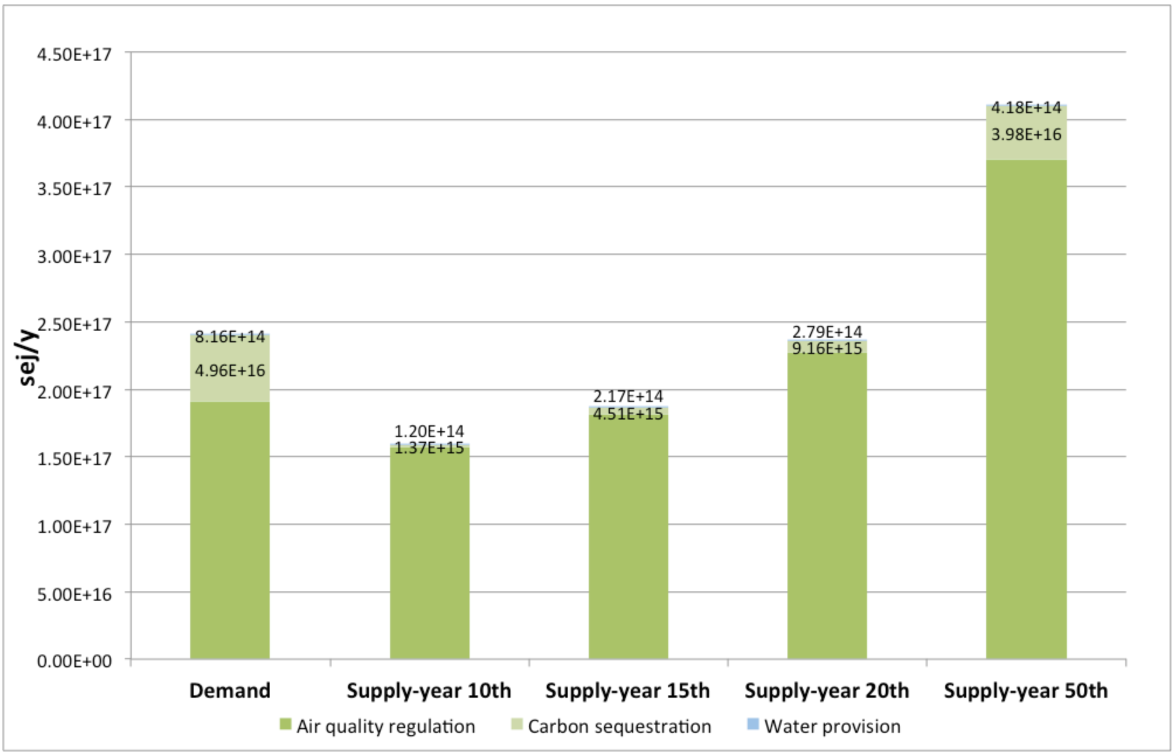


Figure 23. Comparison between demand and supply of water provision, carbon sequestration and air regulation services. For each ecosystem service considered in the study, it is reported the annual demand and the annual supply respectively. The supply is related to the all temporal horizons evaluated in this study.

Such an approach has positive implications for the design process as it provides a synthetic and comprehensive evaluation of the level of sustainability that characterizes a system where different ecological solutions are implemented with the aim to face different environmental issues. It is worth bearing in mind that the aggregated emergy measure of demand and supply and consequently the calculated *V* metric are helpful because they provide synthetic information that is easy to manage especially within the decision-making process, but it is important to evaluate also each ecosystem service separately in order to understand if the condition of sustainability can be actually claimed, according to the TES approach.

CONCLUSIONS

According to the first research question of this study, several methodological aspects about sustainability assessment of biorefinery by means of emergy have been clarified, providing a fundamental support to analysts that want to perform emergy evaluation of biofuels and to decision-makers as well.

The assessment of biofuel production in emergy terms can vary depending on whether the biofuel is first, second or third generation. For first-generation biofuels, production systems work as generic single-output processes, so emergy and the related indicators can be evaluated as usual.

For second-generation biofuels some crucial methodological aspects related to co-production have to be faced. It is important to bear in mind that total emergy of the integrated agro-industrial system gives us useful information about the whole system, not just on the sustainability of the biofuel. Although assigning all of the emergy to the biofuel is appropriate from a methodological viewpoint, it is incorrect to compare it to the emergy of biofuels produced from dedicated cultivations. In this regard Kamp and Østergård (2013) argued that an allocation-based approach could be adopted in emergy evaluation when co-production occurs, by providing a case study about bioenergy production. As explained in section 6.2.2 we believe that is fundamental to distinguish between the evaluation of whole systems and the assessment of outputs considered in isolation in order to avoid misunderstanding, as comparing single-output and multi-output productions can generate some mistakes. In the case of the integrated agro-industrial system, emergy investment is a useful parameter for evaluating how the system performs. These conclusions can also be extended to emergy-based indicators like EYR, ELR and %R that can be calculated either for the whole system or for the additional part that requires emergy investment.

For third-generation biofuels, besides the UEV, it is important to consider the emergy investment for implementing the biorefinery when the feedstock is collected in any case to avoid anoxic conditions of aquatic ecosystems, or the emergy saved in the case of cultivated algae, since they do work that humans would otherwise have to do.

With regard to the second research question, emergy evaluation of selected sugar- and nutrient-rich biowaste identified in five African countries explored the feasibility of using these feedstocks for the production of valuable products, such as biofuels and fertilizers.

Commercial farming systems were found to be more efficient in terms of emergy in exploiting resources. This is principally due to the higher production yields of commercial systems. This is not a general rule, since in some cases the opposite has been observed (see e.g. Brown and McClanahan, 1992; Castellini et al., 2006). Even if they show more effective emergy exploitation, commercial production systems usually have greater environmental impact because they rely on large quantities of materials and large, especially non-renewable, energy inputs.

In comparing the selected residues on the basis of their potential to produce biofuels and fertilizer, the UEVs of each feedstock were calculated according to glucan or ash content, depending on whether they were sugar- or nutrient-rich, respectively. Feedstocks like cassava peels and manure from grazing cattle proved to be the most promising residues from an emergy viewpoint: they had the lowest UEVs and the highest percentage renewability among all the residues considered in this study.

This part of the research provides useful information for interested stakeholders in identifying the most sustainable feedstocks to be processed in the biorefinery plants.

The graphic representation with polar coordinates showing UEV as segment length and renewability as slope can generally be used to compare different systems that produce outputs having the same characteristics and/or to plot the time course of a system that aims to improve its performance.

According to the user-side approach of LCA, biorefinery systems have been evaluated by using this methodology in order to identify the biofuel production that generate the less environmental burdens, responding to the third research question. Specifically the technology route based on sugar-rich feedstocks (i.e. sugar platform) has been analyzed, by comparing two systems fed by lignocellulosic feedstock (i.e. corn stover) and starch feedstock (i.e. cassava peels), respectively. The allocation approach for impacts related to biomass feedstocks is one of the crucial aspects to deal with when LCA of biorefinery is performed. In this regard the present study was carried out according to Ahlgren et al. (2015), who argued that zero environmental burdens should be allocated to the production of biowaste feedstocks, as they are recycled material and the related potential impacts should not be included in the life cycle inventory of biorefinery systems.

