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PRODUCTION AND CHARACTERIZATION OF HYDROTHERMALLY PROCESSRD SOLID BIOENERGY FROM AN INVASIVE SPECIES

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Abstract

Invasive alien species (IAS) are one of the most serious environmental concerns for native biodiversity, as they can alter ecosystem functions through species homogenization. Invasive species can also affect human health and cause economic damage to agriculture. This study aimed to produce and characterize hydrochar as solid bio-energy derived from the invasive species *Sphagneticola trilobata* (ISST) through hydrothermal carbonization. The effect of different factors, namely temperature and reaction time towards the hydrochar yield (%) was optimized by central composite design (CCD) using statistical response surface methodology (RSM). To verify the hydrochar as an energy material, the physicochemical, structural and morphological properties were studied using SEM, FTIR, TGA, elemental and proximate analysis. The optimized temperature was 180.31 °C and the time was 2.23 hours. The best yield of the hydrochar was 51.54%. The calorific value of hydrochar increased from the calorific value of 13.41 MJ/Kg of *Sphagneticola trilobata* biomass to 17.03 MJ/Kg. The amounts of sulfur (S) and ash reduced dramatically. Moreover, greater carbon content and lower oxygen content were found in the hydrochar than in the raw ISST. Consequently, it is an advantageous technology for improving the characteristics of biomass of invasive species to hydrochar as fuel for energy generation.

Keywords: Hydrochar, Invasive species, *Sphagneticola trilobata*, Optimization, Bioenergy, Carbonization

Introduction

The declining supply of fossil fuels and the rising amounts of greenhouse gases have encouraged looking for alternative, renewable energy generation from different sources(Arutyunov & Lisichkin, 2017). One of the most pressing issues confronting humanity today is the escalation of the Earth's temperature caused by the heightened release of carbon dioxide into the atmosphere from the widespread utilization of fossil fuels (Heracleous et al., 2017). Biomass is a renewable resource with great potential as an alternative to fossil fuels for supplying energy (Nanda et al., 2014); (Haribabu et al., 2022). Bioenergy can be generated from leftover organic biomass waste (Cavali et al., 2023); Cao et al., 2021). It is estimated that biomass resources contribute to approximately 80% of energy consumption in developing countries (C. F. Liu et al., 2006). As a result of the increased demand for biomass, new and promising bioenergy crop cultivation has been expanded (Wang et al., 2021). Nevertheless, the majority of the species considered for bioenergy crops are exotic, and the functional characteristics that help to make a species more invasive (Van Meerbeek et al., 2015).

Invasive alien species (IAS) constitute a major environmental problem for native biodiversity as they can alter ecosystem performance through species homogenization (Naeem et al., 2009); (Akter & Zuberi, 2009). While

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numerous studies have been done to determine how invasive crops can have their invasiveness prevented or better controlled, there has been less focus on the potential of invasive species to provide biomass for bioenergy (Davis et al., 2010); (Álvarez et al., 2020). Invasive species-derived hydrochar is an effective carbon-sequestration material (Luo et al., 2024).

Biomass and especially wet biomass is not an ideal fuel due to its fibrous nature, low density and low heating value (Phang et al., 2023). Thermochemical processes, pyrolysis and hydrothermal carbonization (HTC) help to change the properties of lignocellulosic biomass through reactions and produce solid bioenergy (Chen et al., 2012; Heracleous et al., 2017; Volpe et al., 2020). Biochar is produced from pyrolysis process which is often used as soil amendment and increases soil fertility. Hydrochar is produced from the hydrothermal process which is used as biofuel. Hydrothermally process bioenergy has increased its fuel property through thermochemical reaction. HTC makes it easier to transform organic materials into high-carbon hydrochar. HTC is a water-based process that doesn't require any other chemicals or solvents. Because it is a more environmentally friendly choice than some other thermochemical processes, as it produces fewer hazardous byproducts and has a smaller negative impact on the environment. The hydrochar generated through HTC generally possesses favorable attributes, such as a high carbon content, low ash content, and advantageous chemical and physical properties. Presently, biomass conversion practice has been done using biogas plants, biomass briquettes and improved cooking stoves but all these technologies are biomass-specific and not suitable for all biomass including wet biomasses (Nsair et al., 2020); (Obi et al., 2022).

