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ORIGINAL ARTICLE

Ultraporous superactivated hydrochars from food waste: comparing environmental impacts of char impregnation versus direct chemical activation method

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Abstract
The monumental challenge associated with food waste management has emphasized the dire need of upcycling it into useful materials, including ultraporous adsorbent. Among various technologies of maximizing porosity of such waste-derived porous sorbents, potassium hydroxide (KOH) activation of food waste hydrochar has emerged to be a prominent one. There are two different ways to synthesize ultraporous adsorbent, namely, direct chemical activation (DCA) and char impregnation (CI). This study aims in investigating the environmental impact comparison of DCA and CI using life cycle assessment (LCA). The results demonstrate that CI processes in an environmentally sound way for synthesizing ultraporous carbons from food waste, where freshwater ecotoxicity (57.2%) plays the major contributing role in environmental impact category, primarily due to acid neutralization in the mixer unit of the CI technique of activation. In addition, the dryer unit in the CI process, which is powered by natural gas combustion, was responsible for climate change impact category. Therefore, as an alternative, employment of renewable solar energy (from solar thermal power plant) was also investigated, and results highlighted the possibility of achieving reduced climate change and acidification potential.

Keywords Sustainable carbon materials · Food waste · KOH activation · Activated hydrochar · Ecotoxicity · Eutrophication

1 Introduction

Food waste is defined as organic waste that is discarded from households, restaurants, or eateries or food-processing chemical plants [1]. As reported by the United States Environmental Protection Agency (EPA), an approximated amount of 219 pounds food waste is generated per person in the USA, and it is the highest food waste producer country in the world [2]. On the other hand, among the 50 states of the USA, Florida is one of the most populous states [3], rendering its anticipated vulnerability in becoming one of the highest food waste–producing state in the country along with limited food waste mitigation efforts (e.g., food disposal ban, food banks or collection programs, food sharing program, composting and anaerobic digestion facilities) [4]. In Florida during 2020, merely 6% of food waste was recycled, whereas the fate of the rest 94% was in landfill [4, 5]. Not only is landfilling of food waste prevalent in Florida, but also food waste is observed to be the single largest component taking up space inside landfills of the entire USA [2]. As food waste rots in a landfill, it emits greenhouse gases (GHGs) where methane generation from food waste holds a discrete share of 8% of total global GHG emission [6]. Owing to the stringency in landfilling policies, another notorious method of food waste management is incineration. Incineration of food waste can potentially cause loss of its chemical values and contributes in air pollution. In particular, substantial amounts of moisture in the food waste could lead to the production of dioxins (highly toxic chemical compound which is a persistent environmental pollutant) during its combustion [7]. Such immense challenges associated with the methods of discarding food waste urge for its appropriate management.

Recently, hydrothermal carbonization (HTC) has become one of the most intriguing technologies for handling the wet

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waste feedstocks as it is advantageous, bypassing the necessity of drying feedstock which incurs an energy penalty, in addition to the benefits of notable conversion efficiency at low temperature of operation [8]. The carbon-dense solid product from HTC treatment, defined as hydrochar, has broad range of end-applications [9–12], but due to its low porosity, the recent technological advancements of hydrochar utilization involve employing it as a precursor for ultraporous adsorbent development by further modification via chemical activation to synthesize activated hydrochars.

Chemical activation comprises one step that can be conducted at lower temperature in a shorter time with higher resultant carbon yield and most importantly higher surface area, making it suitable as adsorbent [13–16]. Traditionally, it consists of heat-treating the mixture comprising an activator like KOH, NaOH, or H_3PO_4 and a carbon precursor where the activation temperature ranges from 450 to as high as 950 °C [17]. KOH activation of hydrochar benefits pore creation resulting in creation of ultra-high microporosity [18–23], owing to pore initiation achieved during HTC [24]. Chemical activation with KOH can be typically achieved via two distinct methods: direct chemical activation (DCA) and char impregnation (CI). DCA consists of mixing KOH with carbonaceous hydrochar, both in the form of powder. On the other hand, CI constitutes impregnating carbonaceous hydrochar with aqueous KOH solution [25]. Therefore, the process of CI requires a drying step prior to KOH activation. On the other hand, the amount of activated hydrochar produced experimentally at an activation condition of 800 °C varies between a range of 21.9–47.8% and 17.0–21.3% [20, 26–28] for CI and DCA, respectively, indicating the effect of differed routes of KOH activation. In addition, our previous research [29] unveiled the viability of both the KOH activation techniques from an economic perspective where CI technique of activating food waste hydrochar was profitable. Conversely, from the same study, DCA failed to demonstrate economic viability over the course of the same project lifespan (16 years). It is henceforth pivotal to consequently analyze the environmental impact of such practiced KOH activation techniques to avoid creating a worse environmental impact in the process of solving the challenge of upcycling abundant food waste.

