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Research article

Assessment of the water-energy-food nexus in the life cycle of energy products

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ABSTRACT

Given the urgent need to achieve energy security and transition from conventional to renewable energy sources, the energy sector is expanding rapidly. However, this growth often involves trade-offs with food and water resources. One way to address this complex interplay is to adopt the Water-Energy-Food nexus within a Life Cycle Assessment. This approach allows the analysis of interrelationships among the three sectors, aiming to foster synergies and minimize trade-offs. While numerous indicators exist to quantify the water-energy relationship, no similar approaches for the energy-food relationship could be found. To bridge this gap, in this paper, we introduce a novel indicator that measures the amount of food that could be produced causing the same land use impact in form of biodiversity damage as 1 MJ of the energy product. Together with another existing indicator that measures the water scarcity footprint per megajoule, a new framework for the analysis of the Water-Energy-Food (WEF) nexus of energy products is developed. Additionally, we present an optional net factor for both indicators. This factor helps to consider the energy use within the product's processes, contributing to a more comprehensive analysis. In our case study, we implement the outlined framework by examining biodiesel production in Argentina. We specifically analyze the impacts of two distinct agricultural technologies—Early and Late Soybean—on the Food and Water sectors. Our findings reveal that for every megajoule of the evaluated product, one could produce 62 or 93 kcal of food causing the same species loss. Additionally, the production process incurs a water scarcity footprint of 6.5 or 6.8 liters per megajoule, depending on the technology used. The proposed framework offers a means to mitigate the water and land use impacts associated with energy products. Consequently, it has the potential to enhance the WEF nexus.

1. Introduction

A constant supply of water, energy, and food is essential for human well-being. Despite the current scarcity of these resources in numerous regions [1–4], the global demand for them is expected to increase significantly [5,6]. As the growing scarcities reveal the interconnectedness of the different resources [7,8], the idea of addressing them in a unified Water-Energy-Food (WEF) nexus has gained wide recognition [9]. This approach considers the trade-offs and synergies between the three sectors and aims to optimize them in order to minimize environmental and social impacts [10]. It also includes the identification and description of hotspots that are

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Abbreviations

ACVF	Average Calorific Value of Food production
ALUF	Average Land Use impact of Food production
AWARE	Available WAter REmaining
CED	Cumulative Energy Demand
CV	Calorific Value
EC	Energy Content
EROWI	Energy Return on Water Investment
ES	Early Soybean
FIPE	Food Impact per Produced Energy
FINPE	Food Impact per Net Produced Energy
LCA	Life Cycle Assessment
LHV	Low Heating Value
LUP	Land Use impact of the energy Product
LS	Late Soybean
MEs	Methyl Ester
WEF	Water-Energy-Food
WIPER	Water Investment Per Energy Return
WIPNER	Water Investment Per Net Energy Return
WSF	Water Scarcity Footprint

experiencing or causing significant resource stress in order to strengthen the overall sustainability [11]. The current water and food crises demonstrate the need for more integrative approaches and highlight the ineffectiveness of sector-driven management of the resources involved [8]. As a consequence, the nexus was not only recognized in the scientific literature, but also by policy makers [12,13]. It has been the subject of several international conferences and it is being considered in different policy frameworks [9,12,14].

Within the rapidly expanding energy sector, there is also a growing interest in the WEF nexus. Here, intersectoral relationships can be observed, as technologies may require significant amounts of water or deplete resources critical to agricultural processes [15–18]. Likewise, they can create synergies with the other two sectors, for example when applications protect water resources or agricultural land [19,20]. A particular interest can be observed in the nexus of renewable and low carbon energy sources applied. A wide range of different methodologies can be found that evaluate the sustainability of these technologies given their water, land and food requirements. For example, Gasparatos et al. [21] focused on the regional impacts by assessing the household food security in biofuel producing regions of sub-Saharan Africa. Koizumi [22] used economic models to determine whether the production of energy crops significantly escalates food prices. Meanwhile, Yuan et al. [23] conducted a land-use optimization to mitigate the environmental impacts associated with food and energy crop production, taking into account a minimum availability of food and water to meet basic WEF needs.

One useful tool for quantifying the WEF nexus that helps policy and decision makers to develop effective and inclusive resource allocation strategies is the Life Cycle Assessment (LCA). Here, all inputs and outputs within defined life cycle boundaries are collected and categorized. Subsequently, the data is assessed using impact indicators, such as climate change potential, water scarcity or land occupation [24]. This approach has received a lot of attention, especially since the end of the last century, after it was recognized that the analysis of environmental performance requires the consideration of the entire life cycle. The use of LCA was also encouraged by many governments [25]. Consequently, there are numerous studies applying LCA to determine the environmental impacts of renewable energy technologies [26,27]. Most of them focus on their global warming potential and the energy performance [28–30].

