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Application of multi-metric analysis for the evaluation of energy performance and energy use efficiency of sweet sorghum in the bioethanol supply-chain: A fuzzy-based expert system approach

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HIGHLIGHTS

- Several agro-energy management strategies have been applied to sweet sorghum to produce bioethanol.
- 4 metrics used for the energy performance and efficiency provided contrasting results.
- Fuzzy-based system allowed define a single, clear multi-metric indicator.
- The framework defined the management practice with the best energy performance and efficiency.

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ABSTRACT

This study uses a fuzzy-based expert system to assess the impact of soil treatment (conventional tillage vs. no-till) and mineral nitrogen supply (0, 75, 150 kg N ha^{-1}) on the energy performance and efficiency of sweet sorghum in the bioethanol supply chain. The different agronomic strategies were compared using four energy indicators: energy yield, net energy gain, energy use efficiency and energy return on energy invested. The highest productivity in bioethanol and energy yield required the full energy input management, while conventional tillage without N fertilization resulted in the best agronomic strategy in terms of net energy gain. The highest energy use efficiency was achieved from the lowest-agro-energy-input cropping system (no-till without nitrogen fertilization). Uncertainty and vague information resulted from the investigation of multiple different metrics. As a consequence, aggregating information into a single multi-composite indicator can be useful. The multi-metric indicator based on the fuzzy-based expert system clearly indicated the behavior of a cropping system in optimizing the energy performance and efficiency of the sweet sorghum-bioethanol chain in a specific pedo-climatic context. The optimization between energy input and output was achieved by the agronomic strategy that combined conventional tillage without nitrogen fertilization, while no-till with 75 kg N ha^{-1} was inefficient. The proposed method is flexible in building a synthetic index to assess the sustainability of biomass production for energy purposes. An operative module for evaluating the energy performance and energy use efficiency of a cropping system through a multi-composite metric is also provided in this paper.

1. Introduction

Europe is steadily increasing the production of liquid biofuels by introducing biomass-fueled applications in their energy balance [1]. Indeed, energy crops are renewable sources that can reduce environmental loads due to the combustion of the fossil fuels [2,3]. Energy crops and derived biofuels are expected to lead to environmental, social and economic improvements [4–7]. However, these benefits can be achieved on the basis of appropriate energy crops under soil management and agronomic techniques that guarantee adequate energy performance in an environmentally friendly way.

In view of these targets, several studies have focused on biofuel production from energy crops, as well as the energy performance and energy efficiency of their cropping systems [8–10] and the reduction of greenhouse gas emission through the replacement of fossil fuels with biofuels [11]. The energy balance and energy efficiency of a bioenergy cropping systems improve by reducing the external inputs at the field scale while the crop productivity does not change dramatically. For several species (e.g., corn, sugar-beet, sorghum) the reduction of the agro-input levels does not affect the productivity, which is usually

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attained under conventional tillage [7,12]. Conversely, the energy performances of some crops [13] are significantly compromised under soil and crop strategies with low energy supply. For winter sorghum, an energy crop, soil managed with reduced energy input negatively affects the water-use efficiency and, in turn, the grain yield [14].

Globally, the crop energy balance is defined as the difference between the gross energy output and the energy input spent in the cropping system [15]. For energy crops, the sustainability of a specific biomass-bioenergy supply chain is assessed by the balance between the energy input (i.e., fertilizers and pesticide manufacturing and field application, diesel used in tractors and implements for soil tillage and harvesting, fuel or electricity for irrigation) supplied to the cropping system and the energy output, according to a specific bioenergy conversion process (e.g., bioethanol, biodiesel, biomethane, heat and electricity from biomass combustion [16]). However, the energy performance and energy efficiency can be assessed by means of several energy indicators at different stages of the supply chain, in a specific pedo-climatic context and under several cropping systems. Examples of energy indicators are energy yield (*EY*), net energy gain (*NEG*), energy use efficiency (*EUE*) and energy return on energy invested (*EROI*), the latter representing the ratio between the amount of energy delivered by a biofuel plant and the energy used as input in the process to produce the energy [17]. Each indicator can partially highlight the energy performance and/or energy use efficiency of a bioenergy crop in response to different energy management schemes, as different metrics can be put in place for specific energy analyses (e.g., *EY* and *NEG* for the energy performance and *EROI* and *EUE* for the energy efficiency). Moreover, these energy indicators may provide contrasting conclusions, making the assessment of environmental and energy sustainability of the upstream process (production of feedstock) hard to recognize.

A comprehensive, quick and striking outcome can be obtained by taking into account the energy indicators simultaneously and aggregating them into a single output. This approach requires a combination of multiple indicators, which after being standardized and homogenized are aggregated into a single parameter, to clearly express their meaning into a specific metric. Aggregating several metrics in a single parameter poses mathematical (sum, multiplication, or a combination of both) and conceptual problems if a process concerns parameters differing in nature, dimension and range of possible values [18].

