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Original Article

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Sustainability and life cycle analyzes of different biofuel from municipal solid waste processes: an effective environmental guidance

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Abstract

The refining of biowaste into biofuels, particularly focusing on the organic fraction-municipal solid waste (OF-MSW), remains nascent and is influenced by factors such as energy requirements, microbial effectiveness, and structural design. This article presents a sustainable and thorough framework for evaluating the environmental behavior associated with diverse biofuel from OF-MSW conversion methodologies. The evaluation considers three different pre-treatment methods (acetone organosolv, hot water, and acidic pre-treatment), several fermentation techniques (including ethanol fermentation and ABE-F (acetone/butanol/ethanol fermentation)), and acidic or enzymatic hydrolysis approaches. Furthermore, the environmental analysis utilizes the life cycle analysis (LCA) approach. Within this framework, a consequential LCA is implemented, which includes process development to address the issue of multi-functionality and the use of marginal processes for designing foundational processes. The biofuels produced, ethanol and butanol, are analyzed for their environmental impact. To discern the varying and combined effects, methodologies for sensitivity analysis and single score evaluations have been established. Research outcomes suggest that the acetone–ethanol–butanol fermentation scenario does not provide an optimal environmental outcome due to its inability to offset the environmental impacts through the benefits derived from the byproducts. Among the scenarios examined, Scenario SC-IV emerged as the most environmentally beneficial, showing significant net environmental savings including decrements of −854.55 PDF m^{-2} (potentially disappeared fraction, annually), −253.74 kg CO_2.eq per 1000 kg of OF-MSW, and − 3290 MJ per 1000 kg of OF-MSW treated.

Keywords: biofuel; organic fraction of municipal solid waste; sustainability analysis; life cycle analysis; environmental guidance

1 Introduction

The urban development and burgeoning worldwide population have significantly escalated municipal solid waste (MSW) production, prompting an intensified reliance on environmentally detrimental fossil fuels as energy sources [1–3]. The organic fraction-municipal solid waste (OF-MSW), a major component of MSW, presents notable environmental sustainability challenges [4–6]. It is crucial to harness the biodegradable potential of MSW to foster sustainable development [7, 8]. Given its rich content of starchy materials, like unused bread and rice, and lignocellulosic substances such as fruit skins and yard debris, OF/MSW could be a viable source for biofuel production through microbial fermentation [9–11]. The transformation of OF-MSW into bio-energies, biofuels, or bio-materials represents a supportable option compared to fossil-driven options [12, 13]. The volume of waste produced in the whole world in 2023 was more than 2 billion tons, which is expected to increase by 65% by 2050. In China, due to its high population and industrialization, a relatively high volume of waste is produced (about 27% of the world's total waste) [14, 15]. Therefore, the development of green routes for energy production is an important step towards achieving sustainable development and circular economy [16–18].

Gasification is one of the methods of converting primary fuel into useful energy, which faces various challenges and advantages [19]. Despite numerous small-scale experimental attempts, biowaste-driven biorefineries are still in their formative phases, primarily hindered by developmental challenges

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and the absence of large-scale mercantile applications [20]. This is often due to technological constraints and inefficiencies in process configuration [21, 22]. Microbial biorefineries, in particular, face issues related to high energy consumption and dependencies on both the efficiency of the microbes and the process configuration [23]. Additionally, the underlying processes involving infrastructure, energy markets, and chemical industries significantly influence the overall environmental impact of biorefineries. Identifying and improving critical stages in these processes is crucial for reducing the environmental footprint of future biorefineries [24, 25].

Liquid biofuels like ethanol and butanol are favored over gaseous alternatives such as biogas and hydrogen due to their ease of storage, transportation, and blending capabilities with gasoline [26]. The process of converting starch and hexose sugars in OF-MSW into butanol and ethanol via microbial processes remains a key research focus due to its complexity [27]. The conversion challenges primarily stem from the energy-intensive pre-treatments required to breakdown the resilient lignocellulosic component of OF-MSW, thus making the sugars available for microbial utilization, as highlighted in various studies [28, 29]. The organosolv method has emerged as the preferred pretreatment for ABE-F due to its ability to reduce substrate degradation and impressively remove phenolic blends [30]. As reported, acetone organosolv pretreatment effectively prepares and detoxifies OF-MSW for further processing [31]. Moreover, acetone produced as a byproduct in the fermentation cycle can be recycled, reducing overall costs. Alternative pre-treatment options include hot water and dilute acid methods, which require fewer chemicals and have shown efficacy in enhancing OF-MSW digestibility for ethanol production [32, 33]. However, these methods fall short in eliminating inhibitors, which compromises their effectiveness for butanol production.

Literature indicates that several laboratory-scale biorefinery platforms have effectively demonstrated the potential of ABE-F and ethanolic processes for converting OF-MSW into biofuels [34]. There have also been studies exploring the emission and financial behaviors of suchlike bio-refineries. Although organosolv pre-treatment is highly effective for ABE-F of OF-MSW, it remains under-researched compared to chemical pre-treatments [35]. Only a few studies, such as that by Meng *et al.* [36], have assessed the environmental sustainability of this process, focusing on primary energy consumption and global warming potential. While their contributions are notable, a broader evaluation of environmental impacts is essential to avoid unintended consequences. Studies have also reported on OF-MSW-to-ethanol process based on a sustainable framework, addressing impacts like human toxicity, ozone depletion, and resource depletion (RDP) [37, 38].

Assessing the environmental impact of biofuel from OF-MSW conversion methods before their expansion is critical for identifying potential adverse effects on ecosystems (ECS), climate change (CCH), human health (HH), and RDP. A thorough survey of existing literature underscores the need for a detailed comparative analysis of the sustainability of ethanol and ABE-F biorefining plants within diverse fermentation, hydrolysis, and pre-treatment stages, which are pivotal in biorefinery development. Previous studies have mostly relied on attributional life cycle analysis (LCA) models or have not explicitly stated their methodologies. Our research adopts a consequential LCA approach, merging process development to address multi-functionality and using marginal processes for crafting the foundational processes. This study addresses a sustainable and thorough framework for evaluating the environmental behavior of various biofuel from OF-MSW configurations.

To this end, it examines three different pre-treatment methods (acetone organosolv, hot water, and acidic pre-treatment), various fermentation techniques (including ethanol and ABE-F), and acidic or enzymatic hydrolysis approaches. Additionally, the environmental analysis adheres to the LCA methodology in line with standards set by the European Research Center. The focus of this analysis is on comparing the environmental impacts of different biorefinery configurations using microbial fermentation processes to produce ethanol and butanol. The LCA framework evaluates impacts across four dimensions: ECS, CCH, HH, and RDP. Moreover, to discern complex and combined effects, the study employs sensitivity and single score assessments. This research provides preliminary insights into sustainability, identifying the most environmentally friendly scenarios, pinpointing crucial impact levels on environmental indexes, and recommending potential improvements for optimizing processes.

2 Process description and modelling

This article seeks to present a sustainable and wide approach for assessing the environmental behavior of various biofuel from OF-MSW configurations. Conducting an environmental analysis for these structures is crucial before their large-scale implementation to identify potential negative effects on various environmental pillars. This analysis incorporates diverse fermentation, hydrolysis, and pretreatment techniques. The environmental evaluation adheres to the life cycle assessment protocol, consistent with European Research Center standards [39]. The LCA facilitates the quantification of environmental impacts across the life cycle of diverse biofuel from OF-MSW layouts and helps identify the most impactful processes, units, or streams [40]. The LCA process includes four stages: definition of goal and scope, inventory and impact analyses, and interpretation of results, detailed below [41].