Even though not applied as often, there are also life cycle indicators that can assess water, energy and food impacts. One of them is the Water Scarcity Footprint (WSF). This metric is derived by multiplying the system's water consumption by a characterization factor that reflects the water availability in the specific watershed from which the water is drawn. It provides insight into the reduction of regional water availability and is consistent with the international criteria outlined in ISO 14046:2016, using the Available WAter REmaining (AWARE) - method [31]. It was applied for example by Shi et al. [32] to quantify what production technique of hydrogen has the biggest impact on the local water resources or by Araujo et al. [33] to assess the scarcity impacts associated with water use for the production of different biofuels in different regions of Argentina.

Land use (LU) is another crucial facet that is often quantified in indicators by the physical land occupation of a process or the biodiversity damage it causes [34]. One such example is the land use indicator within the ReCiPe2016 method, which calculates the relative species loss attributable to different types of land use (annual crops, permanent crops, mosaic agriculture, used forest, artificial areas, pastures, and meadows) associated with the studied process. This value is then normalized against the global average species loss caused by crops [35]. As the ReCiPe Methodology quantifies several indicators, it was applied in many studies to compare the performance of different production systems with no special regard to the WEF nexus [36,37].

When determining the energy intensity of processes or products, the Cumulative Energy Demand (CED) serves as a common measure. CED comprehensively considers the total primary energy contribution across the life cycle, encompassing both direct energy usage and indirect or gray energy. This broader perspective incorporates factors like raw material production or equipment manufacturing that might induce indirect energy consumption. Impact assessments are presented for several energy resource categories: fossil, nuclear, biomass, wind, solar, geothermal, and hydro [38]. This indicator was used by Piastrellini et al. [39], for example, in order to assess how much energy biofuels contain in relation to the energy input made throughout the process.

Applying these indicators in an assessment can help quantify the water, land and energy impacts caused by renewable energy products and thus provides insight into their nexus performance. For example, Silalertruksa and Gheewala [40] used LCA indicators to determine the water, land and greenhouse gas impact of a specific biofuel production volume determined by a policy target. They could find that the analyzed scenarios may cause major implications for the water and food sector and worked out recommendations to improve the sustainability.

However, while the presented indicators quantify the impacts in the individual sectors, it's been argued that effective nexus LCA requires multi-sectoral approaches that can capture system linkages [41,42]. This would help to conduct comprehensive analyses, as called for by Mohtar and Daher [11], that would enhance the dialogue with policy makers and the private sector.

Some studies have already introduced such indicators. For instance, Pacetti et al. [43] quantified the water footprint of biofuels using the energy content of the product as their functional unit. This approach shows the trade-off between energy gained and water required and was also applied by Ghani et al. [44]. Similarly, Armengot et al. [45] adopted a comparable strategy termed Energy Return On Water Investment (EROWI) to analyze food production within the nexus framework. They developed an indicator revealing the energy derived from produced food per cubic meter of water used in the process. These indices help to identify the most water-efficient methodologies and to highlight processes causing significant water depletion. However, for examining the impact of energy production on food, no similar nexus LCA indicators could be found.

To address this gap, we present a first attempt to a new indicator. Additionally, we adopt Pacetti et al.'s method [43] to measure the impact of the energy product on the water sector. By combining these indicators, we introduce a novel framework for assessing the WEF-Nexus in the production of energy products. Furthermore, to enhance the comparison of technologies with unequal energy consumption, we introduce an optional factor incorporating the CED, aiding to consider the respective impact of the product per net contained energy.

Biofuels serve as an illustrative example of the WEF interconnection. While they offer opportunities for enhancing energy security and reducing greenhouse gas emissions [46–48], they are associated with substantial water and land footprints [49]. Particularly, first-generation biofuels often rely on food crops [50], leading to a trade-off between acquired energy and the availability of water and food resources. Consequently, the developed indicators will be applied in a case study focusing on soybean (*Glycine max*) oil-based biofuels in Argentina.

2. Methodology

2.1. Nexus indicators

The WEF nexus aims to capture interactions between the three sectors. This study analyses specific connections between two resources, focusing on the energy sector while exploring its ties to the other two sectors. Specifically, we examine the relationships between energy and food, as well as energy and water, assessing the impacts of biofuel production on the availability of these resources. We utilize two indicators: one developed in this paper for the energy-food relationship, and another previously used by Pacetti et al. [43] for the energy-water relationship.