For the objective of evaluating and contrasting the ecological, environmental, and health impacts of such ultraporous carbon synthesis techniques, a systematic approach, for example, life cycle assessment (LCA), is necessary. LCA is a recognized technique for quantifying environmental interactions in respect of impacts and credits throughout the life cycle of a process or a product, requiring estimation of inputs and outputs at all stages of its life [30]. Literature based on LCA of porous carbon synthesis, employing H_3PO_4 as an activating reagent, identified use of phosphoric acid and electricity to be prime factors for the vast majority of the effects [31], whereas another investigation found higher environmental burden due to $ZnCl_2$ activation as it increased ecosystem toxicity [32]. From literature [33], LCA of porous carbon production via KOH impregnation of corn pericarp highlighted analogous role of KOH, and electricity was similarly found the largest contributor to the environmental damage where the contributing category indicators followed the order of fossil depletion, ecosystem, and human health climate change. In a similar process of KOH activation of cocoa pods, Tiegam et al. [34] identified electricity as the major contributor where an average of almost 70% was contributed by it in all impact categories, namely, freshwater eco-toxicity potential (FETP), global warming potential (GWP), marine eutrophication potential (MEP), mineral resource scarcity potential (MSP), and terrestrial acidification potential (TAP).

However, to the authors' knowledge, no such research has been conducted to date that highlights LCA in order to contrast the environmental impact of the most common KOH activation techniques, employed in the aim of upcycling food waste via HTC such that the consequences on environment of processing food waste into valuable material can also be brought to limelight. Therefore, this study uses LCA to contrast the environmental impact of upcycling 100 tons of wet food waste per day, by contrasting DCA and CI approach of KOH activation, into microporous activated hydrochars. Moreover, alternative solar thermal energy was also employed in this study as a source of energy that assessed scope of further alleviating environmental impact of producing activated hydrochar from food waste. The key motivation in utilizing solar thermal concentrated power plants is its promising technological adaptation and efficiency among operable solar-to-energy technologies, whereas studies have exhaustively analyzed its feasibility, remarking it as a global trend [35–37]. In addition, due to its proclaimed applicability, dataset availability in Ecoinvent 3.7.1. further supported the evaluation of such alternative energy as a part of this study.

2 Methodology

2.1 System description

2.1.1 Functional unit

The purpose of the study is to contrast the environmental effects of two activation process scenarios: (1) DCA and (2) CI. Brevard County, located in Florida (USA), was chosen as the source of wet food waste for the initial hydrothermal carbonization (HTC) process because of its population and the amount of household food waste produced there annually per person. Since the primary goal of both approaches is to create activated hydrochar from food waste, the functional unit (FU) for this study is taken to be 4167 kg/h wet food waste.

2.1.2 Process description

The system boundary is illustrated in the simplified process flow diagram (PFD), presented in Fig. 1 with the necessary equipment description in Table 1; food waste is converted into activated hydrochar using HTC; afterwards, DCA or CI is employed. Each scenario consists of two subsystems, the first of which is the same for both scenarios: the generation of hydrochar via the identical HTC process, and the second is the generation of activated hydrochar in two different methods. For this study, a cradle-to-gate system is taken into consideration, with wet food waste serving as initial input of the system. The system creates activated hydrochar as an end product, while wastewater and effluent gas are considered waste streams venting directly into the environment. Furthermore, adding waste treatment facilities will end up adding more complexity to the study; hence, as a worst-case scenario analysis, we are considering the waste streams directly venting in the environment. Moreover, the primary components of effluent gas, which mainly comprises CO_2 and CH_4, warrant serious consideration for its detrimental environmental impact. The study covers the plant's lifespan of 16 years.

For DCA, solid KOH pellets were considered to be mixed in a 1:2 ratio with hydrochar formed in the HTC step. Activation is carried out in a rotary kiln at 800 °C temperature for a residence time of 2 h with a continuous purging N_2 flow. Before transferring it to the dryer, the inorganic components of the activated char were removed and neutralized by mixing it with HCl. In contrast, for CI method, the dried hydrochar was combined with the makeup stream of KOH and recovered basic filtrate from water wash to achieve