There are many forms of potential biomass and biomass waste being considered for good solid fuel after hydrothermal treatment. Among them, waste walnut shells (Naderi & Vesali-Naseh, 2021), agricultural waste from corn fields (Wu et al., 2023), paper sludge (Assis et al., 2022), waste ginko leaf residues (Yu et al., 2022), Korean native kenaf (Youn et al., 2023), cow manure (Q. Liu et al., 2023), olive oil industry waste (Balmuk et al., 2023), rape straw (Cheng et al., 2022) and many more are reported. This study marks the first attempt to produce solid bio-energy from the biomass of invasive species to assess its potential. The production of bioenergy from invasive species provides several significant benefits and opportunities. Such as invasive species management, job creation and opportunity, renewable energy sources, and environmental benefits. The focus here is on the production of solid fuel from the invasive species *Sphagneticola trilobata*, and evaluate its energetic valorization through hydrothermal carbonization, and ensuring IAS does not become a burden on the ecosystem. Moreover, the effects of different parameters, namely temperature and reaction time on the bio-energy properties are examined. The development of waste-to-energy technologies has made it possible to commercially implement systems that generate energy from organic waste. The production of biofuels can help in increasing employment and economic development in rural areas. This is especially essential in developing nations where agriculture is a significant employer.

Materials and Methods

Sample collection

Samples of *Sphagneticola trilobata* (ISST) were collected from Khulna University campus. Selected biomass was manually chopped into small pieces and later processed into fine pieces ranging from 1–5 mm in size. Then the sample was air-dried and stored in a sealed jar for further use.

Production of biofuel through hydrothermal carbonization

Hydrothermal carbonization (HTC) was carried out using a 300 ml stainless steel high-pressure reactor (Neilement Engineering Resources and Services, Penang, Malaysia) in a small-scale batch process. Here the objective was to obtain a solid biofuel as the end product. A Watlow EZ-ZONE PID (proportional-integral-derivative) was used in order to measure temperature. The combustion chamber was filled with 10 g of dry raw *Sphagneticola trilobata* and 100 mL of water that was distilled. The container was then sealed, and the reaction conditions were all set using the central composite design (CCD) under statistical response surface methodology (RSM) as described in Table 1.

After the experiment, the *Sphagneticola trilobata* (ISST) hydrochar was need to be washed. After being cleaned with distilled water, it was dried at 105 °C in an oven and stored for further analysis. The hydrochar yield was calculated using the equation below:

$$\text{Yield\%} = \frac{Dry\ mass\ of\ solid\ hydrochar\ (gm)}{Dry\ mass\ of\ raw\ materials\ (gm)} \qquad (1)$$

Table 1. Results of the design matrix for the production of hydrochar from ISST hydrochar

Factors	Ranges and level				
	-α	Low(-1)	Middle (o)	High(+1)	+α
Temperature (^{o}C)	175.86	180	190	200	204.14
Contact time (hr)	1.59	2	3	4	4.41

Run	Temperature	Contact time	Yield%
1	175.86	3	49.87
2	180	4	44.10
3	190	3	50.28
4	190	4.41	44.87
5	200	4	44.69
6	190	1.59	48.56
7	180	2	50.99
8	204.14	3	43.90
9	190	3	49.59
10	190	3	48.90
11	200	2	43.24