2.1.1. Food-energy indicator

Based on the substantial land requirements for both food and energy production, we introduce an indicator termed Food Impact per Produced Energy (FIPE, [kcal/MJ]). This metric calculates the calorific value of food that can be produced in the evaluated region, causing equivalent land use impacts as 1 MJ of the assessed product. To derive it, we divide the average calorific value of the regionally produced food (ACVF, [kcal/kg]) by the production's average land use impact (ALUF, [m^2 crop eq./kg]). This gives us the average calorific value per unit of land use for the regionally produced food, which is then multiplied by the land use impact of the energy product (LUP, [m^2 crop eq./MJ]) (Ec. 1).

$$FIPE = ACVF / ALUF * LUP \tag{1}$$

ACVF is determined by summing the product of calorific value (CV, [kcal/kg]) and the mass share of the gross production volume (MSF, [−]) of food produced in the analyzed region (Ec. 2).

$$ACVF = \sum_i CV_i * MSF_i \tag{2}$$

To compute ALUF, we multiply the land use impact per kilogram (LU, [m^2 crop eq./kg]) of the same food used in ACVF by their respective MSF, summing the products of all crops (Ec. 3).

$$ALUF = \sum_i LU_i * MSF_i \tag{3}$$

All land use impacts were determined using the land use indicator from the ReCiPe 2016 methodology [35].

2.1.2. *Water-energy indicator*

To demonstrate the strain on regional water availability caused by the energy product, we calculate the water scarcity footprint per kilogram of the product (WSF, [m^3/kg]) like Pacetti et al. [43]. This value is then divided by the product's energy content (EC, [MJ/kg]). In line with the name of the indicator by Armengot et al. [19], we call this indicator within our framework Water Investment Per Energy Return (WIPER, [m^3/MJ]) (Ec. 4).

$$WIPER = WSF/EC \tag{4}$$

In contrast to Pacetti et al. [43], we determine WSF using the AWARE method [31], recommended by the Life Cycle Initiative [51].

2.1.3. *Considering the process's energy demand*

Especially for comparing products with varying energy consumption during production, considering the Cumulative Energy Demand 1.00 (CED, [MJ_input/MJ]) [38] could be beneficial. This indicator quantifies all energy utilized in the process per MJ of the final product. Subtracting this value from the product's energy content (as in equations (5) and (6)), we determine the impacts per net acquired energy in the process. This gives us the indicators Water Investment Per Net Energy Return (WIPNER, [m^3 /MJ_{net}]) and Food Investment Per Net Produced Energy (FINPE, [kcal /MJ_{net}]).

$$WIPNER = WIPER/(1 - CED)\ (for\ CED\ < 1) \tag{5}$$

$$FINPE = FIPE/(1 - CED)\ (for\ CED\ < 1) \tag{6}$$

2.2. *Case study implementation: Argentine soybean biodiesel*

In our study, we conducted a cradle-to-gate life cycle analysis of Argentine soybean biodiesel, utilizing 1 MJ of the produced biofuel as the functional unit.

Previous studies in Argentina have highlighted promising energy returns on investment [52] and overall sustainability in biofuel production [53]. However, comprehensive analyses focusing on the WEF nexus were not found.

Argentina has witnessed notable advancements in technology, including transgenics and direct seeding, fostering a significant rise of soybean applications. Presently, soybean is the most extensively cultivated crop [54], contributing to 43 % of the national agricultural output [55]. Over 90 % of the soybean seeds planted in Argentina have the Roundup Ready (RR) modification, which provides resistance to the herbicide glyphosate [56]. Additionally, 93 % of soybean cultivation employs a no-tillage system [57].

The major soybean production areas in Argentina are Buenos Aires (29.9 %), Cordoba (27.45 %), and Santa Fe (17.98 %), while the industrial biodiesel production primarily occurs in Santa Fe (57.2 %) [58,59].

Broadly, the biofuel production process involves both agricultural and industrial phases. The industrial phase includes grain drying, oil extraction, and transesterification, which is the predominant chemical reaction for biodiesel production using soybean oil in Argentina [52].

Soybean cultivation in Argentina has two different planting seasons, resulting in varied conditions. Planting between October and November is called early soybean (ES), while December planting is termed late soybean (LS) [52]. Regarding agricultural reports, one can find different resource requirements for these two technologies: ES requires more herbicides and fertilizers compared to LS. Generally, LS doesn't require additional fertilizers, as the plants can utilize the nutrients left from the preceding crop. On the other hand, ES exhibits a significantly higher crop yield, approximately 40 % greater than LS [52,60]. Also, Piastrellini et al. [39] reported that the energy consumption for manufacturing agricultural inputs for ES is 89 % higher than for LS. Conversely, LS occupies 27 % more land than ES [61]. Although both ES and LS grains undergo an identical industrial process for oil extraction and biodiesel production, ES grains have approximately 8 % higher oil content than LS grains [62].