1) **Goal and scope definition:**

The focus of this study is on analyzing and comparing the environmental impacts of different biorefinery structures using microorganisms to convert biofuels from OF-MSW, specifically C_4H_9OH (butanol) and C_2H_6O (ethanol). The assumption here is the availability of 1 ton of OF-MSW, serving as the functional unit for the plants. This study assumes that parameters like design structure, mass and energy balances, microbial use, and output yields remain consistent across different geographical conditions. It also aims to compare the environmental behaviors of the pre-configured plans with available systems in the target zone to evaluate environmental performance improvements.

2) **Different scenarios definition:**

Various biorefinery layouts are explored through simulation in this study. Building on initial findings from previous studies [22, 23], five distinguished biorefineries are outlined, varying by the type of pre-treatment methods (acetone organosolv, hot water, and acidic pre-treatment), several fermentation techniques (ABE-F by *Clostridium acetobutylicum*

Table 1. Definition of different considered scenarios

Scenario No.	Definition
SC-I	Butanol& Ethanol production under acetone-based pretreatment process and co-culture hydrolysate (*Clostridium acetobutylicum* and *M. indicus*)-based fermentation process& Enzymatic (cellulose fraction)-based hydrolysis process
SC-II	Butanol& Ethanol production under Acetone-based pretreatment process& Hydrolysate (*C. acetobutylicum*)-based fermentation process& Enzymatic (cellulose fraction)-based hydrolysis process
SC-III	Ethanol production under Acetone-based pretreatment process& Hydrolysate (*M. indicus*)-based fermentation process& Enzymatic (cellulose fractions& starch)-based hydrolysis process
SC-IV	Ethanol production under Dilute acid-based pretreatment process& Hydrolysate (*M. indicus*)-based fermentation process& Enzymatic (cellulose fraction)-based hydrolysis process
SC-V	Ethanol production under Hot water-based pretreatment process& Hydrolysate (*M. indicus*)-based fermentation process& Enzymatic (cellulose fractions& starch)-based hydrolysis process

Table 2. The results of the LCA-IA for the OF-MSW valorization based on the offered plans

Item	Plan				
	SC-I	SC-II	SC-III	SC-IV	SC-V
Pretreatment power (Wh)	52965.00	52965.00	52965.00	52965.00	52965.00
Pretreatment heat (Wh)	213770.70	213770.70	213770.70	339421.50	339421.50
Filtration power (Wh)	2574.00	2574.00	2574.00	2574.00	2574.00
Gas stripping heat (Wh)	40926.60	47985.30	871.20	1168.20	1168.20
Acetone recovery power (Wh)	165547.80	165547.80	165547.80	0.00	0.00
Acetone recovery heat (Wh)	428788.80	428788.80	428788.80	0.00	0.00
Hydrolysis power (Wh)	155.55	155.55	301.38	29.17	437.48
Hydrolysis heat (Wh)	85605.30	85605.30	161548.20	14978.70	237926.70
Purification power (Wh)	117433.80	155202.30	82160.10	109355.40	109355.40
Purification heat (Wh)	269943.30	356766.30	157350.60	209444.40	209444.40
Fermentation power (Wh)	1425.60	1425.60	1425.60	1019.70	2108.70
Wastewater treatment power (Wh)	14384.70	14434.20	14454.00	17889.30	17948.70
Wastewater treatment heat (Wh)	9.72	9.72	9.72	9.72	9.72
Heat in marginal case (Wh)	152945.10	159340.50	302375.70	263745.90	45381.60
Power in marginal case (Wh)	279239.40	231759.00	321809.40	76091.40	81120.60
Ethanol in marginal case (kg)	64.10	7.11	93.57	124.55	124.55
CO_2 from Fermentation (kg)	5.16	4.03	0.22	0.29	0.29
Acetone make up (kg)	280.08	273.68	297.99	0.00	0.00
Cellulase (kg)	16.10	16.10	16.10	3.10	19.49

or ethanolic by *Mucor indicus*), and acidic or enzymatic hydrolysis approaches. The specific details and differences among these scenarios are summarized in Table 1, and Block flow schematics are provided in Fig. 1(a–e). Recovery processes, including the treatment of stillage from pretreatment and fermentation, are factored into each scenario, directing them to appropriate wastewater treatment processes (both aerobic and anaerobic).

3) **LCA-inventory assessment (LCA-IA):**

This phase utilizes a blend of background/foreground datasets. Background data relevant to energy carrier and chemical generation is collected from the Ecoinvent-3 database [35, 36], while foreground ones, including mass/energy flows, were gathered from published experiment literature. Table 2 presents the results of the LCA-IA for the OF-MSW valorization based on the offered plans.

4) **Life cycle impact analysis (LCA-IMA):**

This assessment employed SimaPro software, adhering to the framework outlined in ISO 14042. This standard provides direction on the throughout structure, essential features, and constraints of LCA-IMA and advises on selecting suitable impact assessment methods without mandating a specific approach [41–43]. This flexibility allows researchers to tailor the analysis to the specific context of the study. In this study, the Impact 2002+ method was used at the endpoint level to evaluate impacts across four primary pillars: impacts on the ECS, CCH, HH, and RDP. The outcomes interpretation views negative quantities as indicative of savings and therefore environmentally friendly, whereas positive values are seen as burdens/impacts and are considered eco-unfriendly [44, 45].

3 Different phases of biorefinery

i) **Pretreatment process:**

The OF-MSW is initially processed in a prechamber through refining, consuming about 0.43 MWh of electricity per ton. Following this, it undergoes high-pressure pretreatment in a stainless-steel compartment at a 9:1 ratio (liquid/solid) and 790 atm. Under SC-I, SC-II, and SC-III, an 84% acetone solution (hydrous) is used at 120°C for half an hour, allowing for 89% recovery and reuse of the acetone. Further, plans SC-IV and SC-V utilize hot-water and dilute-acid at 130°C for the same duration. The pretreated solids are then routed to the hydrolysis stage, and the wastewater to a treatment unit [31, 46].