A suitable approach to simultaneously and unambiguously evaluate the energy performance and energy use efficiency of a bioenergy crop under a specific cropping system is the application of the fuzzy-based expert system [19] or a tool that follows the logic of human thinking, based on decision rules, inference methods and priorities. This approach involves the establishment of a hierarchy of assessment criteria, selected inside suitable, explicitly stated rules and aggregated [20] to make quicker, more efficient and easier to understand the comparisons of the responses from different energy crops and management schemes. Application of fuzzy logic in the field of bioenergy from biomasses has concerned aspects such as the modeling of sustainable production of biofuels from conventional and advanced feedstock [21]; a method to select the appropriate energy crop mix with regard to sustainability [22] (climate and environmental pressure); and the development of a multi-regional fuzzy input-output model to optimize biomass production and trade under resource availability and environmental footprint constraints [23].

To date, there is a lack of information regarding the use of the fuzzy logic to optimize field/crop management to make the whole bioenergy supply chain energetically and environmentally sustainable. However, investigations on the energy behavior of energy crops are numerous but confined to field assessments. Most of these studies focused on the energy performance and efficiency of crops assessed by individual energy metrics [24–26] or by means of multiple ed [8,27,28]. None of these studies addressed the uncertainty accompanying the evaluation of inhomogeneous energy indicators with different outcomes. This is a crucial aspect in the decision-making process that concerns the environmental and energy sustainability of the upstream process in the bioenergy supply chain; some metrics are oriented towards energy performance, others on energy efficiency. As a result, the decision-making process may involve an intensive use of agro-inputs to maximize energy yield, or if energy saving is favored, the potential energy productivity of a crop could be adversely affected.

Optimization of the procedures for bioenergy conversion at the processing plant through multi-criterion assessment have been widely discussed [29–31], while scarce data are reported concerning the optimization of the upstream process (e.g., production of feedstock). A multi-criterion assessment has been applied to soybean crops to optimize the energy consumption in the field [32]. However, the research was focused on the crop yield and not integrated into an actual bioenergy production context. This oversight is a gap that needs to be filled. The energy and environmental sustainability of the whole bioenergy supply chain (e.g., bioethanol supply chain) depends to a large extent on the performance and energy efficiency of feedstock production [7].

Starting from these premises, the scope of this study was to develop a framework integrating all the main components of the bioethanol supply chain to model (through explicit algorithms) the energy behavior of the whole supply chain as affected by of agro-energy inputs. The developed framework should contribute to a more efficient bioenergy supply chain, promoting the sustainable and eco-friendly production of bioethanol from sweet sorghum, with a particular focus on production of feedstock.

The mathematical structure, intended to attain an integrated, multi-metric indicator based on the fuzzy-logic methodology, was built according to a hierarchical structure, as follows: (i) collecting data from field experiments; (ii) creating several *in silico* cropping systems; (iii) determining the main performance and efficiency energy indicators; (iv) setting the decision rules, weights and inferences for the fuzzy-based expert system; (v) computing a multi-metric energy indicator by using the data measured from the experimental fields; and (vi) recommending the appropriate sweet sorghum agro-techniques for optimizing the energy performance and crop energy efficiency.

2. Materials and methods

2.1. Field experiment

The data presented in this study were collected from a field experiment carried out in Foggia (latitude, 41°88′7″ N; longitude, 15°83′05″ E; altitude, 90 m a.s.l.), in southern Italy (Apulia region), as described in detail by [27]. Sweet sorghum was cropped over 3 growing seasons, from 2010 to 2012. The soil was a vertisol of alluvial origin, Typic Calcixeret [33], classified as silty-clay; field capacity water content, 0.396 $m^{-3}\,m^{-3}$; permanent wilting point water content, 0.195 $m^3\,m^{-3}$; and available soil water, 202 mm m^{-1}. The climate was accentuated thermo-Mediterranean [34], with temperatures below 0 °C in winter and above 40 °C in summer. The annual rainfall (mean, 550 mm) was mostly concentrated in the winter months. Sorghum was sown at the beginning of May and harvested before heading (mid-August) to maintain adequate water content (75%) in the biomass, as necessary for the fermentation process. Irrigation was scheduled according to water crop requirements, as estimated by soil water status variations (measured at 7-day intervals through the gravimetric method in the soil layer 0–0.8 m deep). Each time the water used by the crop reached 60 mm, irrigation was activated. The total amount of irrigation water was 120 mm, 176 mm and 300 mm in the first, second and third experimental years, respectively. Seasonal rainfalls were 79, 73 and 68 mm during the growing seasons 2010, 2011 and 2012, respectively. The different cultivation techniques concerned the soil tillage and nitrogen fertilization.

Conventional tillage (*CT*) was performed with a shallow plowing (soil depth, 25 cm) by means of a five-furrow plow, followed by disc harrowing, power harrowing, and sowing with a precision driller. For