2.2.1. *Application in the Argentine soybean biodiesel case study*

In our case study of soybean biodiesel production in Argentina, we updated the inventory data from Piastrellini et al. [39] and

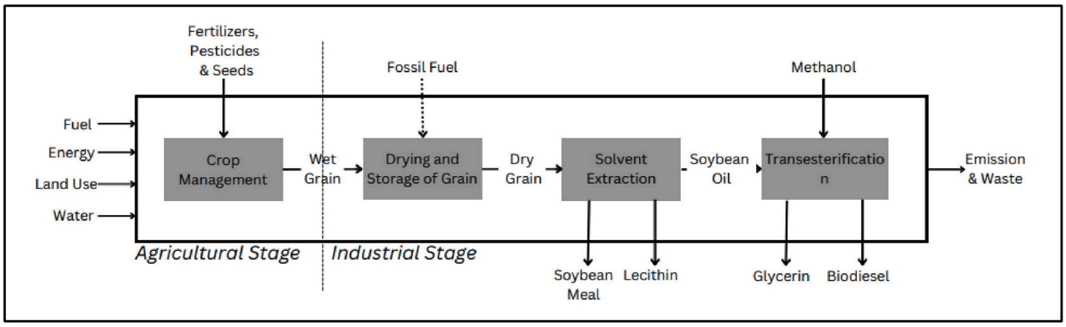

Fig. 1. Illustration of the assessed system.

applied our new framework. Our goal is to compare the performance of biodiesel produced from early and late soybeans.

2.2.2. Study location and scope

The study area is located in Argentina's central soybean region, specifically in the provinces of Córdoba and Santa Fe, which are part of the Pampean region. Data was collected for the 2021–2022 production season.

2.2.3. System boundaries and exclusions

Our analysis includes the primary processes within both the agricultural and industrial stages. However, we've excluded the distribution and utilization of biodiesel and co-products from the system boundaries. Applying an energy cut-off rule, we have excluded flows from the study that contribute less than 2 % of the total energy demanded by the production system.

Fig. 1 outlines all included processes.

2.2.4. Agricultural inventory

Separate inventories were prepared for early and late soybeans, including all inputs and outputs from planting to harvest within the no-tillage systems. Inputs from the technosphere, such as planting density, fertilizer and pesticide doses, and mechanical efforts, were determined using data from the literature and technical reports [60,63–65].

Calculations for carbon captured from the atmosphere and direct field emissions were done following the guidelines by Nemecek et al. [66]. They included emissions to air, surface water, groundwater, and soil. Soybean water requirements were entirely met by precipitation. Adopted crop yields were 3840 kg/ha for early soybean and 2700 kg/ha for late soybean [60]. We assumed a one-year occupation time and that the entire area was sown only with soybeans.

Agricultural transport modeling was based on data on agrichemicals' import rates [67,68], distinguishing between national and international transport. For national transport, we estimated a trucking distance of 145 km, equivalent to the distance between the primary agrochemical production site in Rosario (Santa Fe) and the soybean production center in Marcos Juárez (Córdoba).

International transport considered the countries exporting agrochemicals to Argentina and their market shares [69,70]. Shipping distances were calculated using the average shipping distances from the three ports with the largest capacities in the exporting countries to Buenos Aires and considering the market share of each exporting country in Argentina. Trucking distances were estimated as the distance from Buenos Aires to Marcos Juárez and assuming an equivalent distance in the exporting counrties. Additionally, a 30 km allowance for short freight was added to both national and international transport to consider the final leg from distributors to farms.

2.2.5. Industrial inventory

The industrial inventory reflects the predominant technologies in Argentina: solvent oil extraction and alkaline transesterification. This stage includes dry soybean processing, soybean oil extraction, soybean meal desolventization, micelle distillation, gas condensation, solvent recovery, and alkaline transesterification to produce soybean oil Methyl Ester (MEs) and glycerin. We assume that the industrial plant is located in the "vegetable oil pole" at San Lorenzo–General San Martín Port. Material flows were derived from literature data on soybean oil content [62], chemical inputs, water, land, and energy used during grain drying, oil extraction, and transesterification processes [39,52]. All industrial inputs are produced in Argentina so, equal to Piastrellini et al. [39], we estimated a trucking distance of 150 km for the transportation of the chemicals while the raw grain was estimated to be transported 300 km in truck (80 %) and train (20 %) from the agricultural to the industrial site. To all transports, we added a 30 km in short freight.

For background processes, we sourced data from Ecoinvent 3.8 [71] and Agri-Footprint 5.0 [72] databases, incorporating aspects like agrochemical manufacturing, equipment manufacturing, and freight vehicles.

Within our system, oil extraction and transesterification generate byproducts (soybean meal, glycerin, and lecithin) that require allocations. To allocate impacts, we considered the energy contained in each product based on the low heating value (LHV), because biofuel is an energy source.

2.2.6. Determination of the variables for impact assessment

The ACVF and ALUF were calculated considering the average Calorific Value (CV), Mass Share Factor (MSF), and Land Use (LU) of soybean, maize, wheat, sunflower, sorghum, and barley, which represent 96 % of the mass of crops produced nationally. Notably, we excluded food processing or livestock from FIPE calculations. CV data were sourced from Becker [73], while MSF data were extracted from Di Yenno and Terré [55]. For the calculation of the LU of the respective crops, we used inventory data from the Agri-Footprint 5.0 Database [72]. The CED calculation excludes the renewable biomass present in the soybean crop because this energy is generated through photosynthesis and does not impact the overall energy efficiency of production.