With regard to the impact categories GWP100 and Eutrophication Potential, the observed results showed that the production system fed by cassava peels for producing bioethanol generates lower potential environmental impacts against the biorefinery based on corn stover. Such a result can be explained by the higher energy requirement of lignocellulosic-based biorefineries with respect to the starch-based ones, as the pretreatment phase represent a crucial step in order to make cellulose and hemicellulose accessible for the subsequent enzymatic hydrolysis (Sims et al., 2008).

With regard to the last part of the present research, it is worth to note that the design of manufacturing plants, for what concerns reduction of pollutant emissions, can be developed either on the basis of usual techno-centric approach or by an approach that builds synergies between technological and ecological systems. These two alternative options have been evaluated by means of emergy methodology, with specific regard to the treatment of air pollution emissions and wastewater produced by a biodiesel production plant. For the evaluated case study, the estimated emergy investment that is required to implement the two alternative solutions was found to be negligible if compared to the total emergy input to the manufacturing plant. By analyzing the two ecological systems separately against the analogous technological options, the outcomes highlighted that additional equipment to treat air pollutants needs a higher emergy investment against the forest one, while the technological unit to treat wastewater required less emergy against to the wetland. Broadly speaking, this case study showed that emergy can provide a valuable support in designing processes, identifying the best alternative solutions to adopt in terms of natural resources consumption.

Furthermore the TES framework based on emergy has been tested by means of an application to an integrated techno-ecological system of biodiesel manufacturing that has been evaluated in the present work. While the results showed a good performance for what concerns the air quality regulation service (V= 0.19), we had a condition of local unsustainability with regard to the carbon sequestration (V= -0.82) and water provision services (V= -0.66). The last scenario can be improved by reusing the purified water from the wetland as input to the plant. Overall the emergy has been proved to be a method capable of providing a common basis for the evaluation of multiple ecosystem services on a physical basis. With regard to the forest, for instance, the aggregated value of the TES metric was calculated to be V= -0.02. The thermodynamic basis of emergy makes it able to perform well in the evaluation of integrated systems at the interface between biosphere and technological processes, especially because it provide a common physical basis on which emergy inputs to and ecosystem services provided by ecological systems can be evaluated. This study paves the way for future research on the integration of TES framework with emergy, especially with regard to the extension of such an approach to multiple spatial scales, as suggested by TES model, and to other ecosystem services besides the ones evaluated in the present study.

Appendix

Notes to Table 4:

<u>Olive cultivation</u>

1. Solar radiation = land area × average yearly insolation × (1-albedo)

   land area = 10000 m^2

   average yearly insolation = 6.82 GJ $m^{-2}y^{-1}$

   albedo = 1.90E-01

Solar radiation = 10000 m^2 × 6.82 GJ $m^{-2}y^{-1}$ × (1-1.90E-01) = 55.25 TJ $ha^{-1}y^{-1}$

2. Rain = land area × yearly precipitation × water density

   land area = 10000 m^2

   yearly precipitation = 0.39 m y^{-1}

   water density = 1.00 Mg m^{-3}

Rain = 10000 m^2 × 0.39 m y^{-1} × 1.00 Mg m^{-3} = 3.91 Gg $ha^{-1}y^{-1}$

3. Wind = land area × air density × drag coefficient on land × (geostrophic wind on land)^3 × secondsyear^{-1}

   land area = 10000 m^2

   air density = 1.30 kg m^{-3}

   drag coefficient on land = 0.002

   average annual wind velocity = 3.46 m s^{-1}

geostrophic wind on land = average annual wind velocity / 0.6 = 3.46 m s^{-1} / 0.6 = 5.77 m s^{-1}

Wind = 10000 m^2 × 1.30kg m^{-3} × 0.002 × (5.77 m $s^{-1})^3$ × 31.54Ms y^{-1} = 0.16 TJ $ha^{-1}y^{-1}$

4. Geothermal heat = land area × heat flow × secondsyear^{-1}

   land area = 10000 m^2

   heat flow = 75 mW m^{-2}

Geothermal heat = 10000 m^2 × 0.08 W m^{-2} × 31.54Ms y^{-1} = 23.63GJ $ha^{-1}y^{-1}$

5.Net topsoil loss = land area × erosion rate

   land area = 10000 m^2

   Area of Morocco = 447000000000 m^2

Morocco erosion rate = 13.00PJ y^{-1}

erosion rate = Morocco erosion rate / area of Morocco = 29.11 kJ $m^{-2}y^{-1}$

Net topsoil loss = 10000 m^2 × 29.11kJ $m^{-2}y^{-1}$ = 0.30 GJ $ha^{-1}y^{-1}$

6. Herbicides: sum of two different kinds of herbicide.

a) 1 kg ha^{-1} of Simazine;

b) 1.5 L ha^{-1} of Gramoxone (density = 1.25 g cm^{-3})

Herbicides = 2.88 kg ha^{-1}

7. Motorized sprayer: 2 units used; 12 kg per unit (60% HDPE and 40% steel); lifetime = 5 y

HDPE = ((12000 g × 2 × 0.6) / 5 y) / 5 ha = 576 g $ha^{-1}y^{-1}$

steel = ((12000 g × 2 × 0.4) / 5 y) / 5 ha = 384 g $ha^{-1}y^{-1}$

8. Fuel (gasoline): consumption = 1.5 L h^{-1} (gasoline density = 0.74 g mL^{-1}; operation time = 12 h ha^{-1})

Fuel = 1.5 L h^{-1} × 1000 × 0.74 g mL^{-1} × 12 × 2 = 26 64 kg $ha^{-1}y^{-1}$

9. Manure: 3 t ha^{-1} of sheep manure

Manure = 3.00 Mg $ha^{-1}y^{-1}$

10. Secateurs: 6 units used; 210 g per unit (80% steel and 20% HDPE); lifetime = 1 y

steel = (210 g × 6 × 0.8) / 1 y) / 5 ha = 201.60 g $ha^{-1}y^{-1}$

HDPE = (210 g × 6 × 0.2) / 1 y) / 5 ha = 504.00 g $ha^{-1}y^{-1}$

11. Canes: 8 units used; 500 g per unit (wood).

Canes = (8 × 500 g) / 5 ha = 800 g $ha^{-1}y^{-1}$

12. Bags: 80 units used; 5 g per unit (LDPE).

Bags = (80 × 5) / 5 ha = 80 g $ha^{-1}y^{-1}$

13. Human work (man-hours): 12 h ha^{-1} (pesticide application); 10 h ha^{-1} (fertilizer application); 32 h ha^{-1}(pruning); 24 h ha^{-1} (harvesting).

Human work = 12 h ha^{-1} + 10 h ha^{-1} + 32 h ha^{-1} + 240 h ha^{-1} = 294 h ha^{-1}

14. Olives (harvesting yields) = 700 kg $ha^{-1}y^{-1}$

Transport to olive press

15. Transport: distance of 20 km between cultivation and olive press

Transport = 14Mgkm $ha^{-1}y^{-1}$

Olive oil production

16. Water: 40 L per 100 kg of olives

Water = (40 L × (700 kg / 100 kg)) / 1000 L/m^3 = 0.28 m^3 $ha^{-1}y^{-1}$

17. Electricity: 126 kWh per 2500 kg of olives (energy for machinery)

Electricity = (126 kWh × 700 kg / 2500 kg) × 3600000 J kWh^{-1}= 127.00 MJ $ha^{-1}y^{-1}$

18. Human work (man-hours per 2500 kg of olives): 16 h ha^{-1} (storage); 18 h ha^{-1} (milling); 40 h ha^{-1} (pressing); 16 h ha^{-1} (extraction).