Biofuel characterization

To characterize the *Sphagneticola trilobata* hydrochar and raw materials, analysis was carried out at the INARS (Institute of National Analytical Research and Service) which functions under BCSIR's (Bangladesh Council of Scientific and Industrial Research) authority. CHNS was tested at the BCSIR. Oxygen content was measured with the following formula:

$$O = 100 - (C+H+N+S) \quad (2)$$

Through a muffle furnace (HYSC, Model MF-05, South Korea), the amount of ash and volatile matter was determined via ASTM standard method E1755-01 and DIN 51720, correspondingly. The fixed carbon (FC) was determined by the following equation:

$$FC = 100 - (Ash + VM) \quad (3)$$

The higher heating value (HHV) was measured from Khulna University of Engineering Technology, Khulna, Bangladesh. Fourier transform infrared spectrophotometry (FTIR) testing was carried out in a laboratory at the Forestry and Wood Technology Discipline, Khulna University. FTIR spectra were collected in the 550-4000 cm range using FTIR equipment with the ATR (Perkin Elmer Inc., USA). The JEOL machine (model no. JSM-7610F) was used to capture the energy dispersive X-ray and scanning electron microscopy images.

Metal content (Cr, Fe, Mn, Cu, Ni, Zn, Cd, Al and Pb) was determined using an Atomic Adsorption Spectrophotometer (AAS) (AA 6200, Shimadzu, Japan). For this, both ISST and ISST hydrochar samples were digested using a 3:1 HNO3:HClO4 (v/v) solution following the method described in APHA (Bridgewater et al., 2017). Cellulose, hemicellulose, lignin and extractives content in ISST and ISST hydrochar were determined utilizing the procedures described by Sultana et al. (Sultana et al., 2022).

$$\text{Energy recovery} = \frac{Wt\ of\ HC\ x\ HHV\ of\ HC}{Wt\ of\ Raw\ x\ HHV\ of\ Raw} \quad (4)$$

$$\text{Carbon recovery} = \frac{Carbon\ content\ of\ HC}{Carbon\ content\ of\ Raw} \quad (5)$$

$$\text{Fuel ratio} = \frac{FC}{VM} \quad (6)$$

$$\text{Energy densification ratio} = \frac{HHV\ of\ HC}{HHV\ of\ Raw} \quad (7)$$

$$\text{H/C ratio} = \frac{\dfrac{\textit{Weight percent of hydrogen in HC}}{\textit{Atomic weight of hydrogen}}}{\dfrac{\textit{Weight percent of carbon in HC}}{\textit{Atomic weight of carbon}}} \tag{8}$$

$$\text{O/C ratio} = \frac{\dfrac{\textit{Weight percent of oxygen in HC}}{\textit{Atomic weight of oxygen}}}{\dfrac{\textit{Weight percent of carbon in HC}}{\textit{Atomic weight of carbon}}} \tag{9}$$

Results and discussion

For the production of *Sphagneticola trilobata* hydrochar, the impact of time and temperature were deemed to be processing factors helping produce the response yield by using the central composite design (Table 1). The model's adequacy was assessed through analysis of variance (ANOVA) method. The model regression coefficient of determination (R^2) of 0.962 for yield% reasonably agreed with the experimental results, indicating 96.2% of the variability was revealed by the model and leaving 3.8% residual variability. Moreover, the insignificant lack of fit (LOF) test recognized a good response to the model (Table 2). Subsequently, it can be concluded from the above results that the CCD design was good enough to predict the production yield of ISST hydrochar within the range of factors investigated. The statistical package Design-Expert version 13.0 served as the framework for the experimental plan and data evaluation. The following explains the ultimately estimated process models in terms of real significant factors for yield%.

$$\text{Yield\%} = +49.59 - 1.95{*}\text{Temperature} - 1.33{*}\text{Reaction time} + 0.208{*}\text{Temperature}{*}\text{Reaction time} \\ -1.62{*}\ \text{Temperature}^2 - 1.70{*}\text{Reaction time}^2 \tag{10}$$

From Eq. 10 of the yield%, time and temperature had a notable adverse effect on yield% according to observations. The yield of ISST hydrochar percentage may diminish when temperature or time increases. The maximum yield of ISST hydrochar was found at 182.16 °C over a period lasting 2.12 h, yielding 51.42%. As seen from the model, it is observed that the amount produced of ISST hydrochar (Figure 1) was greatly and positively affected by the interactions between time and temperature. For example, a yield of 50.99% was produced at a temperature of 180 °C and a time of 2 h. After that, as the temperature rose and time became reduced, the yield percentage also decreased. Finally, at the temperature of 200°C with 4 h time, the smallest yield was 44.69%. Judging by the above observations, it can be established that interactions of temperature and time mainly governed the yield of ISST hydrochar.

