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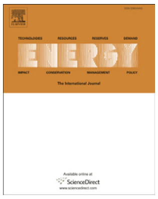

Energy life-cycle analysis of soybean biodiesel: Effects of tillage and water management

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ABSTRACT

The purpose of this paper is to carry out an updated energy Life-Cycle Assessment of soybean biodiesel produced in the Pampean region of Argentina and to analyze the influence of different tillage systems on the Energy Return on Investment (EROI). It aims to identify the processes, materials and methodological aspects that significantly affect biofuel EROI. The procedure considers the main processes and operations of both the agriculture and industrial stages of biofuel production system, but the main novelty of this study is linking EROI with farming and conservation practices and not in the chemical processing of the oil. The results obtained represent the current average energetic performance of soy-based biodiesel produced in the considered region. The EROI values are very encouraging, demonstrating that this biodiesel provides a net energy gain. The results also show that conservation agriculture and the implementation of practices that improve crop yield do not always determine better energetic performance. Sensitivity analysis confirms that EROI values of soybean biodiesel are more responsive to methodological choices such as the system's boundary definition and the choice of the allocation method rather than to the physical aspects of the productive system such as tillage and water management practices.

1. Introduction

Two global threats have fostered the development of biofuels, mainly from the beginning of the current century. One is the proximity of the global oil peak, whose exact date of occurrence is unknown, but which will undoubtedly occur. The other is the economic, social and environmental consequences of the global climate change.

Biofuels appear to be an opportunity for tackling these two problems, suggesting a potential for saving conventional fossil fuels while mitigating climate change. However, they are not exempt from controversy, ranging from land/water competition with food production, the threat to biodiversity, and the lack of cost effectiveness, among others [1].

This discussion is of utmost importance, and the controversy should be addressed by science, allowing these negative aspects to be solved or diminished. However, these efforts will only be compensated if biofuels' essential attribute, the capacity for providing net energy, is verified.

One of the indicators commonly used to verify this capacity is Energy Return on Investment (EROI), calculated as the ratio between the energy delivered by the biofuel and the energy required to deliver that energy. If EROI is greater than 1.0, there is a net energy gain; otherwise, the biofuel is an energy sink. Biofuels with an EROI lower than 1.0 cannot substitute fossil fuels; on the contrary, they accelerate their depletion. Clearly, biofuel sustainability (as any other energy source) relies on the size of the margin between EROI and 1.0 [2–4].

Many studies have been performed to evaluate the EROI of biofuels, with the aim of demonstrating their high-energy value and the important role they can play in the energy sector [3]. However other studies show only modest energy advantages which do not compensate others environmental and social drawbacks [5], and others report EROI which suggest that more energy is required to produce the biofuel than is contained in the biofuel itself [6]. These are just a few of the many studies illustrating the important role that EROI plays in the decision-making process regarding energy sources and vectors.

Soybean (*Glycine max*) is one of the most important feedstocks

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for biodiesel production, as indicated by the huge amount of soybean biodiesel EROI studies that can be found in literature [7–12]. There are few studies on the cumulative energy demand and the energy balance of Argentine biodiesel [13–16]. These studies have been developed for different regions of the country, analyzing different technology levels and following different methodological considerations. However, no studies linking EROI with farming and conservation practices have been found.

No-tillage is a widespread conservation agricultural practice in Argentina that consists in the absence of plowing and in the presence of a permanent soil cover with previous crop stubble. According to the United Nations Food and Agriculture Organization, no-tillage is one of the main factors that favored the global boom in soybean production in the last decade [17]. Currently, about 135 million hectares are cropped around the world under no-tillage [18] concentrated in a few countries: the United States, Brazil and Argentina among them.

The aim of this study is to determine the EROI of soybean biodiesel produced in the Pampean region of Argentina, considering different practices in crop management: a) conventional tillage; b) no-tillage; c) rainfed cultivation and d) cultivation under supplementary irrigation. In addition, the influence of system boundaries and different allocation methods commonly used is studied.

1.1. Soybean biodiesel production in Argentina

Over eighty-six percent of Argentine soybean is produced in the Pampean region situated in the east central region of the country. This region is home to the main vegetable oil and biodiesel hub of Argentina and has specific infrastructure for export through the Parana-Uruguay waterway.

