THE NEW ERA OF EUROPEAN BIOFUELS LANDSCAPE: COMPARATIVE ASSESSMENT OF SOCIO-ENVIRONMENTAL SUSTAINABILITY OF LIGNOCELLULOSIC FEEDSTOCKS

LAMBRINI DIAMANTOPOULOU, SOFIA PAPADAKI, LAZAROS KARAOGLANOGLOU, DIMITRIOS KOULLAS and EMMANUEL KOUKIOS

School of Chemical Engineering, National Technical University of Athens, Zografou Campus, Athens, GR-15700, Greece
✉ *Corresponding authors: LambriniDiamantopoulou, linadiam@mail.ntua.gr*
Sofia Papadaki, spcheng@central.ntua.gr

Dedicated to the 50th Anniversary of CCT
and to the memory of its creator, the legendary
Professor Acad. Cristofor I. Simionescu,
with affection and a verse from our national poet:
"With reason and dream"
(DionyssiosSolomos, 1884)

This paper presents the development of a new conceptual framework and the application of an innovative socio-environmental impact assessment tool of biomass to biofuels production pathways. The proposed sustainability assessment tool consists of one index (BSI), 3 vectors and 12 indicators. The resulting new sustainability index will be used to assess the environmental and social performance of feedstocks and feedstock mixes, as well as biomass supply chains up to the stage of biomass conversion to biofuels. An example of the application of this tool for the assessment of biofuel production options will be presented, using 2 lignocellulosic feedstocks: wheat bran and barley straw. This assessment will take place in the context of two scenarios: "Best practice" and "Maximum profit". Indicative results were obtained from the combination of a thorough literature review and previous work by our research group; European mean values and conditions have been considered.

Keywords: socio-environmental sustainability assessment tool, biofuel feedstocks, biofuel stakeholders, sustainable agriculture

INTRODUCTION

The European Commission set in 2003 the basis for the promotion of the use of renewable energy in transport, trying to deal with the climate change related environmental degradation, as well as the increasing scarcity of conventional energy sources. This legislative act was the "Biofuels Directive", and within its framework indicative targets were set for biofuels use in transport in the European Union up to 2020.[1]It was followed by the Renewable Energy Directive (RED, 2009/28/EC), and the Fuel Quality Directive (FQD, 2009/30/EC),where more specific sustainability targets for the biofuels were determined, in an attempt to improve the performance of the first generation biofuels.[2,3]

Specifically, RED and FQD Directives pose GHG impact, biodiversity, land use and good agricultural conditions as sustainability criteria.

In the next few decades, the global demand for transport fuel is expected to grow significantly up to 55% by 2030 compared to 2004. This will accelerate the growth in demand for biofuels, as they are expected to make an increasing contribution to meeting future energy needs of the mankind. Despite the projected tripling of biofuels production from 20 Mtoe in 2005 to almost 60 Mtoe in 2015 and over 90 Mtoe in 2030, their share in the total road-transport fuel is not expected to surpass 4-5% by 2030. Biofuels production costs still remain comparatively high and substantial cost reductions are required for cost types to become commercially competitive.[4]

One of the main goals of developing the biofuels sector is their expected contribution to the global environmental sustainability. However, this sustainability can be ensured only under specific production and end-use practices. From this perspective, the sustainable use of biomass is defined as "a type of use that can be continued indefinitely, without an increase in negative impact due to pollution, while maintaining natural resources and beneficial functions of living nature relevant to humankind over millions of years".[5–7]

Biofuel sustainability is based on the following three pillars.[6–9]

- Economic sustainability: in economic terms, biofuel production has to be cost effective and competitive;
- Social sustainability: in social terms, biofuel development can create a massive new demand in the agricultural economy, providing employment and entrepreneurship opportunities;
- Environmental sustainability: as biofuel production is an agricultural process, the same elements and inputs contribute to its overall efficiency as for existing agricultural production systems. It is important in each particular case to evaluate the sustainability of raw material production and supply chain to ensure that biofuels are developed in accordance with the special conditions of the areas in order to optimize the use of the basic resources of agricultural ecosystems, such as soil, water, air and biodiversity. Furthermore, taking into account the climate and geographical diversity, initiatives for the use of semi-arid land and other marginal lands could be implemented for the benefit of supporting the development of rural populations in poor regions.

The criteria for decision-making may be general, based on the three pillars of sustainability, but the relative weight given to economic, social and environmental aspects should be a matter for local decision-making. For example, in areas of exceptional biodiversity, due to environmental considerations, the weight of population's subsidies for biofuel feedstock is different from that applied in dense and poor rural areas and can distort markets, contributing to the inefficient allocation of resources.[4,7,10]

There have been multiple attempts for the quantification of the environmental sustainability in general,[11–17] and biofuel sustainability in particular, through the generation of indices.[18] However, in most cases, these indices require a large amount of not easily accessible feedstock and process related detailed data.