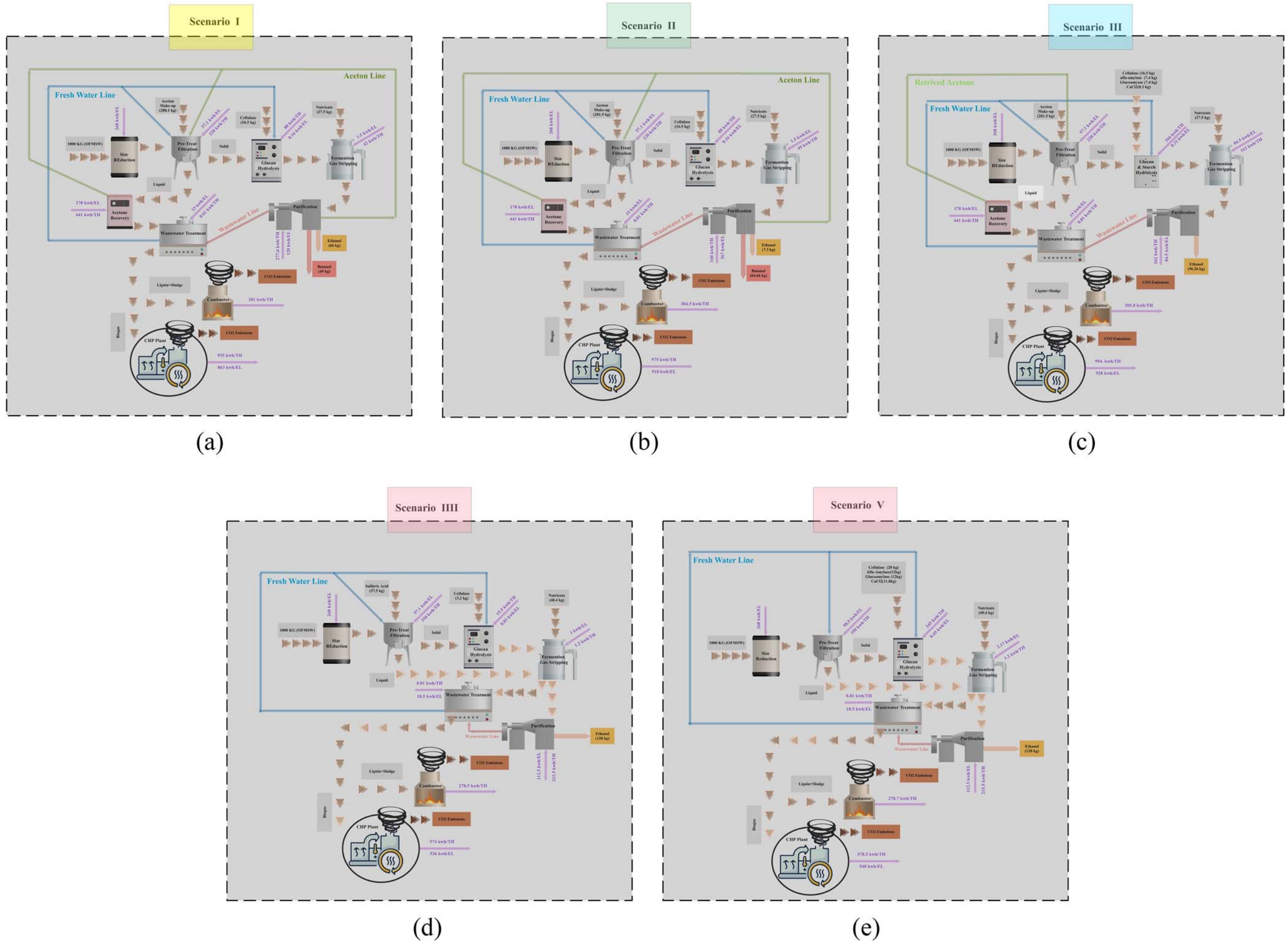


Figure 1. Block flow schematics for various plans, (a) SC-I, (b) SC-II, (c) SC-III, (d) SC-IV, and (e) SC-V.

ii) **Hydrolysis process:**

In this stage, the OF-MSW undergoes further processing in a reactor to convert starch and cellulose into fermentable sugars. This includes liquefaction (using $CaCl_2$ and α-amylase at 90°C for 2 hours) and saccharification (using glucoamylase at 64°C for half an hour). Further, plans SC-I and SC-II feature direct starch hydrolysis by *C. acetobutylicum*'s amylolytic activity [36, 46].

iii) **Fermentation process:**

The resulting hydrolysate is then fermented, producing ethanol, butanol, and other byproducts depending on the scenarios. Essential nutrients are augmented to the hydrolysate under all plans to optimize fermentation, which is performed at ~40°C for two days and nights [47]. Energy requirements for this stage are estimated at 168.3 Wh of electricity per ton of hydrolysate [48, 49]. These steps outline the comprehensive approach taken in this research to evaluate and potentially optimize the environmental performance of biofuel from OF-MSW plans [48, 50].

iv) **Wastewater treatment process:**

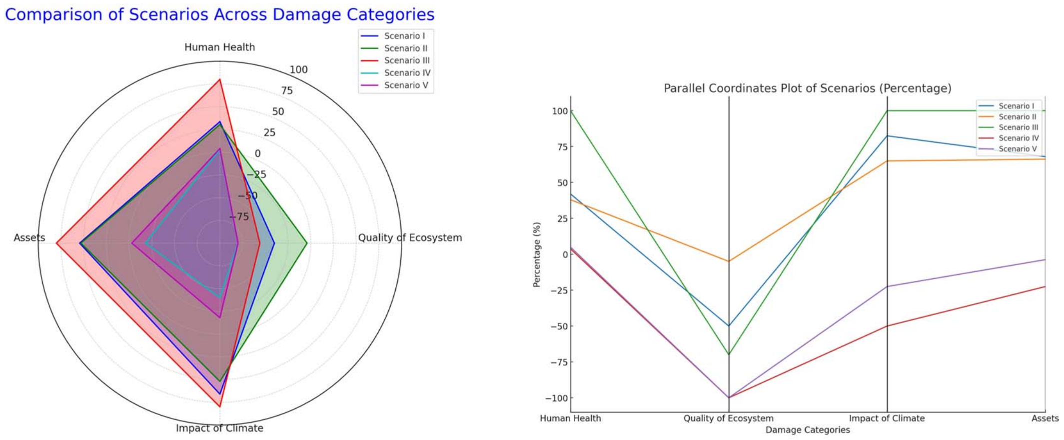
The wastewater treatment model was designed based on the characteristics and mass flow data of waste, which were derived from prior experiments. In instances where data were insufficient, process specifications from the National Renewable Energy Laboratory (NREL) were utilized to fill gaps. The stillage-from-acetone recovery unit in SC-I and SC-II, along with the products purification phases' exits, was directed to the wastewater treatment unit. This treatment involved managing considerable values of lignin and fermentable substances. Insoluble solids were removed using filtration and then sent to an incinerator. Furthermore, the residual liquid underwent treatment in a unit utilizing the aerobic/anaerobic digestion processes [51, 52]. During anaerobic digestion under mesophilic conditions at ~40°C, over 89% of the OF was eliminated (about 84.3% to biogas and approximately 4.7% converted to cell mass). This process also yielded a biogas mixture comprising 48% CO_2 and 52% CH_4 [53]. Moreover, a reverse osmosis unit (ROU) processed about 79% of the incoming water, converting it as cyclic water, while the remaining 21% was treated in an evaporator before being recycled [54].

v) **Energy recovery phase:**

A CHP unit, driven by the combustion of biogas, was integrated to supply the heat/electricity demands of the biorefineries. The system's thermal and electrical efficiencies (according to the biogas's LHV) were pegged at 55% and 36%, respectively [42]. Additionally, sludge and lignin extracted during wastewater treatment were incinerated to produce thermal energy, with calorific values assumed to be 28 200 kJ/kg for lignin and 4160 kJ/kg for sludge [55]. The lignin, sludge, and biogas applications not only supports the biorefineries'

Table 3. Emission factors for the CHP and incinerator systems

	Emission factors (g)	
Item	**CHP system**	**Incinerator system**
Biogenic methane	4.95	29.7
Biogenic carbon dioxide	83.259	74.349
Non-biogenic carbon dioxide	0.0	36.63
Total suspended particulate	1.485	4.158
Sulfur dioxide	24.75	13.86
Carbon monoxide	35.64	9.9
Non-methane volatile organic compound	1.98	1.98
Nitrogen oxides	27.72	162.36
Particulate matter/ 10	1.485	3.168
Nitrous oxide	0.099	3.96
Particulate matter/ 2.5	1.485	2.079



(a) (b)

Figure 2. The detailed findings of the environmental life cycle analysis across four primary categories—ECS, CCH, HH, and RDP—encompasses 18 specific impact categories.

self-sufficiency in heat/electricity needs but also reduces the pollutants footprint related to the solid residues' disposal and produces extra electricity that could potentially displace marginal plants [56]. Emission factors for the CHP are detailed in Table 3.