3. Results

3.1. Food-energy impact findings

Applying the FIPE indicator based on average national agricultural methods, our calculations reveal that each generated MJ of biodiesel causes an equivalent land use impact as the production of approximately 62 (ES) or 93 (LS) kcal of food. The results are illustrated in Fig. 2.

Table 1 shows that, in both cases, the majority of the impacts assessed by the FIPE come from the agricultural process, with a very minimal contribution from subsequent industrial stages. The main impact is from soybean land occupation, as shown visually in Fig. 3.

The difference in FIPE between biodiesel sourced from early and late soybeans is primarily due to the higher yield of early soybeans (3840 kg/ha for ES compared to 2700 kg/ha for LS) and the increased oil content in ES grain (23.5 % for ES and 21.7 % for LS). This combination results in a lower land occupation per MJ of biofuel produced.

3.2. *Water-energy impact*

Using the WIPER indicator in our system, biodiesel derived from early and late soybeans has a water footprint of 6.8 and 6.5 L per MJ, respectively. Consequently, as shown in Fig. 4, both technologies contribute similarly to the reduction of freshwater availability.

Table 2 demonstrates that transesterification is the main contributor to WIPER in both cases, accounting for approximately 50 % of the total impact.

In ES, the agricultural process is the second largest contributor, accounting for 25 % of the total impact, whereas in LS, grain causes the second-largest impact of 26 %. The relatively higher impact of the agricultural process in ES, about 5 % more than in LS, is due to the need for fertilizers and increased use of pesticides.

In both technologies, oil extraction has a minor relative impact, accounting for less than 5 %. Despite ES being more efficient because of its higher yield and oil content, LS demands fewer agrochemicals. This balance leads to similar WIPER results for both technologies.

Upon analyzing the subprocesses, we identified the primary contributors to freshwater availability impact. Methanol usage in transesterification, raw grain transport from cultivation to the industry, and glyphosate application in the agricultural process are the key factors, contributing approximately 25 %, 25 %, and 20 %, respectively, to this impact.

3.3. *Cumulative energy demand*

Fig. 5 illustrates that the cumulative energy demand for both production technologies is comparable. This similarity is a result of a compensatory effect: while ES benefits from a higher crop yield and elevated oil content, LS requires fewer agrochemicals, subsequently reducing the energy needed for their production and application.

In both cases, the primary energy consumer is the Methanol used in transesterification, accounting for nearly 80 % of the overall impact. Only a minor proportion, about 13 % (ES) or 12 % (LS), of the energy is consumed during the agricultural process.

3.4. *Net energy indicators*

Upon applying the FINPE and WIPNER indicators, we observe significantly higher results compared to using FIPE and WIPER. This discrepancy aligns with the smaller net energy output compared to the energy content of the product. Detailed results can be found in Table 3.

Given the similar CED for both technologies, employing the net indicator maintains their relative difference. As measured by both gross and net indicators, the food impact of LS surpasses ES by approximately 50 %. Conversely, ES exhibits a water impact about 5 % higher than that of LS.

4. Discussion

In this study, we have developed a new framework for analyzing the WEF nexus, consisting of two indicators that quantify the

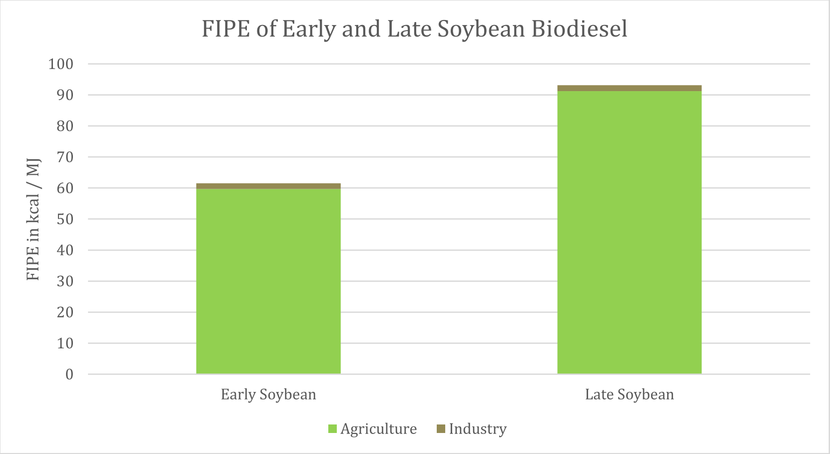

Fig. 2. Fipe of early and late soybean biodiesel.

Table 1

Contribution of processes to FIPE. The Grain Drying, Oil Extraction and the Transesterification are all part of the Industrial Process.