The whole biomass-to-biofuel supply chain concerns a multi-step complex system. Each step generates various co-products/residues/wastes, depending on the selected primary source/supply/refining configurations. The type and quality of these parameters could play a crucial role in the environmental feasibility of the whole system. However, their evaluation is case-dependent and should be handled with extreme care.[6,7]

A major objective of this paper is to explore the conditions and requirements for viable and sustainable novel agro-industrial chains, aimed at biomass-to-fermented biofuels production across Europe. Sustainability is a key condition, as in the long run all existing bio-residue sources will have been exhausted, so that fermented biofuels will have to be generated from dedicated sustainable sources.[7] The research approach is based on matching the bioresource "landscape" with local/regional economies and ecologies. There can be a large amount of cost-efficient or technically suitable feedstocks for each region or economy. However, the next step is to use the Sustainability mapping, in order to filter some of the potential ones.

The main scope of this paper is the construction, formulation, and use of an easy to handle multi-parametric socio-environmental impact assessment tool, the "Biomass Sustainability Index (BSI)", in order to rank biomass-to-biofuels schemes. This tool consists of 3 vectors and 12 indicators and its application was demonstrated, in the context of multiple scenarios, as in a case study for the assessment of fermented biofuel production in Greece, using 2 different feedstocks: wheat bran and barley straw.

EXPERIMENTAL

Feedstocks

The fibre content of the whole wheat grain ranges from 11.6% to 12.7% dry weight. Most of the fibre that is in the outer layers of the grain (pericarp and seed coat) is typically called wheat bran. It is one of the richest sources of fibre, 46% is non-starch polysaccharide (NSP) mainly consisting from arabinoxylan, cellulose and beta-glucan. Specifically, wheat bran contains 36.5-52.4% total fibre from which 35-48.4% is insoluble and only 1.5-4% dry weight is soluble.[19,20] During the milling process, wheat bran remains a major by-product. Annually, over 650 million tons of wheat are produced in the world, of which more than 69% are used for food.[21]

Barley straw is an abundant lignocellulosic by-product from barley production in farming. The availability of barley straw worldwide is about 60 million tons per year. In Europe, barley straw is the second most abundant agricultural waste and its production equals about 75% of the worldwide production, rendering barley straw a promising raw material for biofuel production in Europe.[22] Lignocellulose is the main component in barley straw, which is a compact structure of cellulose (35-40%), hemicelluloses (15-30%) in close association with lignin (15.8%).[20,23,24] The ash content is high probably due to the high content of silica in the raw material. Barley straw also contains 5.1% solvent extracts, 13.7% hot water extracts and 5.2% protein.[22] This cellulose-rich biomass from renewable resources gains increasing importance as a raw material for numerous industries from paper and cardboard industries to biofuels and chemicals industries, due to its low cost, wide availability, little content in non-fibrous materials and ease of processing, showing a high economic and industrial potential.[25]

Biofuel production from lignocellulosic feedstocks

In all studied scenarios, the biofuel production procedure referred to the conversion of lignocellulosic feedstocks to biofuels via the fermentation process. Specifically, fermented biofuel production includes three main steps: steam pretreatment, enzymatic hydrolysis and fermentation. Steam pretreatment, which is performed at a high temperature, facilitates enzymatic hydrolysis of the cellulose and hemicellulose into oligo- or monomers, such as glucose and xylose. The subsequent enzymatic hydrolysis of the cellulose and hemicellulose can be performed simultaneously or followed by fermentation and distillation, in the case of bioethanol.[26]

Methodology of "Biomass Sustainability Index (BSI)"

The main scope of this paper is the construction and formulation of a multi-parameter tool, the "Biomass Sustainability Index (BSI)", in order to rank biomass-to-biofuel schemes, as well as its application in specific case studies. In order to evaluate the sustainability of a biofuel generation system, it is essential to develop indicators capturing the system complexity and reflecting the impact of a very large number of parameters. On the other hand, even by eliminating a lot of parameters and just concluding to a reasonable number of them, their quantification is a further obstacle to pass by. A uniform mapping approach, combining within a single system many quasi-independent sub-systems, and dealing with their interfaces, makes the situation less chaotic and offers a promising pathway to "navigate" in such a complex landscape. The use of these maps identifies technical, economic, environmental, social forces and barriers, drawing potential roadmaps for future applications and market deployment for optimal biofuel generation from biomass, as well as facilitates the exploration of a suitable policy environment to support such roadmaps in the EU, with emphasis on the sustainability.