These sections collectively provide a detailed breakdown of the methodologies employed in the environmental analysis of the biofuel from OF-MSW conversion process, underscoring the comprehensive and integrative approach taken to ensure the sustainability and efficacy of the biorefinery configurations under study.

4 Results and discussion

The environmental life cycle analysis across four primary categories—ECS, CCH, HH, and RDP—encompasses 18 specific impact categories, with the findings detailed in Table 4. From Fig. 2, Plan SC-IV, featuring acid-pretreated OF-MSW converted to ethanol, emerged as the most environmentally favorable option among all scenarios examined. It demonstrated a net negative impact on CCH, ECS, and RDP pillars, positioning it as an advantageous approach to managing OF-MSW. In contrast, Plans SC-I, SC-II, and SC-III, which utilize aqueous acetone in the pretreatment unit, along with Plan SC-V, which employs intensive enzymatic hydrolysis, recorded higher environmental impacts across all categories (as depicted in Fig. 2).

4.1 Impacts on HH

Plans SC-IV and SC-V showed the lowest impacts on HH pillar among all the scenarios analyzed, yet the environmental savings from the biofuels produced are insufficient to completely gratify these impacts. Specifically, Plan SC-IV resulted in a net impact of 1.4969×10^{-5} DALY (disability-adjusted life years) per 1000 kg of OF-MSW, and Plan SC-V had 3.2076×10^{-5} DALY per 1000 kg, as illustrated in Fig. 3. The general trend in the data suggests that organosolv pretreatment processes, which are generally harsher, have a pronounced negative effect on the human health impact category [57]. This is exacerbated by the inhibitory effects of phenolic compounds on the fermentation bacterium, *C. acetobutylicum*. The production of ethanol in Scenario S-1 was notably higher than butanol, with ethanol production rates being approximately 40% greater. It was observed that replacing conventional butanol with bio-butanol yields superior environmental savings than replacing fossil energies-captured ethanol with bio-ethanol, primarily due to the current reliance on fossil fuels for butanol production. The universal market for butanol, which was 5.5×10^{9} metric kg in 2022, is expected to grow by about 32% by 2030 [58].

Table 4. The detailed findings of the environmental life cycle analysis across four primary categories—ECS, CCH, HH, and RDP—encompasses 18 specific impact categories

Category	SC-I	SC-II	SC-III	SC-IV	SC-V
Depletion metal (kg Fe eq)	1.10E+01	1.18E+01	8.28E+01	5.17E+00	4.10E+00
Depletion water (m^3)	-3.14E+01	-2.53E+00	−4.07E+01	−6.46E+01	−6.46E+01
Depletion fossil energy (kg oil eq)	2.91E+02	2.98E+02	3.92E+02	−6.09E+01	−2.54E+01
Depletion ozone (kg CFC-11 eq)	−2.46E-05	−9.70E-06	−2.16E-05	−3.68E-05	−3.68E-05
Ecotoxicity terrestrial (kg 1,4-DB eq)	−7.09E-01	1.26E-01	−1.09E+00	−1.83E+00	−1.83E+00
Toxicity human (kg 1,4-DB eq)	5.89E+01	−1.18E+03	2.94E+03	2.30E+03	2.11E+03
Ecotoxicity marine (kg 1,4-DB eq)	1.86E+03	3.32E+02	4.58E+03	3.32E+03	3.10E+03
Ecotoxicity freshwater (kg 1,4-DB eq)	3.57E+00	1.68E+00	6.21E+00	4.58E+00	4.11E+00
Eutrophication freshwater (kg P eq)	7.03E-02	3.96E-02	2.28E-01	6.24E-02	2.36E-01
Eutrophication marine (kg N eq)	−1.84E+00	−1.77E-01	−2.68E+00	−3.65E+00	−3.65E+00
Climate change (kg CO_2 eq)	3.45E+02	4.24E+02	4.78E+02	−2.08E+02	−8.15E+01
Terrestrial acidification (kg SO_2 eq)	1.60E+00	2.25E+00	1.93E+00	−1.28E+00	−1.20E+00
Particulate matter formation (kg PM10 eq)	5.50E-01	4.86E-01	9.59E-01	7.92E-02	8.91E-02
Agricultural land occupation (m^2a)	−3.84E+02	−8.13E+01	−5.06E+02	−6.79E+02	−6.79E+02
Urban land occupation (m^2a)	4.83E+00	4.46E+00	6.35E+00	5.05E+00	4.99E+00
Natural land transformation (m^2)	−7.92E-02	−1.29E-02	−9.11E-02	−1.46E-01	−1.48E-01
Ionising radiation (kBq U235 eq)	1.63E+01	6.72E+00	1.89E+01	2.24E+01	2.21E+01
Photochemical oxidant formation (kg NMVOC)	3.25E+00	3.33E+00	3.89E+00	−5.16E-01	−4.30E-01

Presently, butanol is typically produced chemically through propylene hydroformylation (Oxo synthesis), recognized for its efficiency and scalability [59].

The ethanol production's environmental advantages are minor significant compared to those from butanol generation, comparing -3.4551×10^{-5} to 22.2651×10^{-5} DALY per 1000 kg of OF-MSW. To reduce the environmental influences related to Plans SC-I and SC-II, alternative approaches might include finding a more eco-friendly solvent for organosolv pretreatment or declining the acetone production's pollution footprint. Among the scenarios, SC-III had the most substantial net impact on human health, quantified at 41.2137×10^{-5} DALY per 1000 kg of OF-MSW. Further, for Plans SC-IV and SC-V, impacts were predominantly influenced by the fermentation process, especially due to the additional nutrient requirements and the associated background pollutants from the generation. Therefore, optimizing the fermentation process, such as reducing nutrient needs or sourcing from more sustainable systems, could be strategic focuses for improving human health impacts in these scenarios. These discussions highlight that while biofuel production from OF-MSW presents potential environmental benefits, careful consideration of the processes involved is crucial to ensure overall sustainability and health safety.

4.2 Impacts on ecosystem (ECS)

From the results, Plans SC-IV and SC-V demonstrate significant ecological benefits, each achieving substantial net ECS savings of −848.588 and − 849.598 PDF/m^2 (annually), respectively. These figures are largely attributed to the role of ethanol substitution, which significantly mitigates ecological impacts. As depicted in Fig. 4, the environmental influences associated with the OF-MSW's pre-treatment in Plans SC-IV and SC-V are markedly lower than those in Plans SC-I, SC-II, and SC-III. Further, the pretreatment cycle of acetone, used in the latter Plans, emerges as the primary contributor to ecological burdens, with impacts ranging from 70.785 to 77.072 PDF/m^2 (annually). Additionally, the fermentation process across all scenarios is noted as a factor in ECS quality degradation, contributing between 13.365 and 19.701 PDF/m^2 (annually). This impact is largely due to the emissions from the production of additional nutrients required during fermentation. However, the strategic OF-MSW's usage (raw material) offsets the environmental costs mainly related to feedstock generation, promoting the use of agricultural land primarily for food production—a critical consideration given the finite nature of land resources. Thus, utilizing waste materials e.g. OF-MSW (feedstock) offers a sustainable substitute for bio-ethanol production that circumvents the long-term viability issues associated with traditional crop-based biofuels.

4.3 Impacts on CCH

Figure 5 highlights the significant CCH pillar's impacts arising from the pretreatment, energy recovery, hydrolysis, and fermentation phases. Notably, Plans SC-IV and SC-V manage to offset these impacts through environmental credits attributed to substituting traditional products with bio-refinery equivalents such as ethanol, butanol, and biogenerated electricity. In particular, Scenario SC-IV benefits from a dilute acid pre-treatment approach that serves both to pretreat lignocellulose and hydrolyze starch, eliminating the need for additional hydrolytic enzymes and thus reducing climate impacts. In Plans SC-I, SC-II, and SC-III, significant environmental credits were also observed due to avoided electricity production, driven by the higher energy outputs from these scenarios. This higher electricity generation stems from the enhanced biodegradability of material streams directed towards anaerobic digestion, including stillage from distillation and organically rich pretreatment effluents.