Human work = (16 h ha^{-1} + 18 h ha^{-1} + 40 h ha^{-1} + 16 h ha^{-1}) × 700 kg / 2500 kg = 25 h $ha^{-1}y^{-1}$

19. Olive oil: yield of 322 kg of oil from 2500 kg of olives

Olive oil = 322 kg × 700 kg / 2500 kg = 90.16kg $ha^{-1}y^{-1}$

20. Olive pomace: yield of 2178 kg of pomace from 2500 kg of olive

Olive pomace = 2178 kg × 700 kg / 2500 kg = 609.84kg $ha^{-1}y^{-1}$

Table A1. Emergy evaluation of traditional cultivation of corn (Egypt).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV, sej $unit^{-1}$	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Corn cultivation								
1	Solar radiation		5.23E+13	J	1.00	Odum, 1996	5.23E+13	R
2	Rain		1.13E+09	g	8.48E+04	Campbell et al., 2005	9.60E+13	R
3	Wind		1.89E+11	J	1.43E+03	Campbell et al., 2005	2.71E+14	R
4	Geothermal heat		1.70E+10	J	6.00E+03	Campbell et al., 2005	1.02E+14	R
5	Water	River water	7.14E+09	g	2.34E+05	Campbell et al., 2005	1.67E+15	R
6	Net topsoil loss		1.40E+07	J	1.12E+05	Cohen et al., 2006	1.57E+12	N
7	Tractor	Iron/steel	2.76E+02	g	3.38E+09	Cabezas et al., 2010	9.32E+11	F
		Tyre	1.23E+12	g	4.22E+09	Buranakarn, 1998	5.17E+11	F
8	Fuel	Diesel	3.44E+05	g	2.83E+09	Bastianoni et al., 2009	9.74E+14	F
9	Plough	Steel	5.18E+01	g	3.38E+09	Cabezas et al., 2010	1.75E+11	F
10	Fertilizer	N	2.88E+05	g	3.73e+09	Cabezas et al., 2010	1.07E+15	F
		P	1.35E+04	g	3.83E+09	Cabezas et al., 2010	5.18E+03	F
		K	3.90E+04	g	1.08E+09	Cabezas et al., 2010	4.21E+13	F
11	Herbicide		3.00E+03	g	8.66E+09	Brandt-Williams, 2002	2.60E+13	F
			5.94E+03	g	8.66E+09	Brandt-Williams, 2002	5.14E+13	F
12	Pesticide		1.50E+01	g	1.45E+10	Cabezas et al., 2010	2.18E+11	F
			7.15E+02	g	1.45E+10	Cabezas et al., 2010	1.04E+13	F
13	Knapsack sprayer	HDPE	2.82E+01	g	5.17E+09	Cabezas et al., 2010	1.46E+11	F
		Steel	1.88E+01	g	3.38E+09	Cabezas et al., 2010	6.35E+10	F
14	Knives	Steel	4.23E+01	g	3.38E+09	Cabezas et al., 2010	1.43E+11	F
		Wood	4.69E+00	g	1.72E+09	Cabezas et al., 2010	8.08E+09	F
15	Human work		3.42E+02	h	1.87E+12	This study	6.39E+14	
Outputs								
16	Corn		7.16E+09	J	6.86E+05	This study	4.92E+15	
			6.66E+06	g	7.38E+08	This study	4.92E+15	
17	Corn stover		5.99E+06	g	8.20E+08	This study	4.92E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A2. Emergy evaluation of commercial production of olive oil (Morocco).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Olives cultivation								
1	Solar radiation		5.52E+13	J	1.00	Odum, 1996	5.52E+13	R
2	Rain		3.91E+09	g	8.48E+04	Campbell et al., 2005	3.31E+14	R
3	Wind		1.57E+11	J	1.43E+03	Campbell et al., 2005	2.25E+14	R
4	Geothermal heat		2.36E+10	J	6.00E+03	Campbell et al., 2005	1.42E+14	R
5	Net topsoil loss		2.91E+08	J	1.12E+05	Cohen et al., 2006	3.27E+13	N
6	Water	Well water	2.00E+09	g	5.48E+05	Ingwersen, 2010	1.10E+15	N
7	Pump	Steel	5.05E+02	g	3.38E+09	Cabezas et al., 2010	1.71E+12	F
8	Pipe	HDPE	8.16E+02	g	5.17E+09	Cabezas et al., 2010	4.22E+12	F
9	Fuel	Diesel	2.27E+03	g	2.83E+09	Bastianoni et al., 2009	6.42E+12	F
10	Herbicides		4.00E+03	g	8.66E+09	Brandt-Williams, 2002	3.46E+13	F
11	Motorized sprayer	HDPE	1.75E+02	g	5.17E+09	Cabezas et al., 2010	9.02E+11	F
		Steel	1.16E+02	g	3.38E+09	Cabezas et al., 2010	3.93E+11	F
12	Fuel	Gasoline	2.66E+04	g	2.92E+09	Bastianoni et al., 2009	7.78E+13	F
13	Fertilizer	N	6.22E+04	g	3.73E+09	Cabezas et al., 2010	2.32E+14	F
		P	1.10E+04	g	3.83E+09	Cabezas et al., 2010	4.21E+13	F
		K	1.05E+04	g	1.08E+09	Cabezas et al., 2010	1.13E+13	F
14	Manure		1.00E+07	g	2.39E+08	This study	2.39E+15	92%R, 8%F
15	Secateurs	Steel	6.11E+01	g	3.38E+09	Cabezas et al., 2010	2.06E+11	F
		HDPE	1.53E+01	g	5.17E+09	Cabezas et al., 2010	7.90E+10	F
16	Boxes	HDPE	2.42E+03	g	5.17E+09	Cabezas et al., 2010	1.25E+13	F
17	Human work		2.41E+02	h	1.14E+12	This study	2.73E+14	
Output								
18	Olives		5.16E+09	J	9.09E+05	This study	4.69E+15	
			3.00E+06	g	1.56E+09	This study	4.69E+15	
Transport to olive press								
19	Transport		1.80E+08	g km	5.38E+04	Pulselli et al., 2008	9.68E+12	F
Olive oil production								
20	Boxes	HDPE	7.03E+02	g	5.17E+09	Cabezas et al., 2010	3.64E+12	F
21	Electricity	Machinery	3.40E+08	J	2.90E+05	NEAD, 2008	9.87E+13	F
22	Water		9.00E-01	m^3	1.57E+12	Chen and Chen, 2009	1.41E+12	N
23	Human work		1.50E+01	h	1.14E+12	This study	1.70E+13	
Outputs								
24	Olive oil		4.97E+05	g	9.70E+09	This study	4.82E+15	
25	Olive pomace		2.50E+06	g	1.92E+09	This study	4.82E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A3. Emergy evaluation of traditional cassava cultivation and processing (Ghana).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Cassava cultivation								
1	Solar radiation		5.40E+13	J	1.00	Odum, 1996	5.40E+13	R
2	Rain		1.26E+10	g	8.48E+04	Campbell et al., 2005	1.07E+15	R
3	Wind		4.38E+10	J	1.43E+03	Campbell et al., 2005	6.28E+13	R
4	Geothermal heat		1.26E+10	J	6.00E+03	Campbell et al., 2005	7.56E+13	R
5	Net topsoil loss		2.98E+08	J	1.12E+05	Cohen et al., 2006	3.34E+13	N