The tool can be used as basis for comparison and decision-making when alternative production pathways for the same regional conditions are considered. Its use through the ranking of the 12 indicators, for each of the considered case study pathway by a multi-disciplinary board, will provide indications for the most promising pathways, as well as for the crucial socio-environmental sustainability issues involved with each of them.[6,7,9] The ranking score for each case study will be produced by the average of the positive (2), negative (0) or neutral (1) impact of each of the 12 indicators. The assessment of the three impact levels is based on the following conceptual approach:[6–9]

- Positive (score=2): the biomass production process and the whole biofuel production system will improve the current level of the specific indicator in the study region;
- Negative (score=0): the biomass production process and the whole biofuel production system will worsen the current level of the specific indicator in the study region;
- Neutral (score=1): the biomass production process and the whole biofuel production system either are not relevant to the specific indicator or their impact is minor for the receiving environment without creating any specific disturbance.

The 12 indicators of the proposed BSI were selected based on previous studies regarding the quantification of environmental sustainability.[5–9,13,15] The selected indicators were grouped in 3 major vectors: i) Preserving the stock of vital natural resources, ii) Maintaining key natural cycles and ecosystem services, and iii) Social acceptance–Income.

Preserving the stock of vital natural resources

The soil, water, and fossil fuel use should be considered as the major natural resources, which are expected to be affected by the biomass-to-biofuel production chains. Therefore, the crucial sustainability concerns related with these chains are that the erosion and water use should do not exceed addition to stocks of soil and water and the levels of nutrients and organic matter in soils should not decrease. Furthermore, the levels of volatile carbon compounds and N_2O in the atmosphere should remain unaffected.[5,27] In this group, the four parameters affecting the environmental sustainability of the system are the following:

Soil erosion and soil organic matter

Resource conservation requires that loss due to erosion should be balanced by soil formation. Current practices do not always meet this condition for sustainability. In many areas of the world, the land use change and the production of annual and perennial crops can give rise to net loss of soil by erosion. Erosion associated with harvesting practices can also be a problem both in agricultural lands and forests.[28,29]

Studies regarding the sustainability focus on the requirements of a type of land-based biomass production, which can be maintained indefinitely. Studies indicate that a critical factor in maintaining high productivity is the maintenance of high levels of organic matter in the soil. Depletion of organic matter results in a decrease in annual crop productivity. Keeping soil organic carbon levels in a steady state requires an overall best practice approach, which should be proved more efficient than leaving the whole amount of agricultural residues on the farm.[5,30]

Nutrients

Another important factor in sustainable agricultural productivity is the continuous availability of sufficient mineral nutrients, such as N (nitrogen), P (phosphorus), S (sulfur), K (potassium), Ca (calcium) and Mg (magnesium).On a time scale valid for forestry and cropping, there is only a very small addition to total reserves of minerals that can be made available to biomass due to geologic processes. This indicator monitors that nutrient levels are maintained and can be maintained indefinitely by the practices used, without leading to increased environmental fluxes of wasted nutrients, such as S, N and P, which contaminate soils via air and/or water.[5,31,32]

Fossil fuels

In the currently followed agricultural practices for biomass production, there are numerous processes involved with "hidden" fossil fuel use. The large-scale leakage of added nitrogen compounds from biomass production systems, when this nitrogen originates from Haber synthesis ammonia, as well as the transport and machinery powering, is the most obvious one. Consequently, the optimization of specific system parameters either at the production side, i.e. use of waste nitrogen sources, renewable energy resources for power and transport needs, or at the consumption side, i.e. optimization of the amount of the fertilizers utilized in cultivation, selection of a plant location that will minimize the transport needs etc., may improve the overall system efficiency.[5,27]

Water

Fulfilling the criterion of sustainable use of fresh water resources requires that the water used during the whole production and supply chain will not significantly exceed the addition to stocks. The potential for biomass production on suitable soils is strongly influenced by water availability, and in semi-arid areas it may well be the main limiting factor. Worldwide, agriculture is the main consumer of fresh water: it accounts for about 75% of the current water use. In many cases, efficient use of scarce fresh water resources is an overriding concern, as fresh water resources are becoming increasingly strained. On the other hand, there are waterlogged places where large uptakes of water by energy crops are considered as a benefit.[5,33,34]

Maintaining key natural cycles and ecosystem services

To maintain the ecosystem services of nature, which are useful to mankind, the restriction of biomass production to degraded and currently fallow land should be preferred. Also, sustainability of biomass-for-energy use requires a high efficiency recycling of nutrients present in any system waste outflows. Meeting such conditions requires major efforts and a holistic system approach, where the waste streams will be considered as system co-products.[5]

In this group, the four parameters affecting the environmental sustainability of the system, are as described below.