To optimize the environmental performance of Plans SC-I, SC-II, and SC-III, it would be crucial to reduce the environmental footprints associated with both the pre-treatment processes and acetone generation. Developing and commercializing more sustainable, biologically based methods for acetone production—utilizing renewable resources like OF-MSW/agricultural waste instead of fossil energies—could significantly lower the ecological and climate-related impacts of these scenarios. This approach not only aligns with sustainable development goals but also enhances the overall

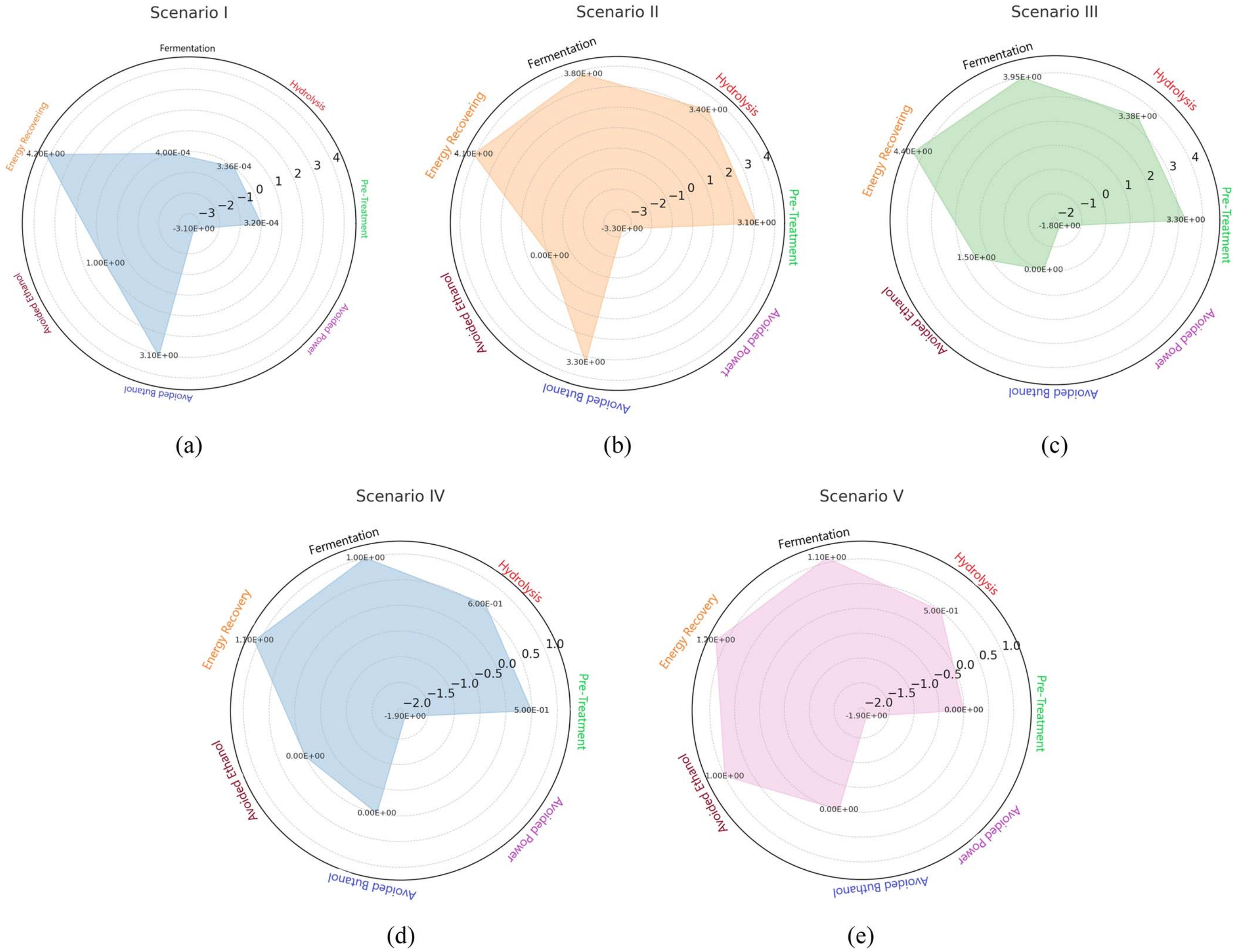


Figure 3. The results of impacts on HH for various plans, (a) SC-I, (a) SC-II, (a) SC-III, (a) SC-IV, and (a) SC-V.

environmental credibility of the biorefinery processes, ultimately achieving net environmental savings of −251.955 and − 87.021 kg CO_2 eq. per 1000 kg of OF-MSW for Plans SC-IV and SC-V, respectively. These findings underline the critical need for integrating sustainable practices within the biorefinery sector to harness the full potential of biofuels while minimizing their ecological footprint.

