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Integrating agronomic factors into energy efficiency assessment of agro-bioenergy production – A case study of ethanol and biogas production from maize feedstock

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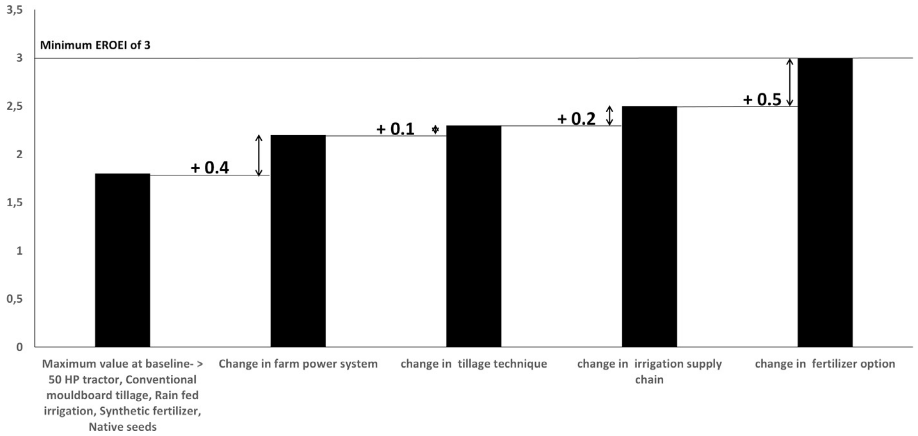
HIGHLIGHTS

- Effect of agronomic factors on agro-bioenergy LCA were considered.
- Effect of farm power, irrigation, fertilizer, tillage and seed options were assessed.
- EROEI of ethanol and biogas from maize increased to 2.1–3 and 15–33.9 respectively.
- Hybrid and GMO seeds have neutral to negative impacts on biofuel's energy efficiency.
- Fertilizer has the highest overall impact on the energy efficiency of biofuels.

GRAPHICAL ABSTRACT



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ABSTRACT

Previous life cycle assessments for agro-bioenergy production rarely considered some agronomic factors with local and regional impacts. While many studies have found the environmental and socio-economic impacts of producing bioenergy on arable land not good enough to be considered sustainable, others consider it still as one of the most effective direct emission reduction and fossil fuel replacement measures. This study improved LCA methods in order to examine the individual and combined effects of often overlooked agronomic factors (e.g. alternative farm power, seed sowing, fertilizer, tillage and irrigation options) on life-cycle energy indicators (net energy gain-NEG, energy return on energy invested-EROEI), across the three major agro-climatic zones namely tropic, sub-tropic and the temperate landscapes. From this study, we found that individual as well as combined effects of agronomic factors may improve the energy productivity of arable bioenergy sources considerably in terms of the NEG (from between 6.8 and 32.9 GJ/ha to between 99.5 and 246.7 GJ/ha for maize ethanol; from between 39.0 and 118.4 GJ/ha to between 127.9 and 257.9 GJ/ha for maize biogas) and EROEI (from between 1.2 and 1.8 to between 2.1 and 3.0 for maize ethanol, from between 4.3 and 12.1 to between 15.0 and 33.9 for maize biogas). The agronomic factors considered by this study accounted for an extra 7.5–14.6 times more of NEG from maize ethanol, an extra 2.2–3.3 times more of NEG from maize biogas, an extra 1.7 to 1.8 times

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more of EROEI from maize ethanol, and an extra 2.8–3.5 times more of EROEI from maize biogas respectively. This therefore underscores the need to factor in local and regional agronomic factors into energy efficiency and sustainability assessments, as well as decision making processes regarding the application of energy from products of agro-bioenergy production.

1. Introduction

The global agricultural-bioenergy value chain is very diverse [1–3], broad scientific generalizations on the sustainability of bioenergy produced on arable lands without adequate consideration of the effects of certain local and regional (farming system level) agronomic factor options (e.g. alternative farm power, irrigation, tillage, fertilizer and seed sowing options etc.) can lead to inaccurate conclusions regarding their local and regional applications for socio-economic functions (e.g. fossil fuel replacements, vehicle fuel etc.) [4–6]. In response to this, this study modified the boundaries of previous life cycle assessment (LCA) frameworks, in order to estimate the effects that these agronomic factor options have on the sustainability and applicability of agro-bioenergy production systems.

Previous LCA for sustainability assessment often consider conventional tillage as the norm for biomass produced from arable land; however in practice many farmers adopt conservation tillage (e.g. no till, stubble mulch, chisel, disk, ridge-plant, strip-till etc.) in order to minimize the effects on soil degradation processes [7,8]. This is a local factor that is often overlooked in most LCA studies for agro-bioenergy production [9,10]. Sustainability assessments of agro-bioenergy systems should not only feature conventional tillage but also conservation tillage systems (i.e. reduced and no-till systems), whenever adopted [11–13].