Table 2. Response Surface Model with ANOVA

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remarks
Model	86.06	5.00	17.21	25.54	0.0014	significant
A-Temperature	30.44	1.00	30.44	45.17	0.0011	significant
B-Reaction time	14.22	1.00	14.22	21.11	0.0059	significant
AB	17.36	1.00	17.36	25.77	0.0038	significant
A^2	14.74	1.00	14.74	21.88	0.0054	significant
B^2	16.35	1.00	16.35	24.26	0.0044	significant
Residual	3.37	5.00	0.67			
Lack of Fit	2.41	3.00	0.80	1.67	0.3956	not significant
Pure Error	0.96	2.00	0.48			
Cor Total	89.43	10.00				

R^2=0.962, Adj-R^2=0.924

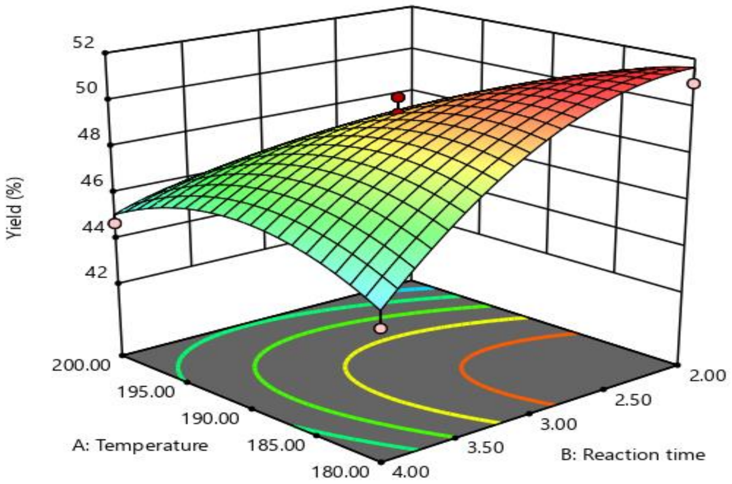

Figure 1. Graph for the yield percentage of ISST hydrochar in three dimensions: temperature and response time at the center (Source: Authors)

Optimization and Confirmation Study

The software's numerical optimization method has been selected to improve process parameters, such as reaction time and temperature, to maximize yield%. Given that both temperature and contact time had an adverse individual impact on yield%, the response was classified to be "within range" and the temperature and contact time were given an appropriate "importance" level of 3. Since higher ISST hydrochar yield percentages are typically preferred, the goal for yield% was chosen to "maximize" with importance level 5.

The central composite design levels functioned to determine the lower and upper limits for each response. Using these parameters, the software optimized the temperature to 182.16^{o}C and the reaction time to 2.12 hour to produce a yield of 51.42% (Figure 2.). Later, a confirmation study was done by employing these optimized parameters and resulted in a 51.03% yield. Shown here is that a central composite design involves quantitative optimization and might be applied to appropriately adjust variables for hydrochar yield of the ISST.