	Agricultural Process	Grain drying	Oil Extraction	Transesterification
Early Soybean	97 %	2 %	0 %	1 %
Late Soybean	98 %	2 %	0 %	0 %

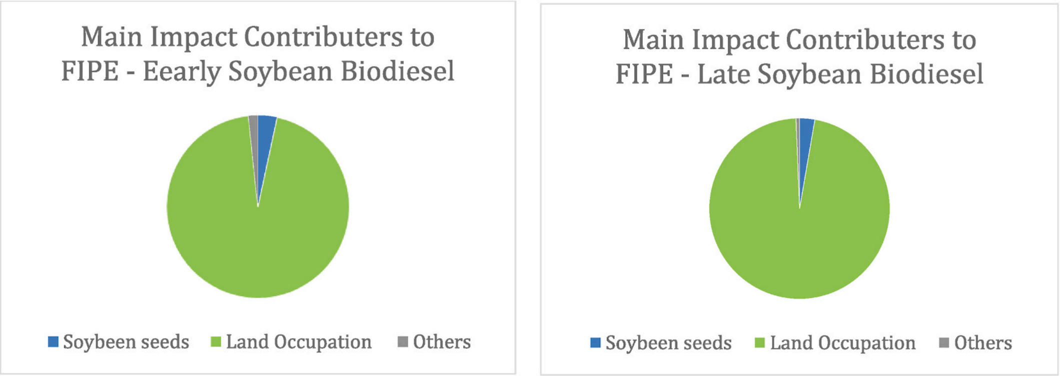

Fig. 3. Main contributors to FIPE of Biofuel from Early and Late Soybean.

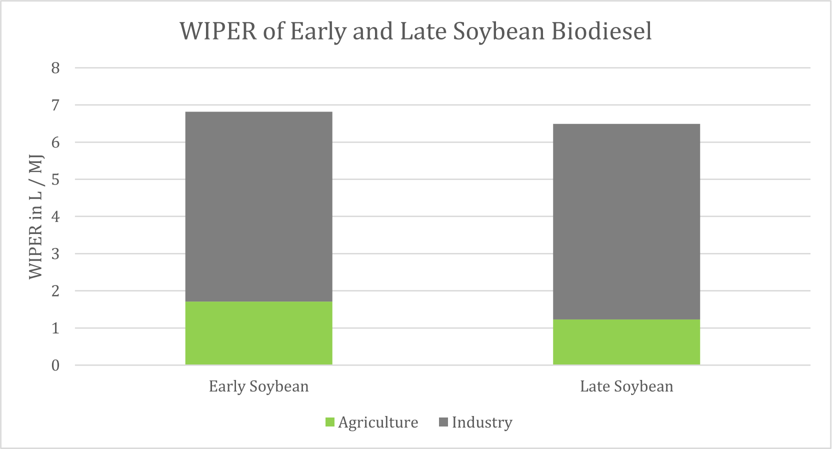

Fig. 4. Wiper of early and late soybean biodiesel.

Table 2

Contribution of processes to WIPER. The Grain Drying, Oil Extraction and Transesterification are all part of the Industrial Process.

	Agricultural Process	Grain drying	Oil Extraction	Transesterifi-cation
Early Soybean	25 %	23 %	3 %	49 %
Late Soybean	19 %	26 %	3 %	52 %

potential impacts of the energy sector on the availability of food and water resources. In the following section, we explain how our methodology fits into the existing literature. Additionally, we provide a more detailed explanation of the indicators and the overall framework.

4.1. An impact-based assimilation approach to the WEF nexus

As there is no standard common methodology for the assessment of the WEF nexus, a wide range of different approaches can be found in the literature [74]. Al-Saidi and Elagib [8] have categorized them into three perspectives, namely the incorporation, the cross-linking and the assimilation. The incorporation perspective aims to draw an overall picture of the analyzed system, offering

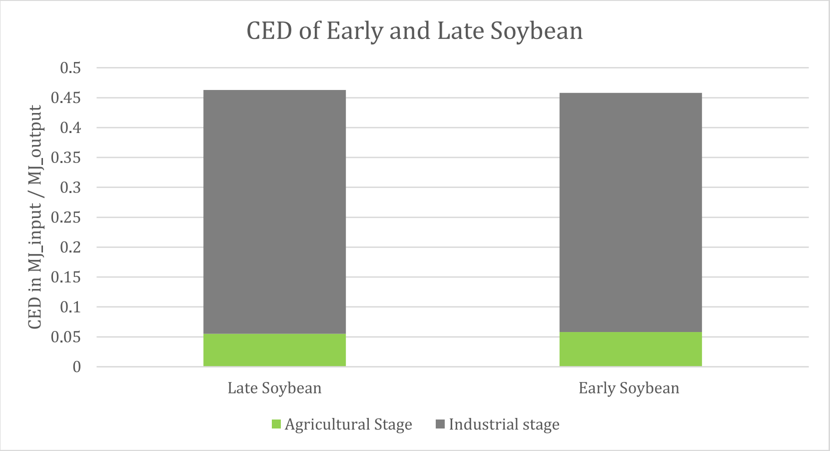

Fig. 5. Ced of early and late soybean biodiesel.