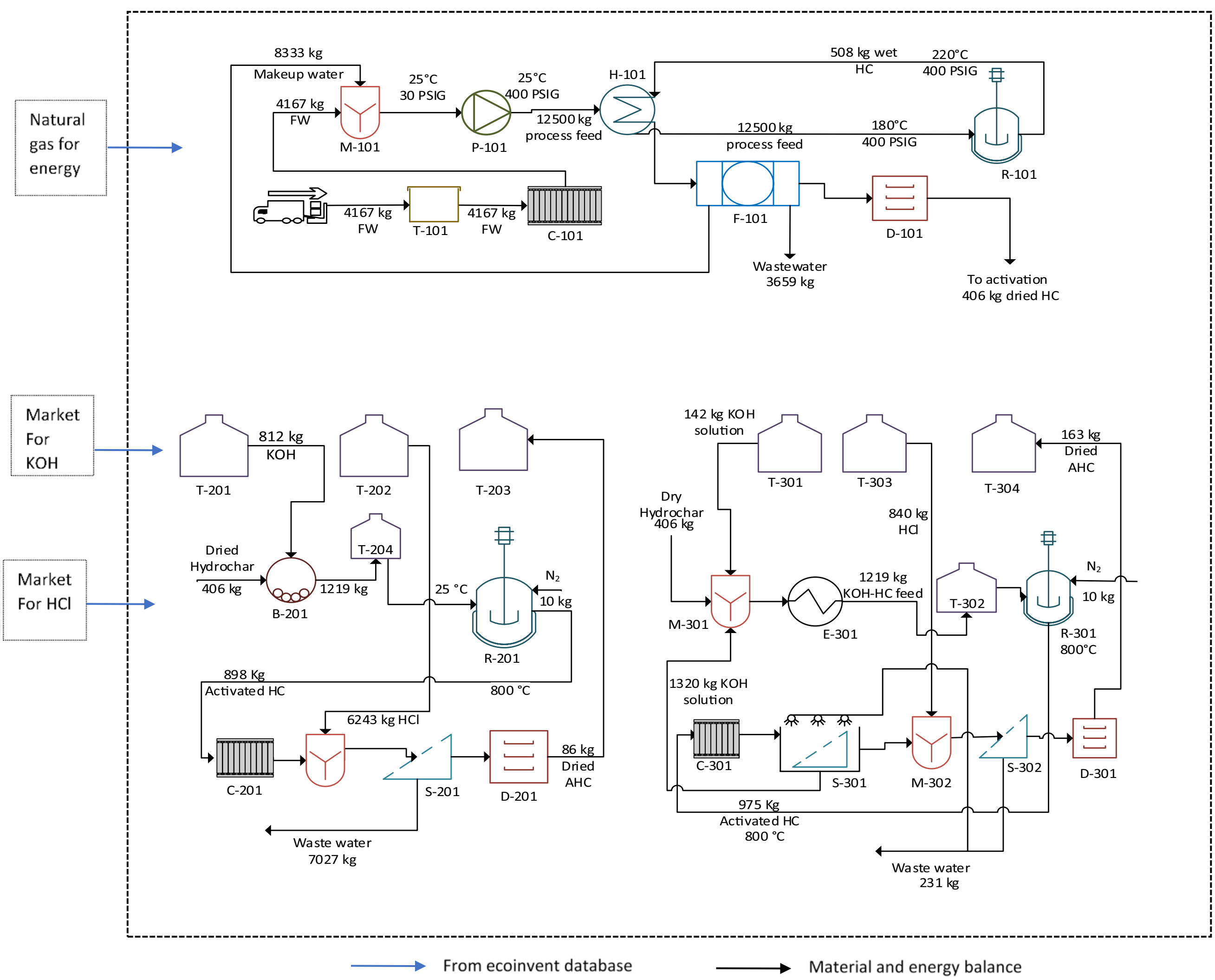

Fig. 1 Modified process flow diagram from reference [29] for activated hydrochar production to contrast activation techniques (DCA vs CI)

Table 1 Process flow diagram (PFD) equipment details for a functional unit of 4167 kg/h wet food waste

Process	Equipment symbol	Explanation	Process	Unit symbol	Explanation
HTC	T-101	Storing collected FW	CI	T-301	Storage for KOH solution
	C-101	Conveyor belt to carry FW to mixer		T-302	Storage for HCl
	M-101	FW is mixed with recycled liquid		T-303	Storage for HC and KOH slurry
	P-101	Pump to pressurize FW slurry		T-304	Storage for dry AHC
	H-101	Heat exchanger to recover energy		R-301	Rotary Kiln
	R-101	Reactor to produce char		C-301	Conveyor belt to carry AHC to
	F-101	Leaf filter to separate process liquid		S-301	Water wash system
	D-101	Tray dryer		M-302	HC is mixed with HCl to neutralize
DCA	T-201	Storage for KOH		S-302	Screening acid-wash mixture
	T-202	Storage for HCl		D-301	Tray dryer
	B-201	Ball mill to mix powered KOH			
	T-204	Stored KOH HC mixture			
	R-201	Rotary Kiln			
	C-201	Conveyor belt to carry AHC to mixer			
	M-201	HC is mixed with HCl to neutralize			
	S-201	Screening acid-wash mixture			
	D-201	Tray dryer			
	T-203	Storage for dry AHC			

hydrochar: KOH ratio of 1:2. A falling film evaporator was used to create a concentrated slurry before introducing the mixture into the rotary kiln for activation under identical conditions. The activated char produced by the process was rinsed with water to create basic filtrate containing KOH residual to be combined with the hydrochar and further mixed with HCl to be neutralized before entering the dryer.

2.2 Life cycle inventory and life cycle assessment

The inventory for abovementioned two activation cases has been collected from the experimental process separately. Activated hydrochar yield (21.1% and 40.0% for DCA and CI, respectively), hydrochar composition, and effluent gas compositions are found from experimental methods [29]. The feedstock information, which includes the solids content, primary analysis, and trace metals content, was primarily derived from relevant literature sources and enlisted in Table 2. Region-specific data and assumptions were used in occasions when data could not be located from existing reports and publications. The detailed activation scenarios with inputs-outputs and emission are shown in Table 2.

Microsoft Excel was used to construct the inventory, and OpenLCA 1.10.3 was used to study impact assessment. The impact techniques were chosen based on the principal sources of emissions identified in the inventory analysis. For each of the five impact classifications of potential climate change, acidification, freshwater ecotoxicity, marine eutrophication, and resource depletion-mineral, fossil and renewables, life cycle impact evaluations were performed using the ILDC2011 (International Life Cycle Data), midpoint technique. However, the effects of the HCl concentration in the discharge from activation methods could not be addressed by the ILCD impact assessment approach. Hence, the IMPACT 2002 approach was utilized to calculate the impact of aquatic acidification on these two cases. A sensitivity analysis was carried out by considering renewable energy source for CI method. In this alternate scenario, solar energy from a hypothetical solar thermal power plant is being used to provide heat and electric energy demands of the plant. A comparison is drawn with the base case for each considered category. The data for solar thermal power plant has been taken from Ecoinvent 3.7.1, thus of secondary data source.