6	Hoes	Steel	7.71E+03	g	3.38E+09	Cabezas et al., 2010	2.61E+13	F
		Wood	8.57E+02	g	1.72E+09	Cabezas et al., 2010	1.47E+12	F
7	Cutlasses	Steel	4.56E+03	g	3.38E+09	Cabezas et al., 2010	1.54E+13	F
		Wood	2.40E+02	g	1.72E+09	Cabezas et al., 2010	4.13E+11	F
8	Human work		9.14E+02	h	5.28E+11	This study	4.82E+14	
Output								
9	Cassava		3.63E+10	J	4.69E+04	This study	1.70E+15	
			1.31E+07	g	1.30E+08	This study	1.70E+15	
Transport to processing plant								
10	Transport		2.63E+08	g km	5.38E+04	Pulselli et al., 2008	1.41E+13	F
Processing plant (washing and peeling)								
11	Knives	Steel	7.66E+01	g	3.38E+09	Cabezas et al., 2010	2.59E+11	F
		Wood	8.51E+00	g	1.72E+09	Cabezas et al., 2010	1.46E+10	F
12	Basins	Aluminum	5.10E+01	g	1.27E+10	Cabezas et al., 2010	6.48E+11	F
13	Water		1.43E+00	m^3	1.57E+12	Chen and Chen, 2009	2.25E+12	N
14	Human work		6.37E+02	h	5.28E+11	This study	3.36E+14	
Outputs								
15	Peels		3.11E+06	g	6.62E+08	This study	2.06E+15	
16	Peeled cassava		8.40E+06	g	2.45E+08	This study	2.06E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table S4. Emergy evaluation of commercial cassava cultivation and processing (Ghana).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Cassava cultivation								
1	Solar radiation		5.40E+13	J	1.00	Odum, 1996	5.40E+13	R
2	Rain		1.26E+10	g	8.48E+04	Campbell et al., 2005	1.07E+15	R
3	Wind		4.38E+10	J	1.43E+03	Campbell et al., 2005	6.28E+13	R
4	Geothermal heat		1.26E+10	J	6.00E+03	Campbell et al., 2005	7.56E+13	R
5	Net topsoil loss		2.98E+08	J	1.12E+05	Cohen et al., 2006	3.34E+13	N
6	Tractor	Iron/steel	1.34E+04	g	3.31E+09	Cabezas et al., 2010	4.44E+13	F
		Tyre	5.97E+03	g	4.22E+09	Buranakarn, 1998	2.52E+13	F
7	Plough	Iron/steel	2.29E+03	g	3.31E+09	Cabezas et al., 2010	7.57E+12	F
8	Tractor fuel	Diesel	3.10E+04	g	2.83E+09	Bastianoni et al., 2009	8.78E+13	F
9	Hoes	Steel	7.71E+03	g	3.38E+09	Cabezas et al., 2010	2.61E+13	F
		Wood	8.57E+02	g	1.72E+09	Cabezas et al., 2010	1.47E+12	F
10	Fertilizer	N	2.86E+04	g	3.73E+09	Cabezas et al., 2010	1.07E+14	F
		P	1.25E+04	g	3.83E+09	Cabezas et al., 2010	4.78E+13	F
		K	3.56E+04	g	1.08E+09	Cabezas et al., 2010	3.84E+13	F
11	Cutlasses	Steel	4.56E+03	g	3.38E+09	Cabezas et al., 2010	1.54E+13	F
		Wood	2.40E+02	g	1.72E+09	Cabezas et al., 2010	4.13E+11	F
12	Human work		9.14E+02	h	5.28E+11	This study	4.82E+14	
Output								
13	Cassava		1.97E+11	J	1.05E+04	This study	2.06E+15	
			2.86E+07	g	7.21E+07	This study	2.06E+15	
Transport to processing plant								
14	Transport		5.71E+08	g km	5.38E+04	Pulselli et al., 2008	3.07E+13	F
Processing plant (washing and peeling)								
15	Knives	Steel	1.66E+02	g	3.38E+09	Cabezas et al., 2010	5.63E+11	F
		Wood	1.85E+01	g	1.72E+09	Cabezas et al., 2010	3.18E+10	F
16	Basins	Aluminum	1.11E+02	g	1.27E+10	Cabezas et al., 2010	1.41E+12	F
17	Water		3.12E+00	m^3	1.57E+12	Chen and Chen, 2009	4.89E+12	N
18	Human work		1.38E+03	h	5.28E+11	This study	7.30E+14	
Outputs								
19	Peels		6.75E+06	g	4.19E+08	This study	2.83E+15	
20	Peeled cassava		1.83E+07	g	1.55E+08	This study	2.83E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A5. Emergy evaluation of traditional pineapple cultivation and processing (Kenya).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Pineapple cultivation								
1	Solar radiation		6.30E+13	J	1.00	Odum, 1996	6.30E+13	R
2	Rain		8.65E+09	g	8.48E+04	Campbell et al., 2005	7.34E+14	R
3	Wind		1.48E+15	J	1.43E+03	Campbell et al., 2005	2.11E+14	R
4	Geothermal heat		2.49E+10	J	6.00E+03	Campbell et al., 2005	1.49E+14	R
5	Net topsoil loss		6.89E+08	J	1.12E+05	Cohen et al., 2006	7.72E+13	N
6	Tools	Steel	8.55E+03	g	3.38E+09	Cabezas et al., 2010	2.89E+13	F
		Wood	9.50E+02	g	1.72E+09	Cabezas et al., 2010	1.63E+12	F
7	Fertilizer	N	4.11E+04	g	3.73E+09	Cabezas et al., 2010	1.53E+14	F
		P	9.17E+03	g	3.83E+09	Cabezas et al., 2010	3.51E+13	F
		K	2.38E+03	g	1.08E+09	Cabezas et al., 2010	2.58E+12	F
8	Dolomite		1.25E+05	g	1.08E+09	Cabezas et al., 2010	1.35E+15	F
9	Manure		9.88E+06	g	2.39E+08	This study	2.36E+15	92%R, 8%F
10	Bags	LDPE	2.00E+03	g	5.17E+09	Cabezas et al., 2010	1.03E+13	F
11	Human work		4.95E+02	h	2.74E+11	This study	1.36E+14	
Output								
12	Pineapple		4.20E+09	J	1.20E+06	This study	5.04E+15	
			1.50E+07	g	3.36E+08	This study	5.04E+15	
Transport to processing plant								
13	Transport		7.50E+08	g km	5.38E+04	Pulselli et al., 2008	4.03E+13	F
Processing plant								
14	Water		5.97E+01	m^3	1.57E+12	Chen and Chen, 2009	9.37E+13	N
15	Electricity	Machinery	1.85E+09	J	2.90E+05	NEAD, 2008	5.36E+14	F
16	Human work		7.60E+01	h	2.74E+11	This study	2.09E+13	
Outputs							4.78E+13	F
17	Peels		7.37E+06	g	7.78E+08	This study	5.73E+15	
18	Juice		5.34E+06	g	1.07E+09	This study	5.73E+15	
19	Pomace		2.30E+06	g	2.50E+09	This study	5.73E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A6. Emergy evaluation of traditional cultivation of banana (South Africa).