Mobilization of elements

In a first approximation, burning of fossil fuels and of biofuels is fundamentally different in the mobilization of elements. In the former case, trace elements that were geochemically stable and were not participating in biogeochemical cycles, are introduced in the biosphere, whereas in the latter, emissions and wastes associated with the whole production chain mostly contain elements that were already participating in biogeochemical cycles. If this were 'the whole truth', the use of biofuels would fit well a steady-state economy. However, the situation does not hold for all the elements. In this context, one should realize that negative impacts associated with biofuel utilization can be increased because biomass can contain significant amounts of elements that have been mobilized from previously geochemically stable deposits and are remobilized during the whole processing chain.[5,27]

Impact on climate

Sustainability, as defined here, requires that climate remains unaffected by modern biofuel-based energy chains. Especially, the mobilization of C, N and S (which may give rise to sulfate aerosols), as well as the generation of small particles, may have an impact on climate. Considering life cycles, one may safely state that modern biofuel production and supply chains are usually associated with burning fossil fuels. The latter is not carbon neutral. Net biogenic emissions of CO_2 and CH_4, originating in the biomass-for-energy life cycle is also sizable. Thus, to keep the relation between biomass use and atmospheric concentrations of volatile carbon compounds and N_2O in a steady state, life cycle emissions of those compounds should be taken into account.[35–38]

Land use

Land use can create diverse cultural landscapes of outstanding aesthetic, economic and ecological value, but it may equally result in land degradation, soil loss and impoverished ecosystems. Very high net emissions can follow from land use change associated with multiple steps of the biofuel production process. For instance, in case a forest is converted to arable land in association with clear cutting for the production of biomass based fuels, carbon stores in soils may be to a large extent converted into volatile carbon compounds, reflecting a high net addition to the carbon cycle, which may well exceed the emissions associated with burning fossil fuels to be replaced by biofuels. In view of the ecosystem services that undisturbed living nature provides, conversion thereof to plantations or land for annual crops seems to violate sustainability. Hence, land use is shaped by processes of society–nature interaction. These processes can detract from society–nature interaction, may deplete the natural capital upon which the provision of ecosystem services for humans depends. Furthermore, the land use change can have a direct or indirect impact on food crop production capacity of the agricultural systems. This impact would jeopardize the sustainability of any biomass-to-biofuel production chain, unless proper provisions have been taken, starting from initial decision-making and design phase.[39–42]

Biodiversity

Sustainability requires that ecosystem services of nature that are useful to mankind should be maintained. This in turn leads to the conclusion that the area allocated to nature and biodiversity should not be reduced. There are several aspects to the impact of biomass for fuel use on living nature. There are major differences in the ecosystem services of energy crops and of nature. In the highly productive plantations, there is furthermore an intensive use of herbicides and others, which will cause increased leakiness regarding nutrients and will severely limit nitrogen fixation. Agricultural practices where specific species are intensively cultivated for biofuel production, due to their high productivity, may well contribute negatively to the overall biodiversity of the natural habitat with highly unpredictable consequences. Therefore, keeping the balance of the biodiversity related intervention of any biofuel production chain will provide the necessary roadmap for maintaining this dimension of the natural environment.[5,43]

Social acceptance - Income

Bioproductive land is one of the most significant natural capitals. Sustainability indicators aim at monitoring key aspects of society–nature interaction in order to communicate complex sustainability problems within the scientific community, to policy-makers and to the broad public. This parameter introduces a special issue that seeks to contribute to the development of sustainability indicators that track society–technology–nature interaction, which will highly determine the long term feasibility and sustainability of any biofuel production system.[5,40]

In this group, the last four parameters of the proposed BSI tool, affecting the social dimension of the system sustainability are included. The detailed presentation of these parameters follows.

Social acceptance

A crucial parameter of the social sustainability is the social acceptance of biofuels. As also mentioned above, there are serious concerns not only about the utilization of biomass for biofuel production, but also about the impact of the end use of the biofuels. The changes in the EU policy, following the poor performance of first generation biofuels can be considered as an initial response to these concerns. However, it should be also mentioned that the lack of proper dissemination of the state of the art technologies to the wider society, as well as the high level of competition not only among fossil fuel energy alternatives, but also within the renewable energy options, can create an unfriendly societal environment for the biofuel based energy products. Current research reports that a large number of external parameters play a significant role in this phenomenon, i.e. the culture, the quality of life and educational level, even the politics of every region.[44–47]

Human health

Being products of renewable sources, biofuels are expected to be clean, non-toxic and non-dangerous to human health. However, it should not be taken for granted that this will be the case under any production and end use practice. The production practices thatwill be followed, at each step should ensure that this provision has been taken. Furthermore, the production scale,whichideally would be smaller than that of the fossil fuel processing units, will create a better distribution of the potential health impacts at local and regional level, avoiding the over concentration of contaminants and consequently the degradation of specific areas.[48,49]

Employment

Nowadays that the employment constitutes one of the major societal and policy concerns in EU, creating new jobs and entrepreneurship opportunities, especially close to the primary sector activities should be considered as an issue of crucial importance. This parameter is significant for the biofuels sustainability and is also strongly connected to the regional development and social acceptance.[50,51]