3 Results and discussion

3.1 Life cycle impact results

From Fig. 2, assessment analysis indicates that CI shows an overall lower environmental impact than DCA in all considered categories. For CI, the highest reductions were observed in freshwater ecotoxicity (57.18%), followed by acidification (22%), marine eutrophication (17%), and climate change (3.17%). One of the main sources of soil and water emissions from both CI DCA process is the usage of chemicals for activation of hydrochar in the process stream. Char impregnation (CI) consumes less chemicals (HCl, KOH) for activation compared with DCA, which

Table 2 Life cycle inventory for LCA of activated hydrochar production for a FU of 4167 kg/h wet food waste

Proximate analysis data					
Properties	Food waste (g/100 g)		Food waste hydrochar (g/100 g)	Food waste activated hydrochar (g/100 g)	Reference
Volatile matter	69.5 ± 1.0		56.4 ± 0.1	17.5 ± 0.3	[28]
Fixed carbon	23.7 ± 0.1		38.4 ± 0.2	81.6 ± 1	
N	5.8 ± 0.5		6.0 ± 0.6	1.0 ± 0.2	
C	47.6 ± 0.5		60.9 ± 0.9	80.1 ± 2	
H	6.7 ± 0.0		5.2 ± 0.1	0.6 ± 0.0	
O	33.1 ± 0.5		22.7 ± 0.1	17.4 ± 0.4	
O/C	0.78		0.37	0.22	
H/C	0.141		0.085	0.007	
Na	23.4 ± 2		-	-	
Mg	2.4 ± 0.7		-	-	
P	11.6 ± 1		22.6 ± 6	-	
S	1.5 ± 0		-	-	
Cl	24.8 ± 6		18.9 ± 0	12.9 ± 0.1	
Ca	16.1 ± 6		29.7 ± 3	-	
Al	0.7 ± 0		8.3 ± 0	22.0 ± 5	
K	15.0 ± 3		14.0 ± 4	15.7 ± 3	
Cu	4.3 ± 0		6.6 ± 0	14.6 ± 2	
Si	-		-	36.2 ± 3	
Emission data					
		Parameter	Value	Unit	Reference
Gas emission	R-101	CO_2	85	Wt. % of dry basis	[38]
		CH_4	1		
		Unidentified gas	14		
	R-201	CO_2	300.5	kg	
		H_2	20.5		
		N_2	10		
	R-301	H_2	15.6	g	
		CO_2	228.2		
HTC effluent	F-101	COD	54000	mg/L	[39]
		TOC	18400		
		Chloride	2.38		
		Nickel	0.06		
		Nitrite	0.01		
		Phenol	5.00		
		Sulfate	259		
		Sulfite	58		
		Surfactants	185		

Table 2 (continued)

Energy balance data				
	Equipment unit	Energy requirement	Unit	Ref
HTC	C-101	24	kW	[40]
	P-101	9.67	kW	[29]
	R-101	7.98	kW	
	D-101	63.7	kW	
DCA	B-201	134	kW	
	R-201	1527168	BTU/hr	
	M-201	181	HP	
	C-201	24	kW	[40]
	D-201	17.91	kW	[29]
CI	M-301	6	HP	
	R-301	1357866	BTU/hr	[29]
	C-301	24	kW	[40]
	M-302	11	HP	[29]
	D-301	25.469618	kW	

results in significantly lower emissions as well due to less waste being generated. However, as both processes utilize natural gas as the source input energy, not much reductions in climate change was observed. Hence, while CI ranks better in mitigating emissions to water and soil, gaseous emissions accounting for climate change remains a concern for both cases as climate change impact, which includes greenhouse gas emissions, is marginally reduced (around 3.17%). The extent of these reductions varies and is directly related to the considered boundary. The exploration of overall or cradle-to-gate and gate-to-gate (only activation of the hydrochar) emissions is critical for accurate interpretation of the results.

The cradle-to-gate analysis, which considers the production of hydrochar, reveals that the energy intensity of hydrothermal carbonization step prior to the activation processes is a substantial source of emission. For both cases, the inventory analysis indicates a high share of fossil-derived carbon emissions due to the required energy supply for food waste hydrothermal carbonization, responsible for over 90% of the entire energy demand. The consequence of using fossil source for process energy supply is explicit for climate change impact results for both scenarios. As natural gas is utilized for providing the required heat and electricity of the thermochemical process, the post combustion gases such as methane and CO_2 are mainly responsible for this high contribution, which negated the apparent benefit of capturing carbon which would otherwise be released to atmosphere via landfilling. Several studies also confirm the negative contribution of using fossil-derived fuels in the overall impact of producing hydrochar or biochar [34, 41–44] Amin et al. [41] reported a significant contribution occurring due to the electricity usage while preparing activated carbon in laboratory. Similarly, [44] identified the usage of heat and electricity having the greatest potential for ensuring environmental optimization.