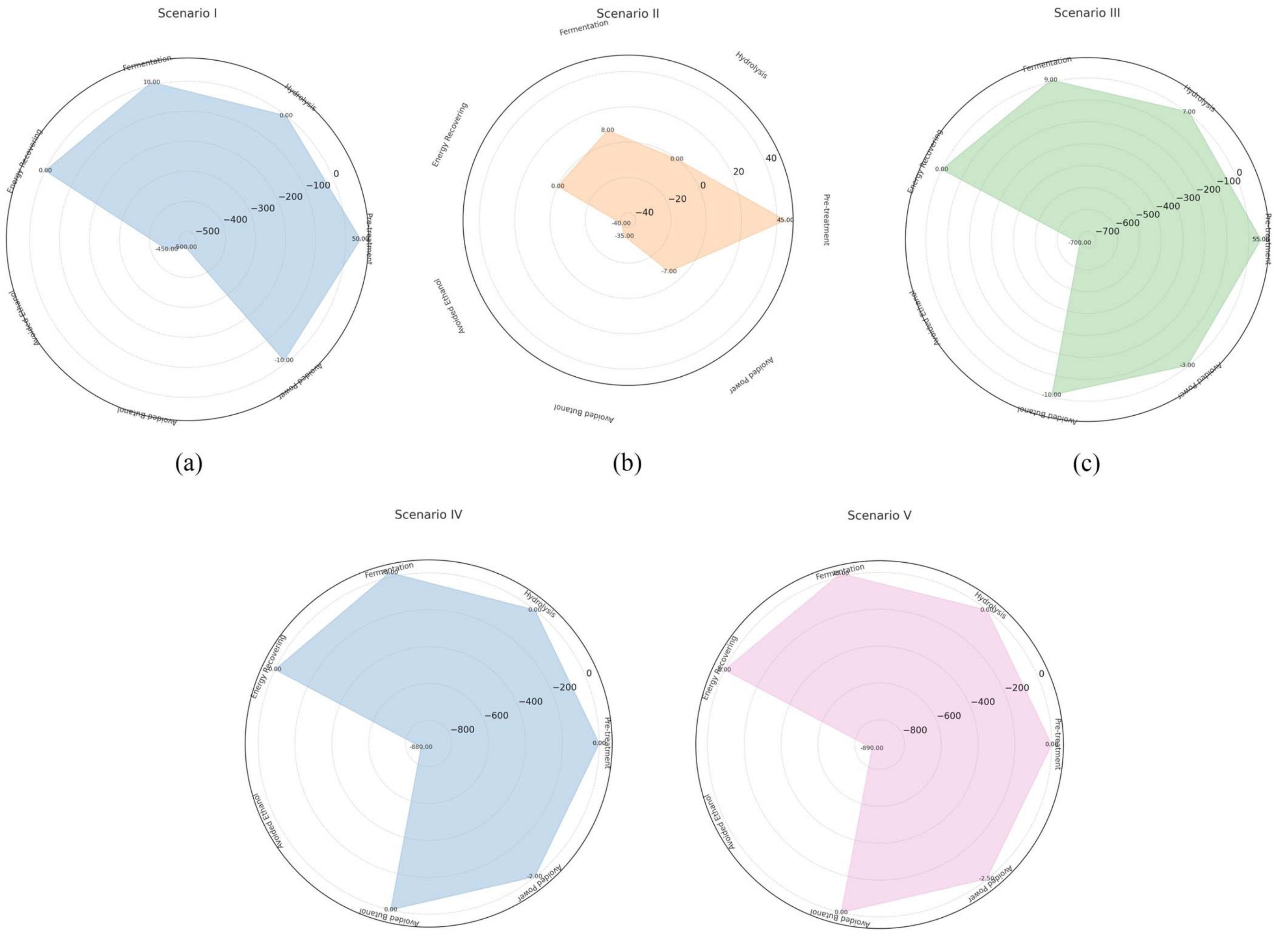
4.4 Impacts on RDP

As illustrated in Fig. 6, Plans SC-IV and SC-V showed the most favorable outcomes in terms of RDP, demonstrating significant net savings in this category compared to other scenarios. Despite the higher environmental savings from avoided product substitution in Plans SC-I, SC-II, and SC-III, their overall resource consumption was considerably higher. Notably, Scenario SC-IV achieved a substantial overall saving of -3.301×10^3 MJ per 1000 kg of OF-MSW, which underscores the lower impact of this scenario despite lesser benefits from product substitution. This finding emphasizes the importance of resource conservation and recovery principles central to the circular and bio-economy models. The resource-efficient nature of the pre-treatment process in Plan SC-IV highlights its alignment with the principles of a circular economy, which favors processes that minimize resource use while maximizing recovery potential. In contrast, Plan SC-V's superior reliance on enzyme utilization translates to greater resource utilization, making SC-IV the more sustainable option from a resource management perspective. The biofuel feedstock's utilization (here, OF-MSW) offers environmental advantages over traditional feedstocks, avoiding the significant environmental burdens associated with agricultural feedstock cultivation.

4.5 Single score and sensitivity and analyses

The cumulative environmental assessment across all categories confirms the superior environmental behaviors of Plans SC-IV and SC-V, as depicted in Fig. 7. Specifically, Scenario SC-IV stands out with the highest net savings at approximately -98.406×10^{-3} Pt, indicating robust environmental benefits, particularly in terms of ECS quality, where it contributed -61.776×10^{-3} Pt to the savings.

The assessment also highlights the critical role of electricity consumption in biomass biorefining processes, a significant factor due to the high energy demands of these systems. The analysis indicated that a 30% reduction in electricity demand within these scenarios could further reduce environmental impacts, enhancing net environmental savings to about -111.276×10^{-3} Pt for Scenario SC-IV and $- 88.11 \times 10^{-3}$



(a) (b) (c)

(d) (e)

Figure 4. The results of impacts on ECS for various plans, (a) SC-I, (b) SC-II, (c) SC-III, (d) SC-IV, and (e) SC-V.

Pt for SC-V. Conversely, increasing electricity usage by 20% adversely affected the environmental outcomes, particularly impacting the human health and resource damage categories. This sensitivity to electricity consumption underscores the need for efficient energy management within biofuel production processes to ensure environmental sustainability. The negative impact of increased electricity demand on environmental performance, especially in human health and RDP categories, suggests that any process optimization should focus on energy efficiency.

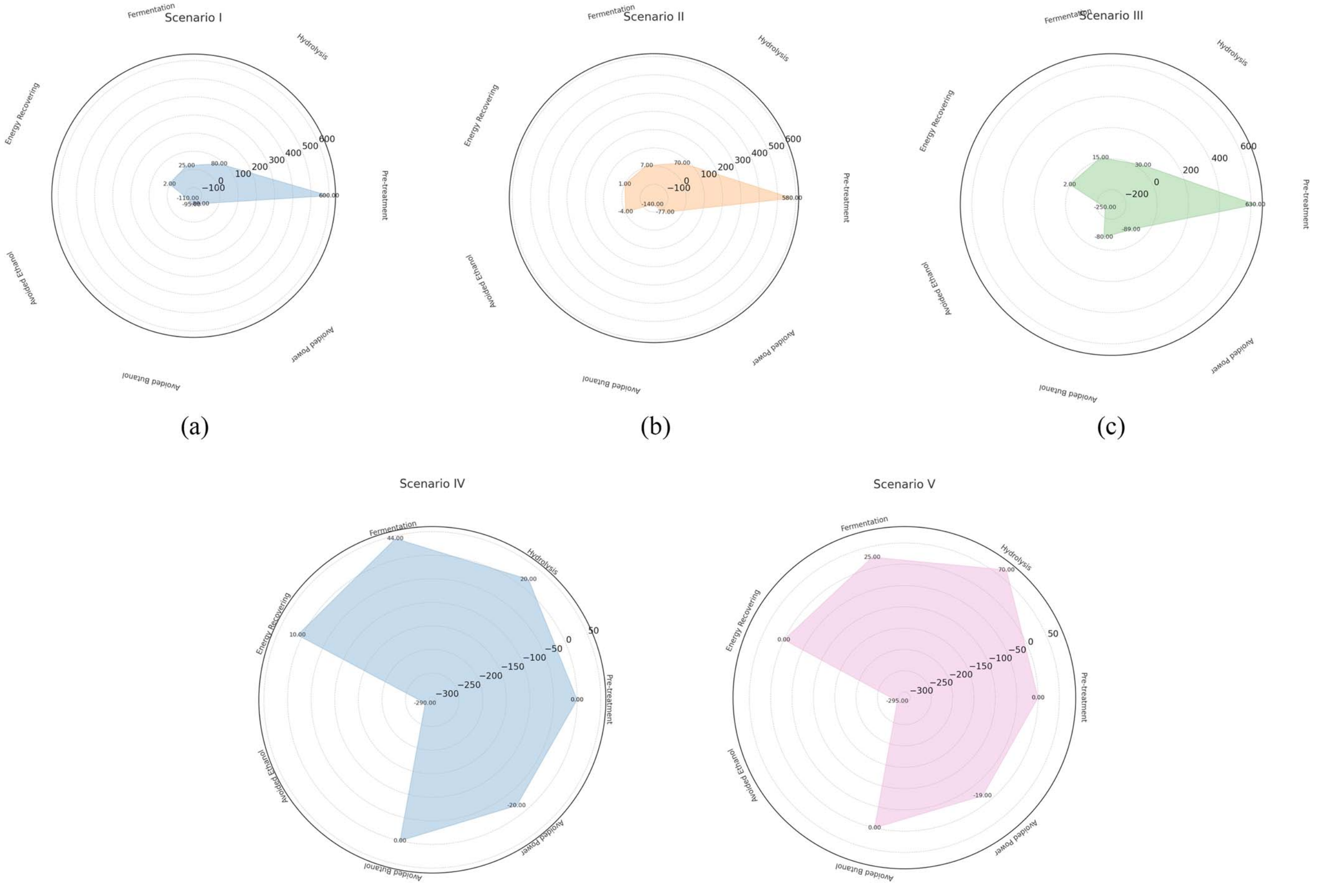
4.6 Integration of excess heat recovery

Further analysis in Fig. 8 explores the potential environmental benefits of incorporating excess heat recovery into the biorefinery's sustainability assessment. By crediting the biorefineries for displacing conventional heat sources with their surplus heat, an improvement in environmental performance is observed across all impact categories. For instance, in Scenario SC-IV, considering augmentation thermal energy as an avoided yield not only enhanced the scenario's environmental sustainability but also increased its overall environmental credits by an estimated 20%.