Regional development

It is more than obvious that the biofuel production in a region will have a direct and significant impact on the regional development. The existing facilities of the area and the regional markets should play the first role in the decision and policy making for the adjustment of the biofuels supply chain in the region. All of the above mentioned social parameters have important interfaces with the regional development.[46,51]

The Biomass Sustainability Index (BSI)

A relatively simple representation tool, based on the concept of mapping the above-defined twelve components and their interfaces, was developed in order to model this analysis. It is based on these twelve specific inputs, which correspond to the main effective sustainability parameters, affecting the whole supply chain sub-systems; the output of this tool has the form of a complex spider graph, but is also a quantitative figure, the "Biomass Sustainability Index" (BSI).[7]

The BSI can be given by the following equation:

$$BSI = [BSI\text{-}A + BSI\text{-}B + BSI\text{-}C]/3 \qquad (1)$$

The metrics of BSI consist in the quantification of the sustainability impact of all the above-mentioned key factors by assigning values in the 0-1-2 range, where 0 denotes a decrease in sustainability of a particular kind, 2 means a significant boost in sustainability, whereas 1 shows no change as far as sustainability is concerned.[7]

All the crucial parameters for the design of the Bioenergy Sustainability Index can be seen in Table 1.

Table 1
The three groups of 12 SI parameters

BSI-A	1. Soil (erosion vs. conservation practices) 2. Nutrients (losses vs. rational management) 3. Fossil fuels ("hidden" links vs. de-coupling) 4. Water (wasting/degrading vs. efficient use)
BSI-B	5. Mobilisation of elements (pollution vs. control) 6. Impact on climate (GHG vs. green accounting) 7. Land use ("fuel or food" vs. biorefineries) 8. Biodiversity (monoculture vs. agroecosystem)
BSI-C	9. Social acceptance (concerns vs. consensus) 10. Human health (ecology vs. economy) 11. Employment (human vs. development and technology) 12. Regional Development

RESULTS AND DISCUSSION

Assessment of BSI

The graphical representation of the 12 indicators previously presented can be seen in Fig.1.It is clear from this demonstration that each feedstock has its own unique "sustainability footprint" represented by its spider diagram, and depending on its unique characteristics and the specified supply chain conditions.

The total surface area created inside the spider diagram by these parameters is defined as "Biomass Sustainability Index" (BSI) and can be used as an additional – to the estimated sustainability figure – tool for the comparative evaluation of different feedstock(s) and various design options. Its correlation with the actual cost data is also examined in order to provide an overall view of its potential utilization.

The sustainability of any biomass-to-biofuel related production and supply chain should be assessed under multiple production practices. This assessment should consider at least two levels of well-defined conditions, which should correspond to the "Best practice" and "Maximum profit" scenarios. Table 2 summarizes these conditions for both levels, as they have been defined in the specific study.

For the development of the "Best practice" and "Maximum profit" scenarios, the study of the specific characteristics of each feedstock is crucial, in order to conclude to an adequate result based on well-established assumptions. Since both examined raw materials are by-products of the agro-food industry, the main characteristics of the examined feedstocks are presented in Table 3, focusing on main products, inputs, seasonality, land and water use.

In Figs. 2 and 3, the performance of the two selected feedstocksis presented, according to "Best Practice" and "Maximum Profit" scenarios, respectively.

The comparative assessment of the sustainability of the examined fermented biofuel production systems from the perspective of the

"Best practice" (see Table 4 and Fig. 2) concept indicated the following: the barley straw, due to its high volume and productivity of oligo- and monomers of sugars, exhibited the best performance by most of the criteria, exceeding in maintaining key natural cycles, ecosystem services and socio-economic relevant indicators.

On the other hand, in the case of the "Maximum profit" scenario (see Table 4 and Fig. 3), both examined feedstocks showed equal performance by all criteria, despite the vector of preserving the stock of vital natural resources where barley straw shows a negative impact on sustainability. In general, both feedstocks show a neutral impact on sustainability.