Gate-to-gate consideration reveals the CI technique had a significantly lower GHG emission (239.8 kg CO_2 eq per functional unit) compared to DCA (4968.37 kg CO_2 eq per FU). The lower energy demand and thus the reduced GHG emissions are an inherent benefit of CI over DCA in techno-economic assessment, and similar trends are thus observed in LCA results. Acidification potential and marine eutrophication were also found to be moderately lower for CI, decreasing the impact by 22% and 17%, respectively, due to lower energy demand than DCA. Similar to climate change, fossil-derived emissions remain the main contributor for other impact categories for both scenarios. Both impacts can be traced back to post combustion gases such as SO_2 and NOx from boiler for natural gas, outweighing the biogenic emissions indigenous to the process. The ILCD impact assessment method however could not capture the effects of HCl concentration in the effluent from activation processes. When analyzed with IMPACT 2002 method, the results of aquatic acidification denote the emissions for gate-to-gate system. For CI, the aquatic acidification is assessed to be 203.28 molc H^+ eq (molar concentration of H+ equivalent) per functional unit, significantly less than DCA (5493 molc H+ eq). The higher requirement of chemicals for DCA thus negatively influences the environmental performance in our assessment. Note that we have presumptively released all of the hydrochloric acid to the environment and considered as emission to the water body where it may get disposed. Hence, the LCA results indicate efficient disposal of

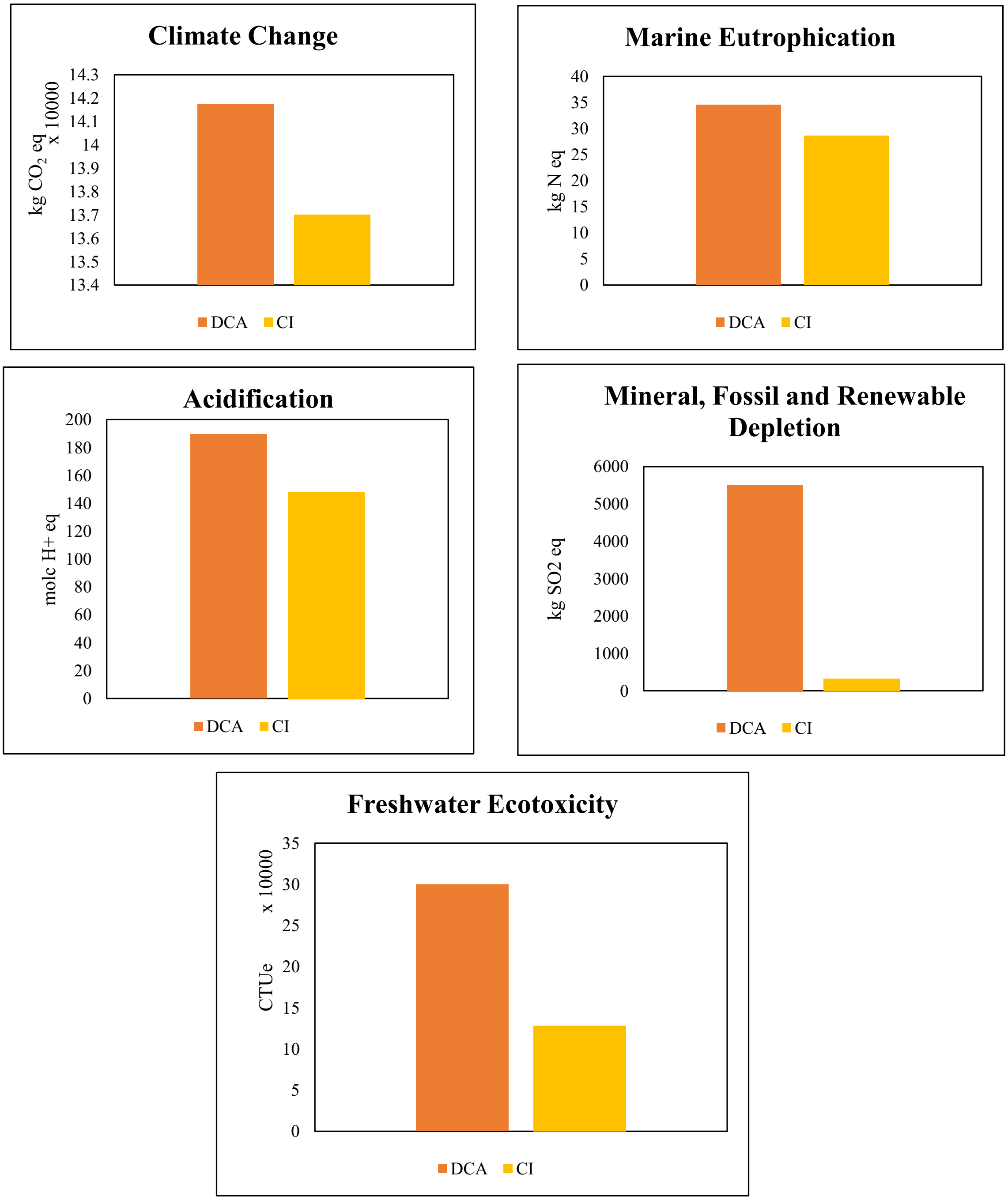

Fig. 2 Life cycle impact parameter evaluation results for DCA and CI KOH activation for a FU of 4167 kg/h wet food waste

wastewater stream is an essential post-treatment. As aforementioned, freshwater ecotoxicity impact was reduced greatly in CI method. The energy supply product chain and the effluent water from hydrothermal carbonization plant are mainly culpable for emissions of heavy metals and phenolic compounds, which translated to majority of the freshwater toxicity for both scenarios. The higher fossil energy demand for DCA further increased freshwater ecotoxicity, resulting in the greater associated impact, whereas gate-to-gate impact in the category is nearly halved for CI compared to that of DCA.