These findings highlight the crucial role of comprehensive energy resumption strategies in enhancing the bioenergy plans' sustainability. Further, they underscore the possibility for bioenergy plants to chip in to broader sustainable energy generation strategies via supplying alternative heat resources, particularly in settings where such integration is conceivable. This holistic approach to energy management is vital for maximizing the environmental credits of biofuel generation scenarios, ensuring they deliver on their promise of sustainable energy.

5 Conclusions

The primary objective of this article was to offer a sustainable and wide framework for examining the environmental influences of various biofuel from OF-MSW conversion methodologies. Our research incorporated a wide array of biorefinery configurations, utilizing three different pre-treatment methods (acetone organosolv, hot water, and acidic pre-treatment), several fermentation techniques (including ethanol-fermentation and ABE-F), and acidic or enzymatic hydrolysis approaches By implementing a consequential-LCA algorithm that includes process development and marginal system design, this study provided a detailed examination of the environmental repercussions across multiple scenarios. The key findings from our study indicate that scenarios



(a) (b) (c)

(d) (e)

Figure 5. The results of impacts on Climate Change (CCH) for various plans, (a) SC-I, (b) SC-II, (c) SC-III, (d) SC-IV, and (e) SC-V.

employing ABE-F did not achieve desirable environmental outcomes. This was primarily due to the environmental burdens of the acetone pretreatment cycle not being adequately offset by the benefits derived from the output products. On the contrary, plans that utilized ethanol fermentation combined with either acidic-pretreatment or hot water demonstrated excellent environmental performance. These configurations effectively minimized environmental impacts more efficiently than those employing acetone pre-treatment.

Among the various scenarios analyzed, scenario SC-IV emerged as the most environmentally advantageous. This scenario, which involved acid pre-treatment and ethanolic fermentation, led to the most significant environmental savings. It reduced potentially disappeared fractions by $-848.588\ m^2$ (annually), CO_2 emissions by -251.955 kg per 1000 kg of OF-MSW, and energy consumption by -3.297×10^3 MJ per 1000 kg of OF-MSW. The inclusion of augmentation thermal energy as an avoided yield further enhanced the environmental benefits of Scenario SC-IV, enhancing its overall environmental credits by approximately 20%. The sensitivity and single score assessments conducted as part of this study revealed the importance of careful energy management within the biofuel production processes, especially in scenarios SC-IV and SC-V. Effective energy use is crucial not only for enhancing overall environmental performance but also for addressing specific impacts related to human health and resource conservation.

This research underscores the potential of integrating OF-MSW into biofuel production as a viable alternative to traditional feedstocks, particularly in terms of reducing environmental impacts and promoting sustainable energy solutions. By optimizing processes and selecting appropriate technological approaches, the environmental footprint of biofuel generation can be outstandingly minimized, thereby contributing to the goals of sustainable development and environmental protection. Accordingly, it is recommended to implement an optimization algorithm in future works to identify optimal results.

Author contributions

Lixia Hou (Data curation [equal], Validation [equal], Writing—original draft [equal]), Ali Basem (Investigation [equal], Validation [equal], Writing—review and editing [equal]), Hayder Shami (Formal analysis [equal], Resources [equal], Software [equal]), Laith S. Sabri (Software [equal], Supervision [equal], Writing—original draft [equal]), Rand Farqad (Data curation [equal], Resources [equal], Writing—review and editing [equal]), Abbas Abdul Hussein (Investigation [equal], Methodology [equal], Writing—original draft [equal]), Wesam Alhaidry (Formal analysis [equal], Supervision [equal], Writing—review and editing [equal]), Ameer Idan (Conceptualization [equal], Validation [equal], Writing—review and editing [equal]), and Hadi Fooladi (Investigation [equal], Methodology [equal], Project administration [equal], Writing—original draft [equal]).

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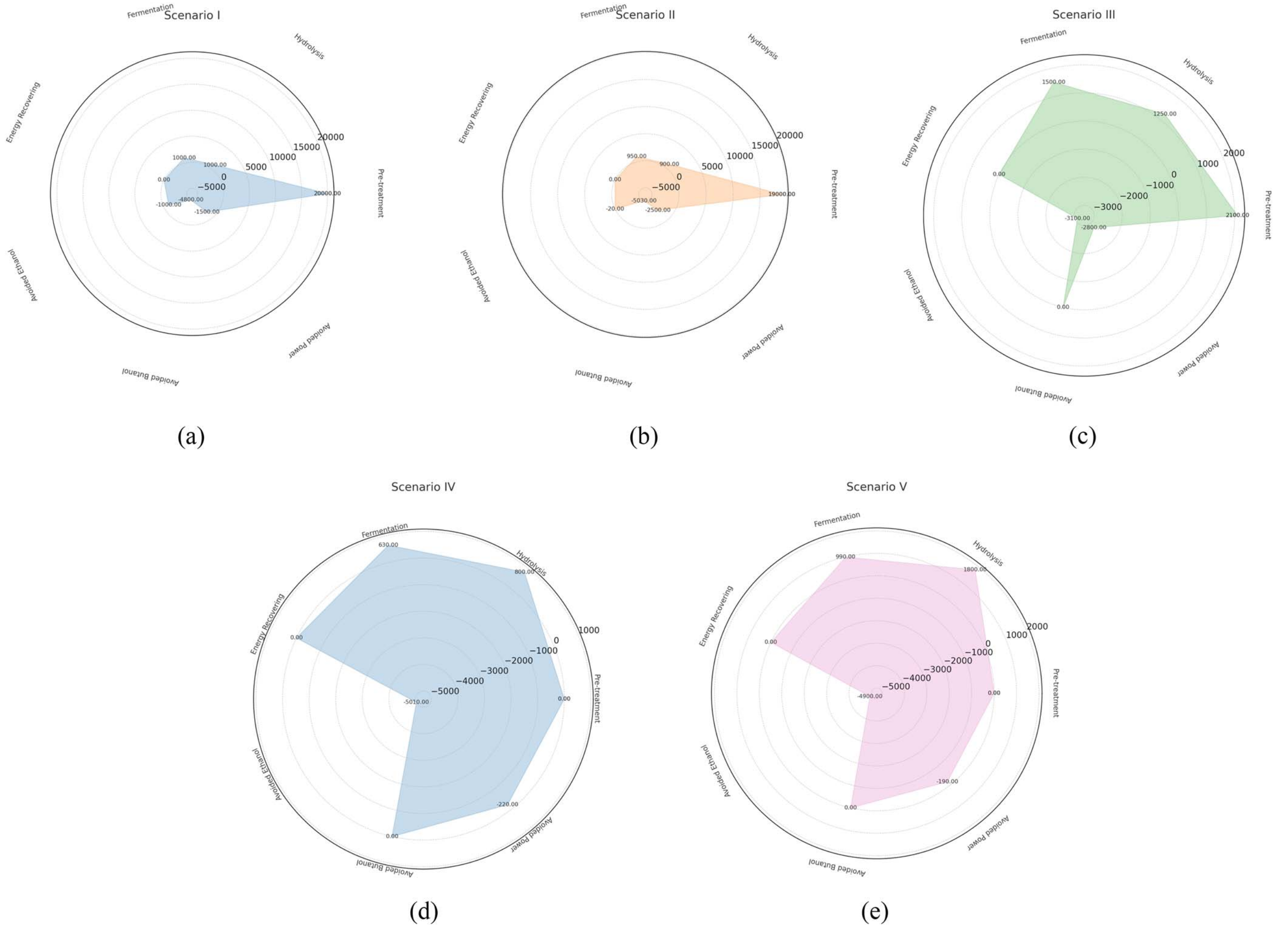

(a) (b) (c)

(d) (e)

Figure 6. The results of impacts on RDP for various plans, (a) SC-I, (b) SC-II, (c) SC-III, (d) SC-IV, and (e) SC-V.