The effects of the use of alternative farm inputs e.g. animal manure or biogas digestate as opposed to synthetic fertilizers, hybrid or GMO (genetically modified organisms) seeds against the use of native seeds etc. are also rarely considered in estimating the NEG and EROEI across bioenergy production chains from arable land [2,14]. While previous LCAs for biomass production on arable land assume the use of only high horse-power (HP) tractors (e.g. four wheel drive 50 HP and above) [7,10], small-scale farmers (especially in developing countries) can only afford lower HP tractors (e.g. single-axle tractors) and in some cases only animal and/or human labour [8,12]. Even though production by small scale farmers is limited by scale and therefore may not be suitable for large scale (commercial) bioenergy production, in the event of severe energy demand (occasioned by climate change mitigation restrictions and global fossil fuel depletion/scarcity), small scale farmers (especially in rural areas) will need energy to drive their agrarian based local economy, and may therefore be forced to form networks (i.e. partnerships or cooperatives) aimed at harnessing their bioenergy potential (using energy crops, agricultural wastes etc.), as well as other renewable energy sources [15,16]. Also, due to the difference in agro-ecological and climatic conditions, the effects of using different irrigation options as opposed to production under rain-fed conditions is rarely discussed within the framework of LCA studies for agro-bioenergy systems [8,17].

Previously, the sustainability of bioenergy production has often been assessed in terms of LCA based energy efficiency indicators such as the net energy gain (NEG) and energy return on energy invested (EROEI) [18,19]. This is because the net energy gain (NEG) indicator measures the effectiveness of bioenergy production activities in contributing to set renewable energy targets [18,20] on the one hand; while the energy return on energy invested (EROEI) is a fair indicator of the capacity of a bioenergy production activity to support continuous socio-economic functions, regardless of the effects of externalities such as soil degradation, water pollution, biodiversity impacts, price fluctuations etc. [17,19]. In this study, we assessed the sensitivity of these energy efficiency indicators (NEG and EROEI) to the above listed agronomic factors using maize feedstock cultivation for ethanol and biogas production at generic agro-climatic zone levels (i.e. tropics-Latitude 0–23.5°N and S, sub-tropics- Latitude 23.6–40°N and S and temperate-Latitude 40.1–60°N and S) as case studies. A wide range of data across the different agro-climatic zones was examined, in order to capture the extent of the sensitivity of the two energy efficiency indicators to the listed agronomic factors globally. This study explicitly assessed the individual and cumulative effects of the listed agronomic factors on NEG and EROEI, especially with respect to the feasibility of application and usage for different energy related socio-economic functions (e.g. fossil fuel replacements, vehicle fuel etc.). The information on the effects of agronomic factor options will offer improved understanding relevant for future energy efficiency improvements to decision makers (from an LCA perspective).

Maize was chosen as a case study because it is the agricultural biomass feedstock with the highest contribution (at least 35%) to global biofuel production [21,22]. Maize is widely cultivatable globally across several agro-ecological and climatic conditions because it exhibits high photosynthetic and water-use efficiency properties, even under conditions of drought, high temperatures, and nitrogen or CO_2 limitations [7,23]. Maize has relatively high carbon fixation and assimilation capacity [24,25]. It is also capable of high yield and high energy output-input ratio (in terms of energy use efficiency or fossil energy intensity) when compared to other major crops (maize-4.0–7.7, soybeans-3.2–4.6. rice-2.2, winter wheat-2.1, potato-1.3, sugar cane-1.2.2.1 etc.) [10,24,26–28]. Since analysis within this study focus more on the effects of field-based agronomic factor options (and not production steps that vary in energy consumption from one energy conversion technology to the other), the methodology adopted, as well as the findings and inferences from this study can be further applied and extrapolated for other crops grown for energy production purposes, as well as other biomass production activities on arable land. Ethanol and biogas production technologies were chosen because they are both widely used globally. Ethanol and biogas are particularly important because they are in high demand for meeting future global sustainability targets such as global greenhouse gas emission reduction, fossil fuel replacement and renewable energy targets [29,30]. Ethanol production has contributed immensely to the meeting of different biofuel mandates (e.g. E10, E15, E25 and E85 gasoline mix, as well as E100) aimed at reducing fossil fuel consumption and associated greenhouse gas emissions [2,12]. Biogas production on the other hand has been widely promoted for its capacity to utilize wide range and different mixes of biomass flows (waste biomass inclusive); and its ease of implementation in smaller units [20,31].

2. Methodology

The methodology involved a life cycle assessment (LCA) approach, which substitutes individual energy and material flows

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