3.2 Hotspot identification

3.2.1 Hotspot analysis of the entire process

Initially, for both cases (DCA and CI) in the climate change category, the dryer unit (D-101) involved in the HTC process is accountable for 98–99% of the total equivalent CO_2 emission as the impact evaluation considers supply of energy by burning natural gas in the unit. The reactor (R-101) used in the HTC process was another substantial contributor to climate change found in both cases. The contribution (only 0.30%) in the area of climate change coming from market for the HCl which is utilized in the filtration unit (F-301) is considered negligible, particularly for CI method. The reactor unit (R-101) emits GHG during the hydrochar production process, which may account for its involvement in the category of climate change impact. Such significant impact of the dryer unit (D-101) and reactor unit (R-101) in the HTC process for climate change category has been documented in literature [45, 46].

Previous research findings [46] claimed that the usage of natural gas in the HTC process had a major impact on climate change, which confirms our findings of the dryer and reactor unit being the protagonists in the climate change impact category. Similar results were observed for marine eutrophication, freshwater ecotoxicity, and mineral, fossil, and renewable depletion, with D-101 process unit accounting for around 99.9% of the total equivalent emission for both the scenarios. In these scenarios, burning of fossil fuels is accountable for the emissions of methane and CO_2 in the impact category of climate change, while combustion processes generating nutrient waste are predicted to contribute to acidification and marine eutrophication, respectively. In DCA method, the dryer unit (D-101) and pump (P-101) in the HTC process were shown to have a considerable contribution (75% and 25%, respectively), but in CI method, the D-101 unit alone is accountable (99.9%) for the acidification impact category. The dryer unit contributes significantly to the acidification category due to the combustion byproducts of SO_2 and NO_X gas in this unit which is converted to equivalent SO_2 (acid gas) emission [47, 48]. Another unit that contributes to acidification and freshwater ecotoxicity impact category is the conveyor belt (C-101) and pump (P-101) used in the HTC process to transport food waste, which is powered by natural gas derived electricity. From the discussion, it is evident that HTC stage, which occurs before the activation procedures, is a significant source of emission in all impact categories for both scenarios. Especially, the dryer unit in the HTC process is identified as the main contributor that supplies the most amount of energy among all other units coming from fossil fuel during the cradle-to-gate analysis. Similar result has been reported in literature where the usage of fuel in HTC unit has been noted as the major contributor in freshwater ecotoxicity and fossil depletion category [45, 49]. Especially, the dryer unit in the HTC process is identified as the main contributor as it requires the largest input of energy that is provided by natural gas.

3.2.2 Hotspot analysis of the activation process

Nonetheless, in order to properly compare the two activation process units, it was attempted to examine their individual contributions. Fig. 3 illustrates the contribution coming from two activation scenarios (without considering the HTC process). In terms of climate change category, reactor (R-201) contributes significantly (50%) for DCA, whereas for CI, even though R-301 reactor unit has considerable contribution, market for HCl in the mixer (M-301) makes up the largest portion of this category. The reactor units burn natural gas to conduct the activation process at a higher temperature, causing GHG emissions and making this unit of energy source the highest contributor to climate change impact category. For the acidification impact category, the highest contributor for both cases were the mixer unit (M-201 and M-302) which combines HCl with activated char from reactor to neutralize it. The release of acid gas is considered to be a substantial contributor in this category, and the upstream process of HCl from the market is identified as the key source. Amin et al. [41] reported a similar environmental consequence due to the activation process using KOH, which increased terrestrial acidification. Literature has made reference to a similar pattern, which states that electricity used in activation process plays a vital role in several impact category [34, 41, 50].

While in publications the electricity used in the reactor unit was produced from natural gas, in our study the heat in the reactor unit for the activation process originates from burning natural gas. Consequently, natural gas combustion is seen to have a large impact on GWP and acidification impact categories. The impacts of freshwater ecotoxicity and marine eutrophication showed similar trends, where the upstream process of HCl from the market in the mixer units (M-201 and M-302) continued to provide the largest contribution to both categories. Lastly, for the impact category of mineral, fossil, and renewable resource depletion, the reactor unit (R-201) in the DCA process accounts for 95% of, while the entire CI activation process has no association with this impact category. This implies that the dryer unit (D-101) in the HTC process accounts for 100% of the outcome in this category for CI activation method. Mayer et al. [45] reported a similar outcome in a life cycle assessment study where authors compared incineration, anaerobic digestion, and hydrothermal carbonization for treating organic waste. The heat input for drying after the HTC process causes significant emissions and thus downplaying the overall environmental benefits. Stobernack et al. [46] however found