#	Item	Detail	Input, Unit $ha^{-1} y^{-1}$	Unit	UEV	Reference for UEV	Emergy, sej $ha^{-1} y^{-1}$	Type[a]
Banana cultivation								
1	Solar radiation		5.54E+13	J	1.00	Odum, 1996	5.54E+13	R
2	Rain		6.06E+09	g	8.48E+04	Campbell et al., 2005	5.14E+14	R
3	Wind		1.55E+11	J	1.43E+03	Campbell et al., 2005	2.21E+14	R
4	Geothermal heat		1.80E+10	J	6.00E+03	Campbell et al., 2005	1.08E+14	R
5	Water	River water	8.38E+06	g	2.34E+05	Campbell et al., 2005	1.96E+12	R
6	Net topsoil loss		1.31E+09	J	1.12E+05	Cohen et al., 2006	1.47E+14	N
7	Tractor	Iron/steel	8.54E+04	g	3.31E+09	Cabezas et al., 2010	2.83E+14	F
		Tyre	3.80E+04	g	4.22E+09	Buranakarn, 1998	1.60E+14	F
8	Fuel	Diesel	3.23E+06	g	2.83E+09	Bastianoni et al., 2009	9.15E+15	F
9	Disc plough	Iron/steel	1.45E+04	g	3.31E+09	Cabezas et al., 2010	4.81E+13	F
10	Tools	Steel	2.29E+04	g	3.38E+09	Cabezas et al., 2010	7.75E+13	F
		Wood	2.39E+03	g	1.72E+09	Cabezas et al., 2010	4.10E+12	F
11	Manure		7.27E+06	g	2.39E+08	This study	1.74E+15	92%R, 8%F
12	Herbicide		9.09E+05	g	8.66E+09	Brandt-Williams, 2002	7.87E+15	F
13	Pump	Steel	6.06E+03	g	3.38E+09	Cabezas et al., 2010	2.05E+13	F
14	Sprinklers	Steel	4.55E+03	g	3.38E+09	Cabezas et al., 2010	1.54E+13	F
15	Pipe	HDPE	4.90E+04	g	5.17E+09	Cabezas et al., 2010	2.53E+14	F
16	Fertilizer	N	2.17E+05	g	3.73E+09	Cabezas et al., 2010	8.09E+14	F
		K	4.57E+05	g	1.08E+09	Cabezas et al., 2010	4.93E+14	F
17	Knapsack sprayer	HDPE	4.36E+03	g	5.17E+09	Cabezas et al., 2010	2.26E+13	F
		Steel	2.91E+03	g	3.38E+09	Cabezas et al., 2010	9.83E+12	F
18	Bamboo		4.87E+09	J	1.42E+04	Bonilla et al., 2010	6.90E+13	F
19	Bags	LDPE	7.27E+03	g	5.17E+09	Cabezas et al., 2010	3.76E+13	F
20	Human work		2.30E+03	h	3.00E+12	This study	6.92E+15	
Outputs								
21	Banana		1.96E+10	J	1.47E+06	This study	2.88E+16	
			1.82E+07	g	1.58E+09	This study	2.88E+16	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A7. Emergy evaluation of commercial cultivation of banana (South Africa).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Banana cultivation								
1	Solar radiation		5.54E+13	J	1.00	Odum, 1996	5.54E+13	R
2	Rain		6.06E+09	g	8.48E+04	Campbell et al., 2005	5.14E+14	R
3	Wind		1.55E+07	J	1.43E+03	Campbell et al., 2005	2.21E+10	R
4	Geothermal heat		3.17E+07	J	6.00E+03	Campbell et al., 2005	1.90E+11	R
5	Net topsoil loss		1.31E+09	J	1.12E+05	Cohen et al., 2006	1.47E+14	N
6	Tractor	Iron/steel	4.27E+03	g	3.31E+09	Cabezas et al., 2010	1.41E+13	F
		Tyre	1.90E+03	g	4.22E+09	Buranakarn, 1998	8.01E+12	F
7	Fuel	Diesel	1.55E+05	g	2.83E+09	Bastianoni et al., 2009	4.37E+14	F
8	Chisel plough	Iron/steel	6.06E+02	g	3.31E+09	Cabezas et al., 2010	2.01E+12	F
9	Cultivator	Iron/steel	6.06E+02	g	3.31E+09	Cabezas et al., 2010	2.01E+12	F
10	Manure		2.33E+05	g	2.39E+08	This study	5.56E+13	92%R, 8%F
11	Fertilizer	N	6.14E+05	g	3.73E+09	Cabezas et al., 2010	2.29E+15	F
		P	5.92E+05	g	3.83E+09	Cabezas et al., 2010	2.27E+15	F
		K	8.12E+05	g	1.08E+09	Cabezas et al., 2010	8.77E+14	F
12	Limestone		5.82E+06	g	9.81E+08	Cabezas et al., 2010	5.71E+15	F
13	Herbicide		7.27E+05	g	8.66E+09	Brandt-Williams, 2002	6.30E+15	F
14	Water	Well water	8.38E+06	g	5.48E+05	Ingwersen, 2010	4.59E+12	N
15	Pump	Steel	1.52E+02	g	3.38E+09	Cabezas et al., 2010	5.12E+11	F
16	Sprinklers	Steel	5.00E+03	g	3.38E+09	Cabezas et al., 2010	1.69E+13	F
17	Pipe	HDPE	4.90E+04	g	5.17E+09	Cabezas et al., 2010	2.53E+14	F
18	Electricity		2.48E+02	J	2.90E+05	NEAD, 2008	7.18E+13	F
19	Tools	Steel	2.24E+03	g	3.38E+09	Cabezas et al., 2010	7.57E+12	F
		Wood	2.49E+02	g	1.72+E09	Cabezas et al., 2010	4.28E+11	F
20	Bamboo		3.90E+09	J	1.42E+04	Cabezas et al., 2010	5.52E+13	F
21	Bags	LDPE	5.82E+03	g	5.17E+09	Cabezas et al., 2010	3.01E+13	F
22	Human work		1.66E+03	h	3.00E+12	This study	4.99E+15	
Output								
23	Banana		1.31E+11	J	1.83E+05	This study	2.40E+16	
			2.91E+07	g	8.27E+08	This study	2.40E+16	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A8. Emergy evaluation of free-grazing breeding (Morocco).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Dairy farming								
1	Solar radiation		2.82E+14	J	1.00	Odum, 1996	2.82E+14	R
2	Rain		2.07E+10	g	8.48E+04	Campbell et al., 2005	1.76E+15	R
3	Wind		8.00E+11	J	1.43E+03	Campbell et al., 2005	1.14E+15	R
4	Geothermal heat		9.76E+10	J	6.00E+03	Campbell et al., 2005	5.86E+14	R
5	Cubicles	Wood	1.20E+05	g	3.97E+08	Castellini et al., 2006	4.76E+13	F
6	Water troughs	Concrete	3.20E+04	g	1.06E+09	Pulselli et al., 2008	3.39E+13	F
7	Water		1.60E+05	g	5.48E+05	Ingwersen, 2010	8.76E+10	N
8	Machineries	Steel	4.50E+03	g	3.38E+09	Cabezas et al., 2010	1.52E+13	F
9	Electricity		3.46E+08	J	2.90E+05	NEAD, 200	1.00E+14	F
10	Human work		1.30E+04	h	1.14E+12	This study	1.48E+16	
Outputs								
12	Milk		2.40E+07	g	7.21E+08	This study	1.73E+16	
13	Manure		7.20E+07	g	2.40E+08	This study	1.73E+16	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A9. Emergy evaluation of zero-grazing breeding (Morocco).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Dairy farming								
1	Cubicles	Wood	1.44E+06	g	3.97E+08	Castellini et al., 2006	5.72E+14	F
2	Feed troughs	Concrete	7.20E+03	g	1.06E+09	Pulselli et al., 2008	7.62E+12	F
3	Water troughs	Concrete	9.60E+04	g	1.06E+09	Pulselli et al., 2008	1.02E+14	F
4	Feed	Forage	6.69E+08	g	7.37E+08	This study	4.94E+17	48%R, 52%F
5	Water		3.46E+05	g	5.48E+05	Ingwersen, 2010	1.58E+09	N
6	Machineries	Steel	9.00E+03	g	3.38E+09	Cabezas et al., 2010	3.04E+13	F
7	Electricity		7.78E+08	J	2.90E+05	NEAD, 2008	2.26E+14	F
8	Human work		6.50E+03	h	1.14E+12	This study	7.38E+15	
Outputs								
9	Milk		2.52E+08	g	1.99E+09	This study	5.02E+17	
10	Manure		4.32E+08	g	1.16E+09	This study	5.02E+17	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A10. Emergy evaluation of traditional cocoa plantation (Ghana).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Cocoa Plantation								
1	Solar radiation		5.28E+13	J	1.00	Odum, 1996	5.28E+13	R
2	Rain		1.20E+10	g	8.48E+04	Campbell et al., 2005	1.02E+15	R
3	Wind		6.37E+10	J	1.43E+03	Campbell et al., 2005	9.11E+13	R
4	Geothermal heat		1.26E+10	J	6.00E+03	Campbell et al., 2005	7.56E+13	R
5	Net topsoil loss		2.98E+08	J	1.12E+05	Cohen et al., 2006	3.33E+13	N
6	Tools	Steel	1.05E+03	g	3.38E+069	Cabezas et al., 2010	3.54E+12	F
		Wood	7.20E+01	g	1.72E+09	Cabezas et al., 2010	1.24E+11	F
7	Fertilizer	N	7.70E+04	g	3.73E+09	Cabezas et al., 2010	2.87E+14	F
8	Manure		1.10E+06	g	2.39E+08	This study	2.63E+14	92%R, 8%F
9	Pesticide		1.38E+01	g	1.45E+10	Cabezas et al., 2010	2.00E+11	F
10	Knapsack blower	HDPE	2.88E+02	g	5.17E+09	Brown and Buranakarn, 2003	1.49E+12	F
		Steel	1.92E+02	g	3.38E+09	Cabezas et al., 2010	6.49E+11	F
11	Fuel	Gasoline	2.04E+04	g	2.92E+09	Bastianoni et al., 2009	5.96E+13	F
12	Human work		2.40E+02	h	5.28E+11	This study	1.27E+14	
Outputs								
13	Cocoa beans		4.42E+09	J	4.23E+05	This study	1.87E+15	
			4.00E+05	g	4.67E+09	This study	1.87E+15	
14	Cocoa pods		4.00E+05	g	4.67E+09	This study	1.87E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A11. Emergy evaluation of traditional cultivation of cabbage (Kenya).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Cabbage cultivation								
1	Solar radiation		6.28E+13	J	1.00	Odum, 1996	6.28E+13	R
2	Rain		9.75E+09	g	8.48E+04	Campbell et al., 2005	8.26E+14	R
3	Wind		1.36E+11	J	1.43E+03	Campbell et al., 2005	1.95E+14	R
4	Geothermal heat		2.68E+10	J	6.00E+03	Campbell et al., 2005	1.61E+14	R
5	Net topsoil loss		6.89E+08	J	1.12E+05	Cohen et al., 2006	7.72E+13	N
6	Tools	Steel	1.76E+04	g	3.38E+09	Cabezas et al., 2010	5.96E+13	F
		Wood	1.96E+03	g	1.72E+09	Cabezas et al., 2010	3.37E+12	F
7	Fertilizer	N	2.40E+04	g	3.73E+09	Cabezas et al., 2010	8.95E+13	F
		P	1.05E+04	g	3.83E+09	Cabezas et al., 2010	4.01E+13	F
		K	1.99E+04	g	1.08E+09	Cabezas et al., 2010	2.15E+13	F
8	Pesticide		1.28E+05	g	1.45E+10	Cabezas et al., 2010	1.86E+15	F
9	Human work		5.95E+02	h	2.74E+11	This study	1.63E+14	
Output								
10	Cabbage		1.25E+09	J	2.64E+06	This study	3.30E+15	
			1.20E+07	g	2.75E+08	This study	3.30E+15	
Transport to market								
11	Transport		1.60E+01	h	2.74E+11	This study	4.38E+12	
Vegetable market								
12	Cabbage (waste)		1.25E+09	J	2.64E+06	This study	3.30E+15	
			1.20E+07	g	2.75E+08	This study	3.30E+15	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Table A12. Emergy evaluation of commercial soybean cultivation (South Africa).