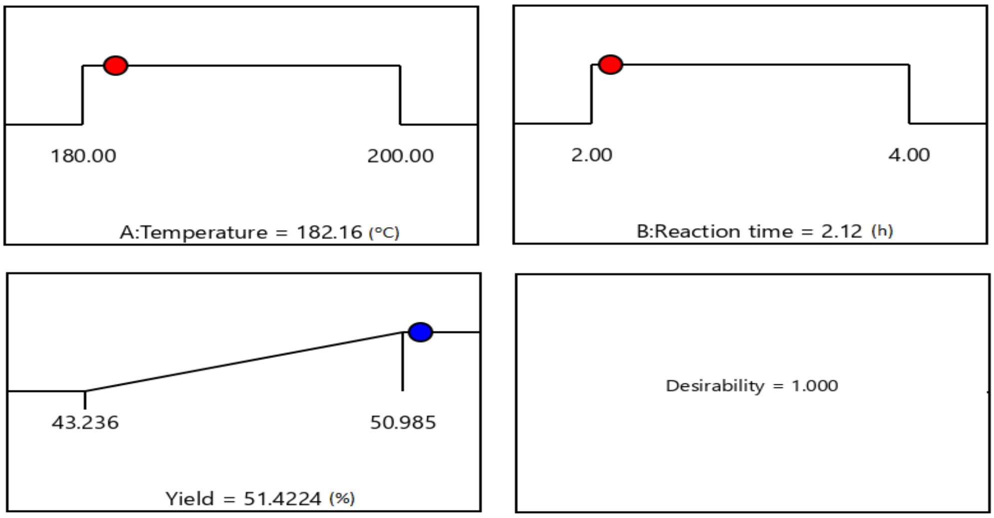

Figure 2. Desirability ramp for improving ISST yield % hydrochar (Source: Authors)

Physicochemical properties of ISST-raw feedstock and ISST hydrochar

Table 3 provides an overview of ISST-raw and ISST-HC's primary physicochemical features. The proximate analysis's goal is to ascertain the sample's fixed carbon, volatile chemical content, and ash content. The characteristics and properties of a good source of fuel having higher heating value and high fixed carbon with lower ash content are considered.

Proximate analysis is crucial in determining these elements. Numerous changes in proximate values for the ISST feedstock and ISST hydrochar were observed in this study. According to the proximate analysis, in the best conditions, ISST-HC's, VM content dropped from that of ISST-raw while FC content rose as a result of conversion. ISST-raw materials contain 70% volatile matter and 7% fixed carbon. In optimized conditions, the ash content fell slightly from 22% for ISST hydrochar to 21% for ISST-raw was found. Proximate analysis indicates the calorific value or higher heating value of biomass which is essential for energy measurement.

The ultimate analysis is indicated as one of the key tests not only to measure the air-fuel ratio for a clean burn but also to assess the fuel's capacity to pollute (Telmo et al., 2010). The energy content of biomass materials can be determined through ultimate analysis. It offers details on the elements that compose biomass, such as the amounts of ash, carbon, hydrogen, oxygen, nitrogen, and sulfur. To determine whether biomass is suitable for producing bioenergy, it is necessary to calculate the biomass's calorific value or energy content. Based on ultimate analysis results, in comparison to ISST-raw, the hydrochar's carbon content rose under optimal conditions, where the oxygen content fell as temperature rose. It is observed that the carbon amount of ISST green biomass and ISST hydrochar were 34.63% and 37.57% (Table 3). Conversely, the amount of hydrogen, oxygen, and nitrogen of green biomass were 4.93%, 57.10%, and 2.62%, respectively, while the hydrogen, oxygen, and nitrogen contents of ISST-HC were 4.47%, 54.37%, and 2.28%, respectively. The HHV (higher heating values) of the ISST raw and treated samples are shown (Table 3). In the results, we can see that during hydrothermal carbonization, the higher heating value of ISST was increased.

The calculated HHV increased from 13.68 MJ/kg to 17.03 MJ/kg in the case of hydrochar. The amount of carbon in hydrochar and higher heating value were found to be significantly related. As the process became more intense, the rate of reactions like decarboxylation accelerated, resulting in a larger amount of carbon and a small amount of oxygen (Basso et al., 2015). The chemical composition has an impact on the higher heating value of fuel. When HHV increased then carbon content also increased but oxygen content declined (Demirbas, 2008).