Table 3
Results of case study: FINPE and WIPNER are significantly larger than FIPE and WIPER.

	CED	FIPE *[kcal/MJ]*	FINPE *[kcal/MJ]*	WIPER *[l/MJ]*	WIPNER *[l/MJ]*
Early Soybean	0.458	61.5	113.5	6.8	12.6
Late Soybean	0.463	93.2	173.5	6.5	12.1

valuable data for policy making. The cross-linking approach focuses on important intersectoral relations, providing help for environmental coordination and regulation. Assimilation studies help the operational management by analyzing the relationship of the different resources from the perspective of one sector. To draw a holistic picture, it is necessary to consider all three perspectives [75]. However, as noted by Allouche [76], it is not necessarily beneficial to bring all approaches together in a single, interdisciplinary study. Rather, it is important to recognize that each of the different methodologies makes a specific contribution to a highly dynamic debate. The framework presented in this article is an assimilation approach focused on the renewable energy sector. It measures the water and food trade-offs made for energy production. The aim is to provide quantitative data to compare the physical impacts of different complex energy production systems. However, as some aspects such as social or economic information are not included in the indicators, they are obviously not intended to provide an overall recommendation on which technology to choose.

One approach similar to our framework was taken by Mroue et al. [77]. They developed the Energy Portfolio Assessment Tool (EPAT), which can quantify the amount of water and land resources required for energy production systems. This analysis provides valuable data on the number of resources traded off for energy production. However, it does not take into account the resulting impacts, which we have considered by applying LCA impact factors. Our approach is also novel in that it establishes a direct link between the energy and food resources. This may be more comprehensive than the link between energy and land use.

4.2. FIPE indicator: Opportunity cost calculation

The FIPE (Food Impact per Produced Energy) indicator evaluates the ecological trade-offs between food and energy production, focusing on the opportunity cost of land usage. It calculates the potential food production, measured in kilocalories (kcal), that could be generated with an equivalent species loss as caused by energy production. This indicator considers two critical parameters: the Average Calorific Value of Food (ACVF) and the Average Land Use Impact (ALUF). The ACVF represents the average caloric value of food produced regionally, while ALUF reflects the average land use impact associated with the biodiversity damage, particularly the species loss caused by the regional food production. When juxtaposed, these two indicators provide insight into the average calorific value of food produced in the assessed region relative to the average species loss, resulting from regional food production. A higher ACVF in the region increases the assessed impact, indicating that the typical food produced has a substantial caloric value, potentially making a significant contribution to the food sector. Conversely, a high ALUF reduces the measured impact, indicating that the regional food production causes substantial damage to biodiversity.

In our case study, the ALUF calculation focused solely on the land use of national food crop production, which is typically lower than the average impact attributed to the entire food system [78,79]. Inclusion of additional food production technologies would likely elevate the ALUF and subsequently reduce the impacts assessed by the FIPE. Notably, since both ES and LS biodiesel originate from the same region, variations of the ALUF would equally affect both results.

The FIPE indicator is as an opportunity cost assessment, revealing the ecological sacrifices related to land use for energy production: As long as FIPE shows positive values, it indicates a trade-off scenario in which resources typically allocated to food production are redirected towards energy. It helps stakeholders understand the resource trade-offs between the food and energy sectors, particularly in regions where land availability for both sectors is limited.

A study by Shepon et al. [80] draws parallels by comparing the opportunity costs associated with wasted food to those arising from inefficiencies in the food system due to animal stock. However, the FIPE calculation takes a distinct approach by considering ecological trade-offs of food for different energy products, rather than solely food-to-food trade-offs. Furthermore, the FIPE methodology relies on the ReCiPe2016 assessment approach [35], which evaluates biodiversity loss due to a product's land use rather than merely its physical occupation.

4.3. WIPER indicator: Assessing water-energy impact

The Water Investment Per Energy Return (WIPER) indicator quantifies the reduction of freshwater availability per unit of energy produced. This metric evaluates the water efficiency of energy production processes by highlighting the impact on regional water resources. The higher the value, the larger the water investment per energy outcome and the lower the water efficiency. If new developments in the energy sector create synergies with the water sector, the WIPER would be negative. One example where this might occur is floating photovoltaics (FPV), where solar panels are installed on the water surface in order to produce energy and reduce evaporation [81].

WIPER considers the water shortage in the extraction regions in order to portray the implications for regional freshwater availability. It therefore provides critical insight into the water-energy nexus, helping to understand the potential stresses on water resources associated with the energy production processes. We have chosen not to add such a consideration to the FIPE calculation as water security is mainly dependent on the use and management of the regionally available resources [82] while food security depends on a complex global market and is rather related to poverty [1].