#	Item	Detail	Input, Unit ha^{-1} y^{-1}	Unit	UEV	Reference for UEV	Emergy, sej ha^{-1} y^{-1}	Type[a]
Soybean cultivation								
1	Solar radiation		5.13E+13	J	1.00	Odum, 1996	5.13E+13	R
2	Rain		9.38E+09	g	8.48E+04	Campbell et al., 2005	7.96E+14	R
3	Wind		2.30E+11	J	1.43E+03	Campbell et al., 2005	3.30E+14	R
4	Geothermal heat		1.70E+10	J	6.00E+03	Campbell et al., 2005	1.02E+14	R
5	Net topsoil loss		1.31E+09	J	1.12E+05	Cohen et al., 2006	1.47E+14	N
6	Tractor	Iron/steel	1.18E+04	g	3.38E+09	Cabezas et al., 2010	3.97E+13	F
		Tyre	5.22E+03	g	4.22E+08	Buranakarn, 1998	2.20E+13	F
7	Fuel	Diesel	9.42E+05	g	2.83E+09	Bastianoni et al., 2009	2.66E+15	F
8	Disc plough	Steel	2.63E+03	g	3.38E+09	Cabezas et al., 2010	8.90E+12	F
9	Tools	Steel	3.06E+03	g	3.38E+09	Cabezas et al., 2010	1.03E+13	F
		Wood	3.40E+02	g	1.72E+09	Cabezas et al., 2010	5.85E+11	F
10	Herbicide		1.80E+04	g	8.66E+09	Brandt-Williams, 2002	1.55E+14	F
11	Knapsack sprayer	HDPE	1.80E+02	g	5.17E+09	Cabezas et al., 2010	9.31E+11	F
		Steel	1.20E+02	g	3.38E+09	Cabezas et al., 2010	4.06E+11	F
12	Fertilizer	N	1.20E+04	g	3.73E+09	Cabezas et al., 2010	4.48E+13	F
		P	7.86E+03	g	3.83E+09	Cabezas et al., 2010	3.01E+13	F
		K	1.99E+04	g	1.08E+09	Cabezas et al., 2010	2.15E+13	F
13	Harvester	Iron/steel	1.18E+04	g	3.38E+09	Cabezas et al., 2010	3.97E+13	F
		Tyre	5.22E+03	g	4.22E+09	Buranakarn, 1998	2.20E+13	F
14	Fuel	Diesel	2.17E+05	g	2.83E+09	Bastianoni et al., 2009	6.15E+14	F
15	Human work		2.57E+03	h	3.00E+12	This study	7.73E+15	
Outputs								
16	Soybean		5.27E+10	J	2.36E+05	This study	1.25E+16	
			2.10E+07	g	5.93E+08	This study	1.25E+16	
17	Soybean residues		1.05E+07	g	1.19E+09	This study	1.25E+16	