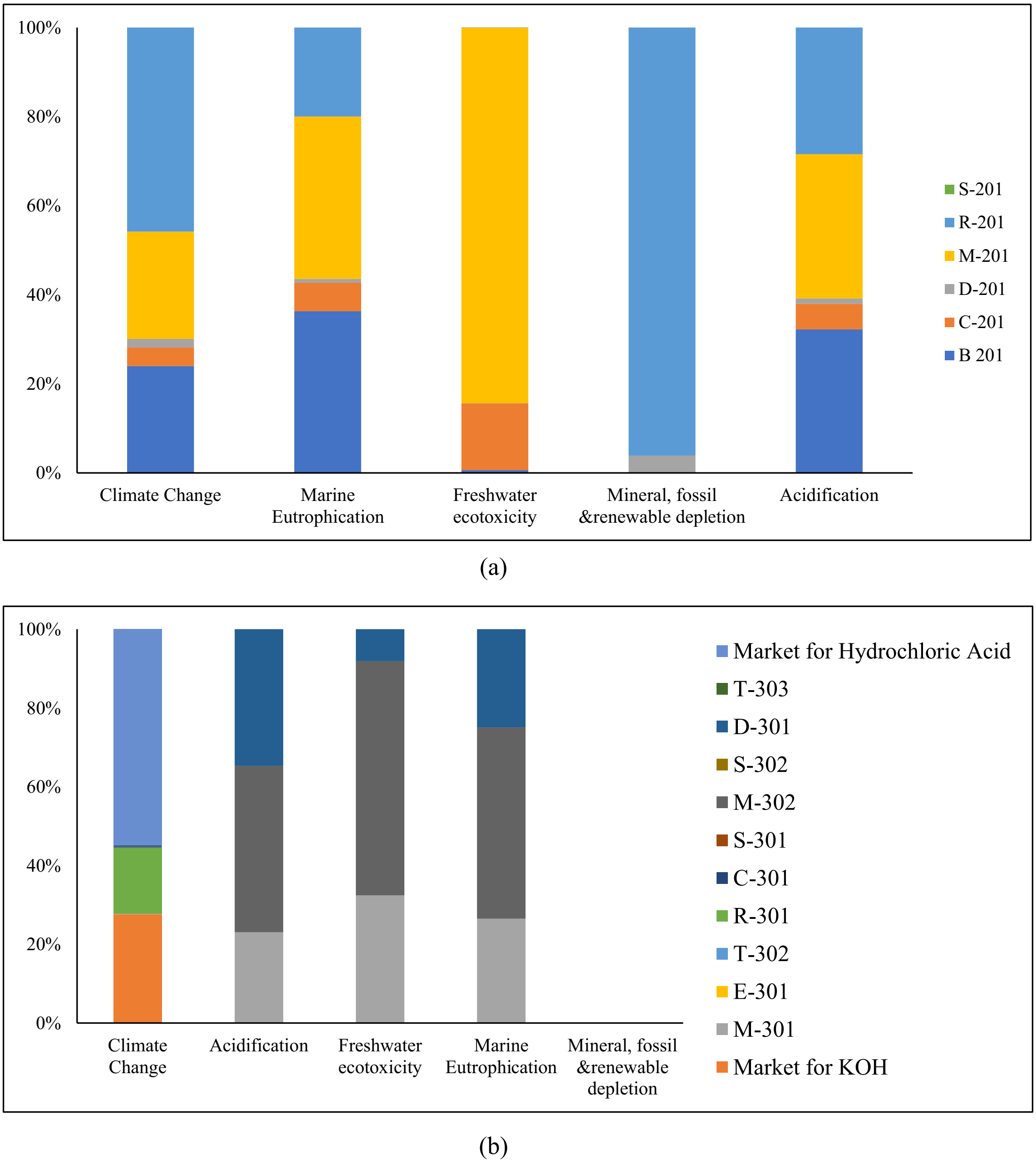

Fig. 3 Hotspot analysis for DCA (**a**) and CI (**b**) KOH activation for a FU of 4167 kg/h wet food waste

the thermal demand of autoclave reactor for HTC and subsequent drying as the major contributors for emissions, respectively, indicating the replacement of fuel source could improve the environmental performance.

3.3 Alternative scenario: effect of changing fuel for energy supply

As shown in the impact results, most environmental problems were caused by the consumption of natural gas as the principal energy source. Therefore, a sensitivity assessment was carried out to comprehend the influence of integrating renewable energy with the activated hydrochar production plant. In this instance, only CI is being considered as the activation technology due to its superior environmental and techno-economic performance. Here, a hypothetical alternate scenario was examined in which the essential heat and electric energy inputs of the production plant are supplied by an adjacent solar thermal parabolic trough power plant. Ecoinvent was used for data regarding the construction and operation of the solar-powered power plant (detailed in the "Supplementary information"). Two of the five impacts