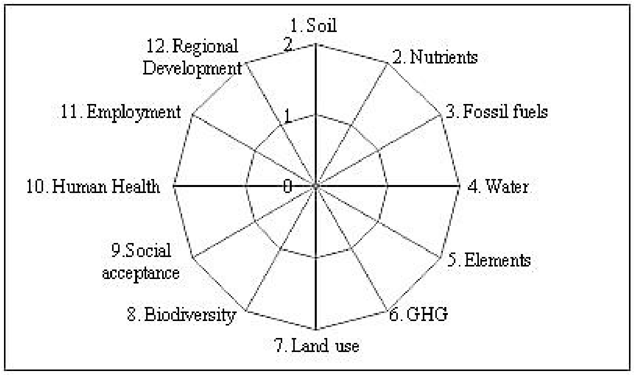

Figure 1:Graphical representation of the 12 sustainability indicators

Table 2
"Best practice" vs. "Maximum profit" concepts

Feedstock	Best practice	Maximum profit
Wheat bran	➢ Optimization of the production scale: ✓ Feedstock use with respect to current uses ✓ Minimize the transport distance ➢ Synergies with existing wheat related activities ➢ Multiple product generation ➢ Minimization of the system emissions to the environment	➢ Production capacity according to the economy of scale ➢ Plant producing only a single product, i.e. bioethanol ➢ System emissions to the environment just within the limits of regulations
Barley straw	➢ Optimization of the system inputs ➢ Holistic valorization of the crop ➢ Minimization of the system emissions to the environment ➢ Maintaining soil quality	➢ Maximization of barley straw yield per hectare ➢ Production capacity according to the economy of scale ➢ Plant producing only a single product; i.e. bioethanol ➢ System emissions to the environment just within the limits of regulations

Taking into consideration the "Best practice" and "Maximum profit" concepts, as well as the specific characteristics and peculiarities of each studied feedstock, the evaluation of the 12 sustainability indicators was realized (see Table 2).The ranking score for each case study was produced by the average of the positive (2), negative (0) or neutral (1) impact of each of the 12 indicators, estimating the sustainability of each test feedstock. In Table 4, the analytical ranking score for each case study is presented.

Table 3
Main characteristics of the examined feedstocks

	Agro-food industry by-products
Main outputs (products)	Multi-product (animal feed, energy product etc.)
Seasonality	Yes
Inputs	Low input (since the inputs can be considered as allocated to the main product, the wheat and barley grain)
Land use	Low input
Water use	Low input
Rotation time	Short time
Competition	Food /Feed

Table 4
"Biomass Sustainability Index (BSI)" according to "Best practice" vs "Maximum profit" scenarios

	Wheat bran		Barley straw	
	Best practice	Maximum profit	Best practice	Maximum profit
1. Soil (erosion vs. conservation practices)	1	1	2	0
2. Nutrients (losses vs. rational management)	1	1	1	0
3. Fossil fuels ("hidden" links vs. de-coupling)	1	1	1	0
4. Water (wasting/degrading vs. efficient use)	1	0	2	1
5. Mobilisation of elements (pollution vs. control)	2	1	2	1
6. Impact on climate (GHG vs. green accounting)	1	1	1	0
7. Land use ("fuel or food" vs. biorefineries)	1	1	2	1
8. Biodiversity (monoculture vs. agroecosystem)	1	1	2	1
9. Social acceptance (concerns vs. consensus)	1	1	2	1
10. Human health (ecology vs. economy)	1	1	2	1
11. Employment (human vs. development and technology)	1	1	2	1
12. Regional development	1	0	2	1
Overall score	1.1	0.8	1.8	0.7

In the case of wheat bran (see Table 4 and Fig.4), the indicator soil was characterized as neutral in both scenarios, since no apparent impact on the erosion was expected. Moreover, the indicators nutrients and fossil fuels were characterized as neutral in both scenarios, since the resources used for the agricultural activities can be allocated to the main product of the process, which is wheat grain. Within the best practice approach, the biofuel production process is not expected to have a significant impact on water resources. Furthermore, in both scenarios no expected impact on the biodiversity and human health could be noted, which will be a function of the seed biofuel production rather than of the main product demand. In both studied scenarios, there are indicators that are characterized as positive towards sustainability. Specifically, the potential use of residues as soil enhancer or animal feed will most probably decrease the fossil fuel use. Moreover, the LCA studies carried out indicate that the use of oil containing agricultural or industrial wastes has a positive impact on multiple pollution related issues, such as the mobilization of elements and GHG emissions. Furthermore, regarding local employment and regional development, an overall positive impact was estimated, although it is not expected to have a really important direct or indirect impact thereupon, given that the production scale will be limited and the whole sector is not a labor intensive one (especially given that the main crop product, being much more valuable takes most of the credits for the cultivation and pretreatment phase). In addition, wheat bran is currently used as food. Therefore, its use as a biofuel raw material will create an indirect land use change. However, it is assessed that the best practice approach will limit the actual impact on the food supply chain (i.e. only low quality oil to be used for biofuel production). Finally, the current use of wheat bran will not be affected, since within the "Best practice" approach the biofuel production will be totally integrated in the current system, through the synergies exploitation, gaining societal acceptance.

In the case of the barley straw feedstock, the cultivation is not expected to have an impact on soil and nutrients under the best practice conditions, where part of the crop and part of the system co-products will be left on the field after harvesting, ensuring the rational management of the nutrients, while the maximum profit approach promotes the extensive use of nutrients for the increase of production.