4.4. Comparative analysis

The presented framework allows for comparative analysis of different energy production technologies, revealing disparities in the use of land and water resources. Especially in regions where there is water or food scarcity or that are economically dependent on food production, comparisons applying our framework can help to choose the technology that causes the lowest sacrifices.

In our case study, we found that the biodiesel produced from early soybean has a significantly lower relative land use impact due to the higher crop yields and the higher oil content of the grain, leaving more resources for food production than the same amount of biodiesel produced from late soybean. Regarding the water consumption, late soybean production requires less fertilizer and pesticide application, which implies a lower water use for their manufacture (indirect water) and application (direct water). However, this technology needs to transport, dry and process a greater amount of soybean per unit of energy generated than the early soybean production, and therefore has greater direct and indirect water consumption associated with industrial processes. These advantages and disadvantages in terms of resource demand are compensated in the different stages of the life cycle, so that the impact on water availability of late soybean biodiesel is like that of early soybean biofuel.

4.5. Identification of critical impact areas

Besides optimizing the interactions between the different sectors, Mohtar and Daher [11] also mentioned the identification of existing and potential resource hotspots as a fundamental nexus goal. Our framework can contribute to this by identifying critical impact areas within the energy production chain. In particular, WIPER shows which processes have a significant impact on the regional water availability helping to identify vulnerable areas. For example, in our case study, the methanol for the transesterification caused a major impact. On the other hand, FIPE indicates which processes displace large amounts of food production that may be critical for food security. By identifying these high-impact processes, the indicators enable proactive changes to improve sustainability.

4.6. Net energy indicators: FINPE and WIPNER

The existing nexus indicators by Pacetti et al. [43] and Armengot et al. [45] only consider the impact per gross energy content, omitting the energy consumed in the process. This exclusion complicates comparisons between technologies that require varying energy inputs. To bridge this gap, optional additions to the indicators were presented. FINPE (Food Investment per Net Produced Energy) and WIPNER (Water Investment per Net Energy Return) consider the net energy output by subtracting the energy used in the production from the product's final energy content. Therefore, these metrics allow to compare technologies with varying energy consumption. The indicators are only applicable when the Cumulative Energy Demand (CED) per energy content (EC) is smaller than one as only then, net energy is provided by the system. When CED values are comparable, as observed in our case study, the impact of its consideration on comparative results is minimal as any alterations in one measurement equally applies on the other.

4.7. Comparison of the findings to results from the literature

Although there are several studies that have evaluated the WEF nexus of biofuels using LCA indicators, it is difficult to compare our results with them. This is because they were conducted under different assumptions and methodological choices (system boundaries, cut-off rules, allocation criteria, etc.) or in different regions. It has been found that LCA results vary widely depending on these parameters [30,83,84].

However, one can observe some qualitative parallels between our findings and the literature. For example, we have found that the impact of water use is strongly influenced by the production of inputs (indirect consumption) and not by activities involving direct use of this resource. Faist Emmenegger et al. [29] made the same observation in their assessment of Argentinean rapeseed biodiesel. It is likely that this would change completely if the energy crop were developed under an irrigated system [29,33] or in a region with significant water scarcity.

We also found that the agricultural stage consumes less energy than the industrial stage and that the critical point is the production of the methanol used in the oil transesterification process. While this is in line with the results obtained for soybean biodiesel by Piastrellini et al. [39], we find that in our case, the contribution of the agricultural stage to the cumulative energy demand is significantly lower (approximately, from 45 % to 13 % of the total CED value). This is because the systems analyzed in our study use fewer agrochemicals than the production systems previously evaluated.

If the application of our framework to compare energy technologies would find a significantly higher FIPE for biofuels than for other technologies, they would verify the many warnings that biofuels require extraordinary amounts of ecological resources [85,86].

5. Conclusions

In this paper, we present a new approach to analyze the WEF nexus of energy products that includes a novel LCA indicator called FIPE, which quantifies the food resources required to produce energy.

The application of this framework to the case study of biodiesel production in Argentina allows a comprehensive comparison of two different agricultural technologies. It shows that ES has less impact on the food sector than LS, while both technologies have about the same impact on the water sector.

The additional inclusion of a novel net factor facilitates the consideration of the energy requirements of the different technologies. This allows to compare the performance of technologies with different energy requirements in a simple way. Since the CEDs of the technologies considered in our case study were similar, the net factor increased the impact of both technologies analyzed equally.

We expect that, with a few adjustments, LCA practitioners will be able to apply the new framework to other systems involving linkages between different sectors of the WEF nexus.

Data availability

All impact assessment data found in our study is presented in the paper. The inventory data generated and analyzed during the study are presented partially and will be made fully available on request.

CRediT authorship contribution statement

Sven Kock: Writing – original draft, Methodology, Investigation. **Roxana Piastrellini:** Writing – review & editing, Supervision. **Alejandro Pablo Arena:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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