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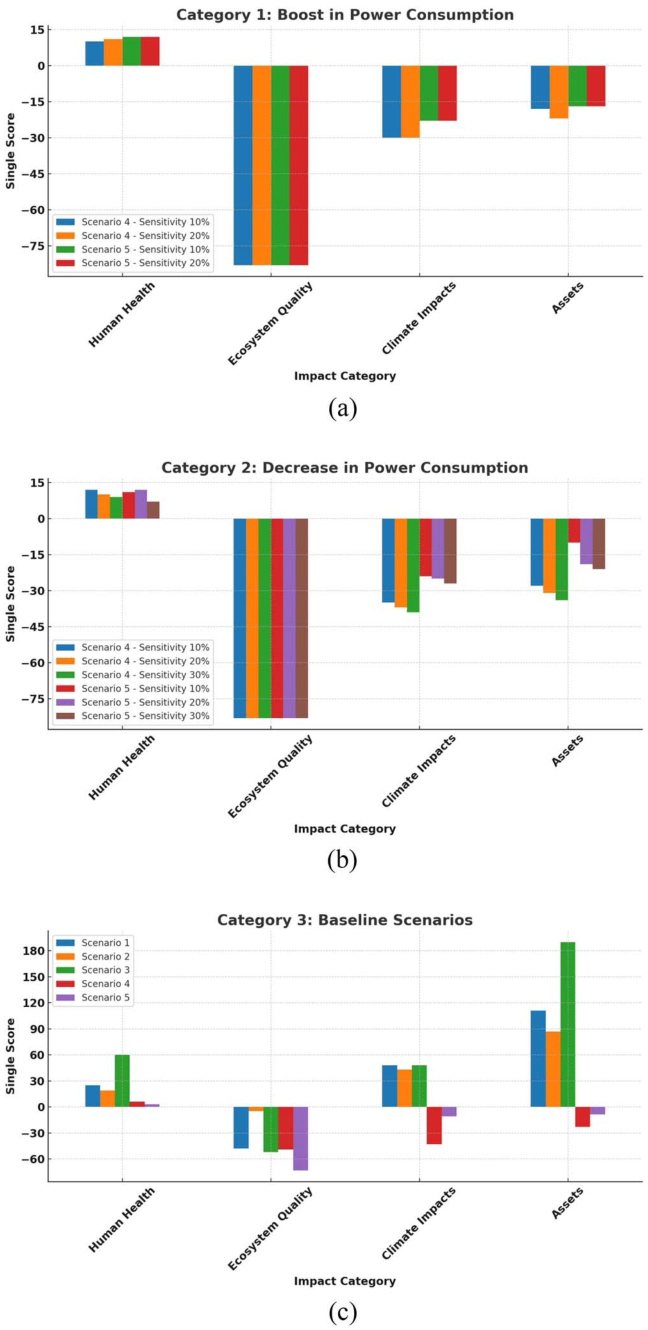

(a)

(b)

(c)

Figure 7. The cumulative environmental assessment across all categories.

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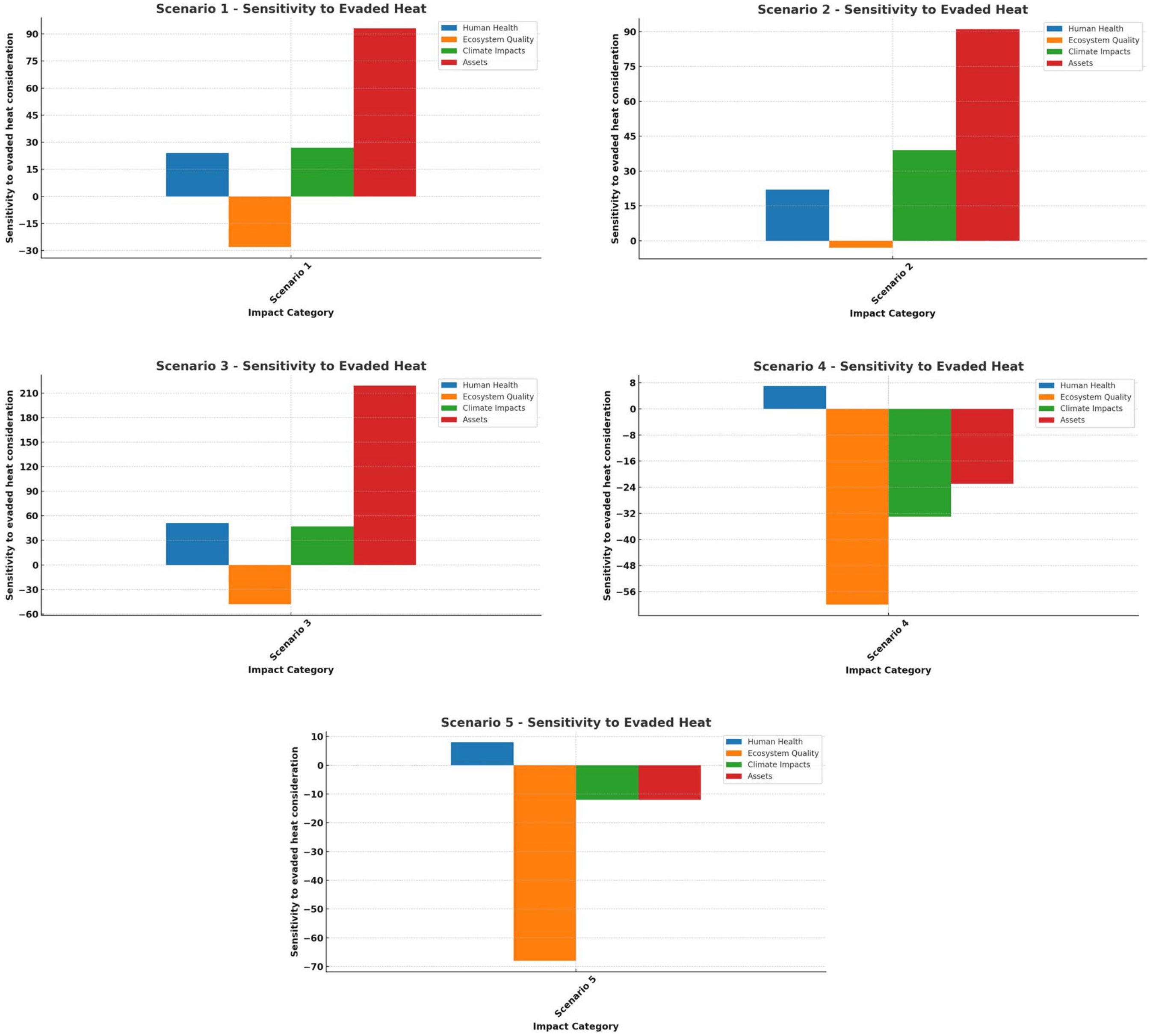

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