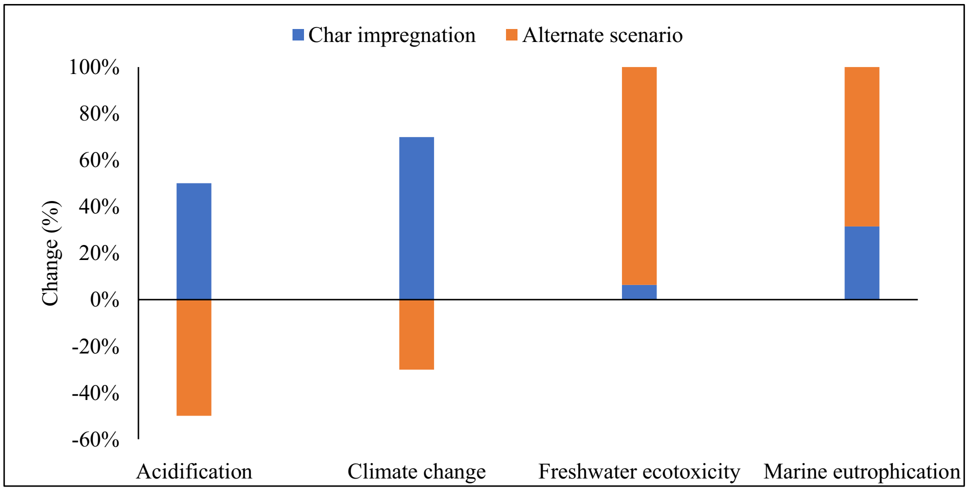

Fig. 4 Change in emission due to solar energy integration as alternative energy for activated hydrochar production for a FU of 4167 kg/h wet food waste

(climate change and acidification) were significantly reduced because of substituting natural gas with green energy, indicating environmental benefits. The emissions of greenhouse gases and acid gases were reduced by roughly 99% and 43%, respectively, resulting in enormous reductions in climate change and acidification potential (Fig. 4). The substantial quantity of carbon sequestration is because the carbon footprint of solar thermal power plants (0.0484 kg CO_2e per kWh) is a factor of almost one order of magnitude lower than natural gas power plants. Comparatively, lower acid gas emissions during the construction and operation of solar thermal plants significantly reduced acidification potential compared to natural gas combustion.

Nonetheless, the assessment of the alternative scenario revealed an increase in freshwater ecotoxicity and marine eutrophication in comparison to the baseline condition (S2). The solar-integrated activated hydrochar production plant's ecotoxicity to freshwater was determined to be 15 times that of the basis case, while marine eutrophication was projected to be three times higher. Both increases can be traced back to emissions during the concentrated solar thermal collector construction phases. For instance, freshwater ecotoxicity was caused by the emission of copper during copper treatment of powerblock scraps. Copper is a crucial component in the construction of solar thermal power plants due to its versatile application in electrodes and widespread availability. However, as suggested by our study, this could have negative environmental effects if not monitored. Similar to ecotoxicity, marine eutrophication is caused by the construction phase, notably the installation and operation of the heat transport fluid system, the creation of the collector field for the solar collector, and the thermal storage system. This is the flip side of ostensibly green energy resources, which reduce greenhouse gas emissions significantly but impose other severe environmental costs. Thus, emerging green technologies such as solar thermal plants need to have improved construction materials with reduced possibility of leaching into the environment. In addition, it is essential to note that the focus of this study is confined to attributional life cycle assessment and that the alternative scenario takes into account an already-existing solar thermal power plant. However, solar thermal technology is not yet mature and is limited by land use, the effect of which is not considered. Consequently, future studies examining hybrid renewable energy technology should take market shift effects into account.

4 Conclusions

Environmental impact of fabricating ultraporous activated hydrochar from food waste, in the aim of mitigating such waste, has been extensively evaluated in this study. Results from LCA underscored the increased favorability of implementing CI technique for KOH activation in comparison to DCA, to produce activated hydrochars. In the process of upcycling 100 tons of food waste per day (on a wet basis), char impregnation posed lesser environmental hazard where it was found that the highest category indicator, contributing majorly to the environmental impact, was freshwater ecotoxicity (57.2%) with the least being climate change (3.17%). Moreover, noteworthy observation was made from hotspot analysis in climate change impact category where for both the KOH activation techniques, dryer in the HTC process was the primary responsible unit because of its necessary operational condition of using natural gas as the source of energy. As natural gas consumption severely impacted environmental factors, a substitute scenario of an integrated renewable solar power plant was also incorporated. Results strongly highlight that by utilizing alternative energy, climate change and acidification categories could be substantially reduced whereas freshwater ecotoxicity and marine eutrophication was increased by 15 and 3 times, respectively, attributed to emission associated with solar thermal collector construction phases. Hence, this study distinctly unveils the environmental impacts of food waste–derived ultraporous carbon synthesis, whereas the application of energy from solar power plants could advance such activation techniques for porous material synthesis towards another step of achieving more sustainable food waste management.

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Author contributions AIS: Writing, original draft; writing, review and editing; data curation; methodology; visualization. SH: Formal analysis; investigation; writing, original draft; writing, review and editing. SS: Methodology; investigation; writing, original draft; writing, review and editing. KK: Resources; methodology; software; supervision; validation; visualization; writing, review and editing. TR: Funding acquisition; methodology; project administration; resources; supervision; validation; visualization; writing, review and editing.

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Data availability Data will be available upon request.

Declarations

Ethical approval Not applicable.

Competing interests Not applicable.

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