[a]R=renewable emergy; N=local non-renewable emergy; F=imported emergy

Notes to Table 14:

Biodiesel plant (base case)

1. Cement= (volume x density) / lifetime

Constructed area	31,025.93	m^2
Perimeter of constructed area	704.57	m
Height of the wall	15.00	m
Walls area	10,568.51	m^2
Total constructed area (floar+walls)	41,594.43	m^2
Mean cement thickness	0.20	m
Volume of cement	8,318.89	m^3
Density of cement	2,400.00	$kg\ m^{-3}$
Lifetime	80.00	y
Mass of cement	2.50E+08	$g\ y^{-1}$

2. Reinforcing steel= mass / lifetime

Reinforcing steel (floar+walls)	291,161.03	kg
Reinforcing steel (roof)	310,259.27	kg
Lifetime	80.00	y
Mass of reinforcing steel	7.52E+06	$g\ y^{-1}$

3. Soybean

Mass of soybean	7.47E+10	$g\ y^{-1}$

4. Electricity

Electricity	5,449,403.25	$kWh\ y^{-1}$
	1.96E+13	$J\ y^{-1}$

5. Steam (mass)= energy / energy content

Steam	16,013,527.03	$kWh\ y^{-1}$
	5.76E+13	$J\ y^{-1}$
Steam energy content	2,800.00	$J\ g^{-1}$
Mass of steam	2.06E+10	$g\ y^{-1}$

6. Process water= water per unit of biodiesel x mass of biodiesel

Water per unit of biodiesel	0.0126	$kg\ kg^{-1}$
Mass of biodiesel	16,770,860.00	$kg\ y^{-1}$
Mass of process water	2.11E+08	$g\ y^{-1}$

7. Human labor

Person per shift	1	
Hours per shift	8	h
Shifts per day	3	

Days per year	365	
Man-hours	8.76E+03	h y^{-1}

Output

8. Biodiesel (energy)= (mass / density) x energy per volume unit

Biodiesel mass	1.68E+10	g y^{-1}
Biodiesel density	0.88	kg L^{-1}
Biodiesel energy content	34,500,000.00	J L^{-1}
Biodiesel energy	6.57E+14	J y^{-1}

9. Air emissions

NO_2	1.69E+06	g y^{-1}
SO_2	9.29E+05	g y^{-1}
PM10	3.73E+06	g y^{-1}
CO_2	5.36E+08	g y^{-1}
O_3	3.05E+06	g y^{-1}

10. Wastewater

Wastewater	1.52E+03	m^3 y^{-1}

<u>Scenario A (techno-centric option)</u>

Additional equipment – water treatment

11. Cement= (volume x density) / lifetime

Tank volume	7.60	m^3
Walls height	0.80	m
Tank area	9.50	m^{-2}
Tank perimeter	12.33	m
Walls area	9.87	m^{-2}
Total tank area (floar+walls)	19.37	m^{-2}
Cement thickness	0.20	m
Volume of cement	3.87	m^{-3}
Density of cement	2,400.00	kg m^{-3}
Lifetime	80.00	y
Mass of cement	1.16E+05	g y-1

12. Reinforcing steel= mass / lifetime

Reinforcing steel (floar+walls)	135.59	kg
Lifetime	80.00	y
Mass of reinforcing steel	1.69E+03	g y^{-1}

13. Pump (steel)= mass / lifetime

Pump	2	

Pump mass	45	kg
Lifetime	20	y
Steel	4.50E+03	g y^{-1}

Additional equipment – air treatment

14. Electricity

Electricity	106,000.00	kWh y^{-1}
	3.82E+11	J y^{-1}

15. Process water (mass)= volume x density

Water volume	991.50	m^3 y^{-1}
Water density	1,000.00	kg m^{-3}
Water mass	9.91E+08	g y^{-1}

16. Titanium dioxide (mass)= volume x density

TiO_2 volume	0.71	m^3 y^{-1}
TiO_2 density	4.23	g cm^{-3}
TiO_2 mass	3.02E+06	g y^{-1}

17. Ammonia (mass)= volume x density

NH_3 volume	0.25	m^3 y^{-1}
NH_3 density	0.73	kg m^{-3}
NH_3 mass	1.82E+02	g y^{-1}

18. Lime

Lime mass	2.13	t y^{-1}
	2.13E+06	g y^{-1}

19. Fabric filter (mass)= (volume x density) / lifetime

Area	49.56	m^2
Thickness	0.0016	m
Volume	0.08	m^3
Density	440,000	g m^{-3}
Lifetime	5	y
Mass	6.98E+03	g y^{-1}

20. MEA (mass)= (mol of CO_2 absorbed / absorption capacity of MEA) x molar mass of MEA

CO_2 absorbed	98,987.36	kg y^{-1}
Molar mass CO_2	44	g mol^{-1}
Absorption capacity MEA	0.5	mol CO_2 (mol MEA)$^{-1}$

Molar mass MEA	61	$g\ mol^{-1}$
MEA mass	2.74E+08	$g\ y^{-1}$

Output

21. Biodiesel (energy)= (mass / density) x energy per volume unit

Biodiesel mass	1.68E+10	$g\ y^{-1}$
Biodiesel density	0.88	$kg\ L^{-1}$
Biodiesel energy content	34,500,000.00	$J\ L^{-1}$
Biodiesel energy	6.57E+14	$J\ y^{-1}$

22. Air emissions

NO_2	0.00E+00	$g\ y^{-1}$
SO_2	0.00E+00	$g\ y^{-1}$
PM10	0.00E+00	$g\ y^{-1}$
CO_2	4.37E+08	$g\ y^{-1}$
O_3	3.05E+06	$g\ y^{-1}$

23. Wastewater

Wastewater	1.52E+03	$m^3\ y^{-1}$

Scenario B (ecological option)

Wetland

24. Solar radiation= land area x average yearly insolation x (1-albedo)

Land area	4,451.55	m^2
Average yearly insolation	3.80	$kWh\ m^{-2}\ d^{-1}$
	4,992,105,000.00	$J\ m^{-2}\ y^{-1}$
Albedo	0.14	
Solar radiation	1.91E+13	$J\ y^{-1}$

25. Rainfall= land area x yearly precipitation x water density

Land area	4,451.55	m^2
Yearly precipitation	2.97	$mm\ d^{-1}$
	1.08	$m\ y^{-1}$
Water density	1,000.00	$kg\ m^{-3}$
Rainfall	4.83E+09	$g\ y^{-1}$

26. Wind= land area x air density x drag coefficient on land x (geostrophic wind on land)^3 x seconds year^{-1}

Land area	4,451.55	m^2
Air density	1.30	$kg\ m^{-3}$
Drag coefficient on land	0.002	

Average annual wind velocity	4.20	m s^{-1}
*Geostrophic wind on land	7.00	m s^{-1}
Wind	1.25E+11	J y^{-1}

*Geostrophic wind on land= average annual wind velocity / 0.6

27. Geothermal heat= land area x heat flow x seconds $year^{-1}$

Land area	4,451.55	m^2
Heat flow	40.00	mW m^{-2}
Geothermal heat	5.62E+09	J y^{-1}