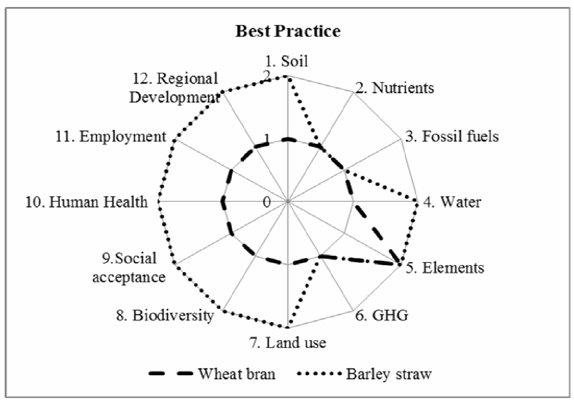

Figure 2: "Best practice" scenario for both selected feedstocks

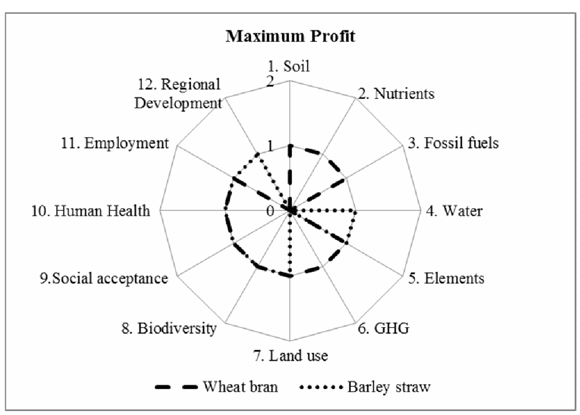

Figure 3: "Maximum profit" scenario for both selected feedstocks

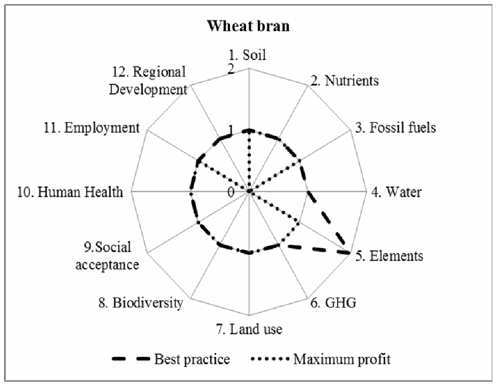

Figure 4: “Best practice” vs. “Maximum profit” scenarios: the case of wheat bran

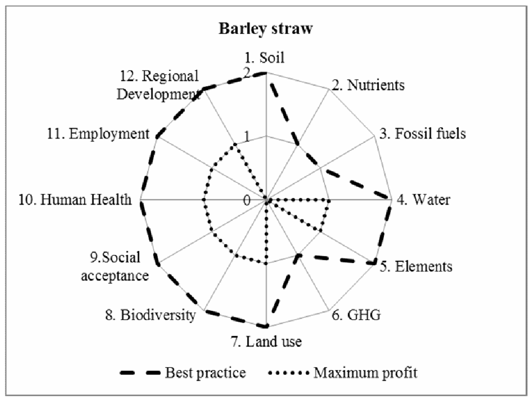

Figure 5: “Best practice” vs. “Maximum profit” scenarios: the case of barley straw

On the other hand, the whole culture and collection/harvesting processes will require fossil fuel consumption, even under the best practice conditions. Regarding irrigation, water use gives a negative water balance, however considering that under the best practice conditions this type of culture will not be worse than other already existing agricultural products on the same land, the overall impact is considered neutral. Moreover, in the “Best practice” scenario, the rational use of fertilizers and insecticides and the return of the nutrients to the system can keep the system in equilibrium, whereas in the “Maximum profit” scenario the intensive use of fertilizers is promoted for increased productivity. Furthermore, the use of agricultural land for the production of a biofuel feedstock of low productivity (under Greek conditions) will definitely have a negative impact. Despite that, the best practice approach could ensure the balanced use of the ecosystem. Given that the specific feedstock is already used for food products, the social acceptance is expected to be an issue only from the perspective of the maximum profit concept. Finally, the use of barley straw as a biofuel feedstock does not show any significant impact on local employment and regional development given that the land use change (shifting from another type of culture to barley) is considered to add very limited value to the local economy.