In the Pampean region, 88% of the total cultivated area is under no-tillage [19]. This agricultural technology does not harm the soil, often improving its physical, chemical and biological conditions, thus increasing productivity levels per hectare of occupied land. Around 70% of the area under no-tillage is sown between October and November (early soybean), and the remaining area during December (late soybean). Typically, the late soybean is planting after a winter crop and develops its cycle during a limited period, exposing itself to unfavorable environmental conditions (such as early frost, insufficient incident solar radiation or temperature). Therefore, crop yields are usually lower for late soybean than for early soybean.

In addition, some production schemes respond to conventional tillage, which involves disking, plowing, and other methods of tilling up crop stubble left behind after harvest. This technology reduces the presence and incidence of pests and diseases, but increases the risk of soil erosion.

The rainfall rate of the Pampean region allows soybean cultivation under rainfed conditions. However, there is an increase in the land area occupied by soybean under supplementary irrigation, usually supplied from groundwater sources [20], which allows achieving more stable yields, advancing the planting date and implementing an Integrated Pest Management (IPM) system. The IPM system allows for a more rational use of pesticides, which are applied to remove only target organisms.

At harvest time, soybean moisture content is 16%, which should be reduced up to 10% to optimize storage and subsequent entry into the oil-milling process. Solvent extraction is the most common technology for production of vegetable oil in Argentina [21]. This process includes the extraction of soybean oil, soybean meal desolventization, micelle (oil solution in solvent) distillation, gas condensation and solvent recovery. Later, the refined soybean oil is subject to alkaline transesterification to obtain soybean oil Methyl Ester (MEs) and glycerol.

2. Methodology: Life Cycle Assessment and energy return on investment

Life Cycle Assessment (LCA) is a tool for evaluating the potential environmental impacts generated by products and services during their whole life cycle, from raw material acquisition through manufacturing, use, end-of-life treatment, recycling and final disposal. The International Organization for Standardization (ISO) has standardized this method in ISO 14040:2006 [22] and ISO 14044:2006 [23]. An LCA provides comprehensive evaluations of all upstream and downstream inputs and multimedia environmental emissions. The environmental impact information provided by an LCA can be connected to many impact categories, such as abiotic resource depletion, global warming potential, energy consumption or human toxicity, to name just a few. Many LCA studies consider only a single environmental issue instead, like for instance global warming potential (known as the product's carbon footprint), the impact of water use (known as the product's water footprint), or the amount of energy required for the creation of a given product.

There are different useful indicators that have been devised for estimating product energy efficiency from a life cycle perspective. Their calculation methodology includes an energy balance, where the energy inputs and outputs are compared through arithmetic operations. EROI is the most widely used indicator, calculated as the ratio between the energy obtained and the total energy spent to obtain it. The concept was coined by ecologist Charles Hall for the metabolism of fish [23]. Later on, its use was extended to human activities such as fuel production [2–4]. An EROI of 1.0 is the cutoff point for an energy source [24].

Of the many impact categories that can be included in a product's LCA, only energy will be examined in this paper, using the standard energy return on investment ratio ($EROI_{ST}$) indicator, calculated as the ratio between the energy output and the sum of the direct and indirect energy consumed to generate that output [4] (Eq. (1)).

$$EROI_{ST} = Energy\ \ output/(Direct\ energy\ input + Indirect\ energy\ input) \quad (1)$$

Since both the numerator and denominator of Equation (1) are expressed in the same energy units, the result is dimensionless. The numerator of the EROI formulae, i.e. the energy that the biofuel can provide (usually expressed as Lower Heating Value), does not present significant variability, when the same biofuel produced from the same feedstock is considered. The denominator - the energy consumed to obtain the biofuel - presents a wide variability instead, some of them due to the intrinsic characteristics of the system, and other to methodological choices.

The main characteristics of the system that influence EROI are the crop yield, the amount and type of fertilizers and pesticides applied, the farming and harvest technology, the origin of the inputs, the transportation distances, the climatic conditions, the irrigation system and the processing technology among others.

The methodological issues are related with the calculation procedure, which includes some conceptual and practical choices such as the definition of the functional unit, system boundaries, data collection and allocation procedure.

In the following, both the intrinsic characteristics and the specific methodological issues of the system under study are described.

2.1. Description of the system

The production of soybean biodiesel is composed of two main stages: agricultural and industrial (Fig. 1). In general terms, the agricultural stage includes site preparation, seed inoculation,