28. Topsoil= land area x erosion rate

Land area	4,451.55	m^2
*Erosion rate	80,895.60	J m^{-2} y^{-1}
Topsoil	3.60E+08	J y^{-1}

*Erosion rate= US erosion rate / area of US = 9,147,593,000,000.00 m^2 / 740,000,000,000,000,000.00 J y^{-1}

29. Liner (mass)= (volume x density) / lifetime

Liner volume (HDPE)	22.26	m^3
HDPE density	980.00	kg m^{-3}
Lifetime	20	y
Liner mass	1.09E+06	g y^{-1}

30. Gravel (mass)= (volume x density) / lifetime

Land area	4,451.55	m^2
Depth	0.60	m
Volume	2,670.93	m^3
Gravel density	1,500.00	kg m^{-3}
Lifetime	80	y
Gravel mass	5.01E+07	g y^{-1}

31. Pipe (mass)= (volume x density) / lifetime

Cross-section area	0.0027	m^2
Lenght	300.00	m
PVC density	920.00	kg m^{-3}
Lifetime	20	y
Pipe mass	3.74E+04	g y^{-1}

32. Tractor (mass)= (material mass / lifetime) / operation time

Steel	5,400,000.00	g
Lifetime	15,000.00	h
Operation time	11	h ha^{-1}

Rotation	20	y
Steel mass	8.81E+01	g y^{-1}

Tyre-rubber	600,000.00	g
Lifetime	15,000.00	h
Operation time	11	h ha^{-1}
Rotation	20	y
Tyre-rubber mass	9.79E+00	g y^{-1}

33. Fuel (mass)= (fuel volume x fuel density) / rotation

Diesel	122.00	L
Density	0.84	kg L^{-1}
Rotation	20	y
Diesel mass	2.28E+03	g y^{-1}

34. Human labor

Man-hours	4.82E+01	h y^{-1}

Forest

35. Solar radiation= land area x average yearly insolation x (1-albedo)

Land area	104,732.74	m^2
Average yearly insolation	3.80	kWh m^{-2} d^{-1}
	4,992,105,000.00	J m^{-2} y^{-1}
Albedo	0.14	
Solar radiation	4.50E+14	J y^{-1}

36. Rainfall= land area x yearly precipitation x water density

Land area	104,732.74	m^2
Yearly precipitation	2.97	mm d^{-1}
	1.08	m y^{-1}
Water density	1,000.00	kg m^{-3}
Rainfall	1.14E+11	g y^{-1}

37. Wind= land area x air density x drag coefficient on land x (geostrophic wind on land)^3 x seconds year^{-1}

Land area	104,732.74	m^2
Air density	1.30	kg m^{-3}
Drag coefficient on land	0.002	
Average annual wind velocity	4.20	m s^{-1}
*Geostrophic wind on land	7.00	m s^{-1}
Wind	2.95E+12	J y^{-1}

*Geostrophic wind on land= average annual wind velocity / 0.6

38. Geothermal heat= land area x heat flow x seconds year^{-1}

Land area	104,732.74	m^2
Heat flow	40.00	mW m^{-2}
Geothermal heat	1.32E+11	J y^{-1}

39. Topsoil= land area x erosion rate

Land area	104,732.74	m^2
*Erosion rate	80,895.60	J m^{-2} y^{-1}
Topsoil	8.47E+09	J y^{-1}

*Erosion rate= US erosion rate / area of US = 9,147,593,000,000.00 m^2 / 740,000,000,000,000,000.00 J y^{-1}

40. Tractor (mass)= (material mass / lifetime) / operation time

Steel	5,400,000.00	g
Lifetime	15,000.00	h
Operation time	11	h ha^{-1}
Rotation	20	y
Steel mass	2.07E+03	g y^{-1}
Tyre-rubber	600,000.00	g
Lifetime	15,000.00	h
Operation time	11	h ha^{-1}
Rotation	20	y
Tyre-rubber mass	2.30E+02	g y^{-1}

41. Fuel (mass)= (fuel volume x fuel density) / rotation

Diesel	122.00	L
Density	0.84	kg L^{-1}
Rotation	20	y
Diesel mass	5.37E+04	g y^{-1}

42. Human labor

Man-hours	1.57E+02	h y^{-1}

Output

43. Biodiesel (energy)= (mass / density) x energy per volume unit

Biodiesel mass	1.68E+10	g y^{-1}
Biodiesel density	0.88	kg L^{-1}
Biodiesel energy content	34,500,000.00	J L^{-1}
Biodiesel energy	6.57E+14	J y^{-1}

44. Air emissions

NO_2	0.00E+00	g y^{-1}
SO_2	0.00E+00	g y^{-1}
PM10	0.00E+00	g y^{-1}
CO_2	4.37E+08	g y^{-1}
O_3	3.05E+06	g y^{-1}

45. Wastewater

Wastewater	1.52E+03	m^3 y^{-1}

46. Peat

Peat deposit	0.00084	m y^{-1}
Peat density (wet)	1000.00	kg m^{-3}
Peat density (dry)	400.00	kg m^{-3}
Volume deposit	3.74	m^3 y^{-1}
Mass (wet)	3.74E+06	g y^{-1}
Mass (dry)	1.50E+06	g y^{-1}
Energy	3.38E+10	J y^{-1}

47. Wood biomass

Growth rate	3.99E+07	g y^{-1}

Ecosystem services demand and supply

Table A13. Air quality regulation service

Pollutant	UEV, sej/g	Demand	Supply				Unit	V (year 20th)
			year 10th	year 15th	year 20th	year 50th		
NO_2	4.00E+09	6.76E+15	6.43E+15	6.71E+15	7.26E+15	9.67E+15	sej y^{-1}	0.07
SO_2	3.08E+10	2.86E+16	2.00E+16	2.45E+16	3.26E+16	6.79E+16	sej y^{-1}	0.14
PM10	1.19E+10	4.46E+16	5.65E+16	5.79E+16	6.07E+16	6.75E+16	sej y^{-1}	0.36
O_3	3.64E+10	1.11E+17	7.45E+16	9.27E+16	1.27E+17	2.25E+17	sej y^{-1}	0.14
Total		1.91E+17	1.57E+17	1.82E+17	2.27E+17	3.70E+17	sej y^{-1}	0.19

UEVs reference:

Campbell and Tilley, 2014

Table A14. Carbon sequestration service

Pollutant	UEV, sej/g	Demand	Supply				Unit	V (year 20th)
			year 10th	year 15th	year 20th	year 50th		
C	3.39E+08	4.96E+16	1.37E+15	4.51E+15	9.16E+15	3.98E+16	sej y^{-1}	-0.82

Table A15. Water provision service

Water source	UEV, sej/g	Demand	Supply				Unit	V (year 20th)
			year 10th	year 15th	year 20th	year 50th		
Rainfall	8.48E+04[a]	-	7.46E+13	7.46E+13	7.46E+13	7.46E+13	sej y^{-1}	-
Underground	5.48E+05[b]	6.59E+14	4.59E+13	1.42E+14	2.05E+14	3.44E+14	sej y^{-1}	-
River	2.34E+05[a]	1.58E+14	-	-	-	-	sej y^{-1}	-
Total		8.16E+14	1.20E+14	2.17E+14	2.79E+14	4.18E+14	sej y^{-1}	-0.66

UEVs references:

[a] Odum et al., 2000

[b] Ingwersen, 2010

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