Table 5
Total BSI score according to “Best practice” vs. “Maximum profit” scenarios

Feedstock	Best practice	Maximum profit
Wheat bran	1.1	0.8
Barley straw	1.8	0.7

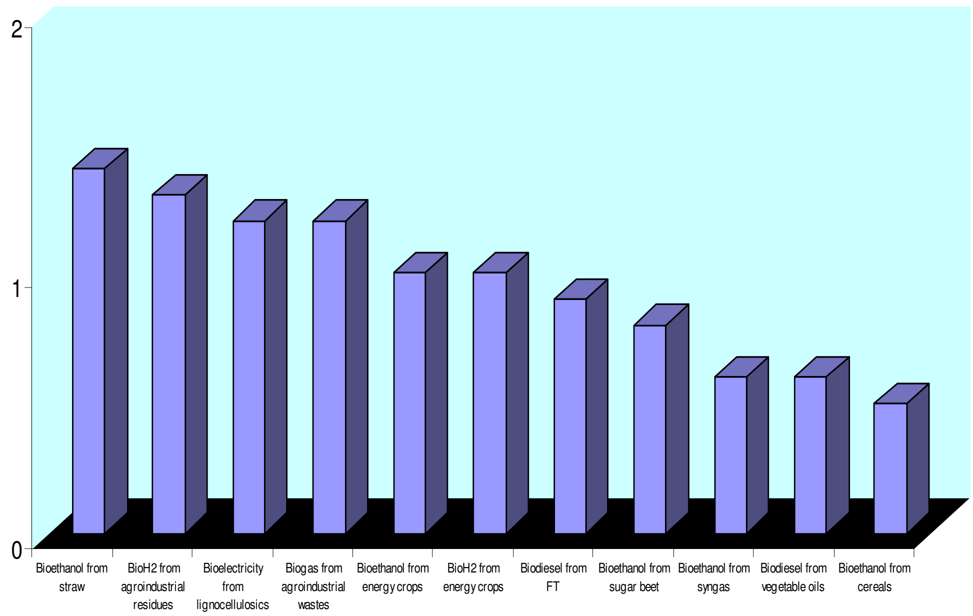

Figure 6: BSI of various biofuels[7]

According to the total BSI score (see Table 5), the two selected feedstocks show significantly different performance in the case of the "Best practice" scenario, with barley straw to be distinguished. Specifically, the score of barley straw is close to the excellent score of 2 units, due to its great performance in the second and third vectors, "Maintaining key natural cycles and ecosystem services" and "Social acceptance – Income", respectively. On the other hand, wheat bran slightly passes the basic score of 1 unit being marginally acceptable, with its impact being minor for the receiving environment without creating any specific disturbance. Finally, in the case of the "Maximum profit" scenario, both feedstocks show equal performance, as the difference of 0.1 units is not significant. In this case, the use of both feedstocks worsens the socio-environmental sustainability in the study region.

Other biofuels

A demonstration of the application of the biomass-to-biofuels sustainability mapping tool to energy crops and common agro-residues, which are potential feedstocks considered for biofuel production, is provided in Fig.7. According to Fig.7 and the sustainability indices of each of the examined cases, it is obvious that first generation biofuels do not appear to be sustainable, by any means. Their Score-Index is much lower than the score of one, which is the lowest limit for any chain to be characterized as feasible and sustainable. The use of this new mapping tool can also be useful in designing multi-feedstock supply chains, according to the regional biomass potential, the desired plant capacity, and other factors, such as seasonal biomass availability patterns.[7]

CONCLUSION

The creation of a tool that will be used for efficient comparison of different biomass-to-biofuels systems and rational decision-making in this field is therefore considered as a major outcome of this work. The proposed sustainability index can be used to assess the environmental feasibility of any feedstock, and feedstock mix, and thus of the biomass supply chain up to the stage of biofuel generation. Moreover, the tool can be used to analyse and utilise data from both the literature and the market in order to compare different feedstocks on an equal basis.

It should be pointed out that the figures used in the above reported examples should be considered as an indicative application of the methodology, based on European mean values and conditions. Applying the tool to more specific, region-based data, where feedstock availability, depending on the competing applications, as well as the seasonal patterns, weather conditions, etc. will be taken into consideration, is expected to produce results deviated from the outcomes of the presented case study. Consequently, the decision process, which will be based on this tool, will be affected by the landscape as a background for these parameters, producing the input for a unique and customised biomass exploitation strategy for each region.

The whole biomass-to-biofuels supply chain concerns a multi-step complex system. Each step generates various co-products/residues/wastes, depending on the selected primary source/supply/refining configurations. The type and quality of these parameters could play a crucial role in the environmental feasibility of the whole system.

To conclude, the transition to more efficient biofuel production systems seems to be a necessity that cannot be ignored. The already existing production systems, having fulfilled their pioneering role, have to be reassessed, within a unified and objective framework, as far as their sustainability is concerned. The proposed approach can provide an easy-to-use tool combining the systematic and in-depth system analysis with an expert-based evaluation system, facilitating the user-friendly screening of potential biomass-based energy production pathways.

The objectivity, the weight and reliability of the results obtained from the suggested sustainability assessment tool could be ensured through rating the indicators by a multidisciplinary biofuel stakeholders panel, composed of experts in biofuel issues coming from academia, industry, rural economy and local community.

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