Table 3. The Analysis of the characteristics of ISST feedstock and ISST hydrochar

Analysis	Parameters	Units	ISST Raw	ISST Hydrochar
Ultimate analysis	C	%	35.09	37.57
	H	%	3.55	4.47
	N	%	2.65	2.28
	S	%	0.72	0.71
	O	%	58.71	54.37
Proximate analysis	Ash content	%	22	21
	Volatile matter	%	71	62
	Fixed carbon	%	7	17
Energy properties	H/C ratio		1.70	1.54
	O/C ratio		1.24	1.17
	N/C ratio		0.06	0.07
	Yield	%		49.46
	Higher heating value (HHV)	MJ/kg	13.68	17.03
	Energy densification ratio			1.24
	Fuel ratio		.09	.27
	Energy recovery	%		0.62
	% of HHV improvement	%		24.49
	% of C increase	%		8.49
	Carbon retained in hydrochar	%		0.53
	Carbon recover ratio			1.08

Table 3 lists the outcome of the tests for ultimate analysis, proximate analysis, energy properties. These experiments are usually used to evaluate the char products which is obtained from the lignocellulosic biomass. In general, the energy recovery of char decreases with increasing temperature (L. Liu et al., 2013). Table 3 shows that ISST-HC's energy recovery was 0.62 and energy densification amounted to 1.24. ISST-HC had a carbon extraction rate of 1.08. Alternatively, the fuel ratio is the proportion of VM to FC. This is because, in hydrochar, the fixed carbon burns slowly in the solid state while the volatile components are driven off by heat and burn quickly in the gaseous phase. Low combustion temperatures are common in materials with a considerable VM. The ISST-raw and ISST-HC fuel ratios in this instance were respectively 0.09 and 0.27. That means hydrochars have a higher fuel-producing ability than raw materials in this study.

The chemical properties of ISST feedstock and ISST-hydrochar are shown in Table 4. ISST-raw has the largest amount of cellulose 29% compared to ISST-HC (24.3%). ISST-raw also had higher lignin (30.5%) and hemicellulose contents (35.5%), respectively. The lower percentage of ISST-HC in chemical composition compared to ISST-raw may be due to three things: the breakdown of hemicellulose, the degradation of cellulose polymer and the degradation of lignin. Since the temperature at which carbonization occurred was below 300°C, a large number of lignin and cellulose breakages proved to be challenging to dissolve and spread in the liquid phase (Kang et al., 2012).

By raising the process temperature the HHV rises and this is mainly explained by the carbonization process (Mumme et al., 2011; Zhang et al., 2018). In the relevant literature, authors observed that the material's heating value rose when increasing the temperature in the process. Figure 3, is the Van Krevelen diagram and it illustrates the molecular ratios of O/C and H/C. This diagram is useful for depicting the change in the lignocellulosic material during thermal decomposition. The chemical reactions of carbon-rich substances are clearly shown in this figure. The O/C and H/C ratios decreased as the temperature rose. As a result, hydrochar presents traits that are comparable to those of lignite or peat. Due to the high temperature, dehydrating and decomposing reactions occurred, and the amount of carbon in the sample rose while the amount of oxygen fell. It is anticipated that the lower O/C and H/C ratio will result in less combustion-related pollution and a small amount of moisture (L. Liu et al., 2013). In Figure 3, it has been seen that the position of ISST-HC is close to lignite and under the ISST-raw.

Table 4. Chemical properties of ISST feedstock and ISST hydrochar

Parameters	Unit	ISST feedstock	ISST hydrochar
Cr	mg/L	0.14	0.13
Fe	mg/L	0.92	1.03
Mn	mg/L	0.60	0.70
Ni	mg/L	0.10	0.07
Cu	mg/L	3.76	1.16
Zn	mg/L	3.09	1.58
Al	mg/L	8.56	10.85
Cd	mg/L	<0.003	<0.003
Pb	mg/L	0.50	0.32
Extractives	%	5	32.4
Cellulose	%	29	24.3
Hemicellulose	%	35.5	18.3
Lignin	%	30.5	25

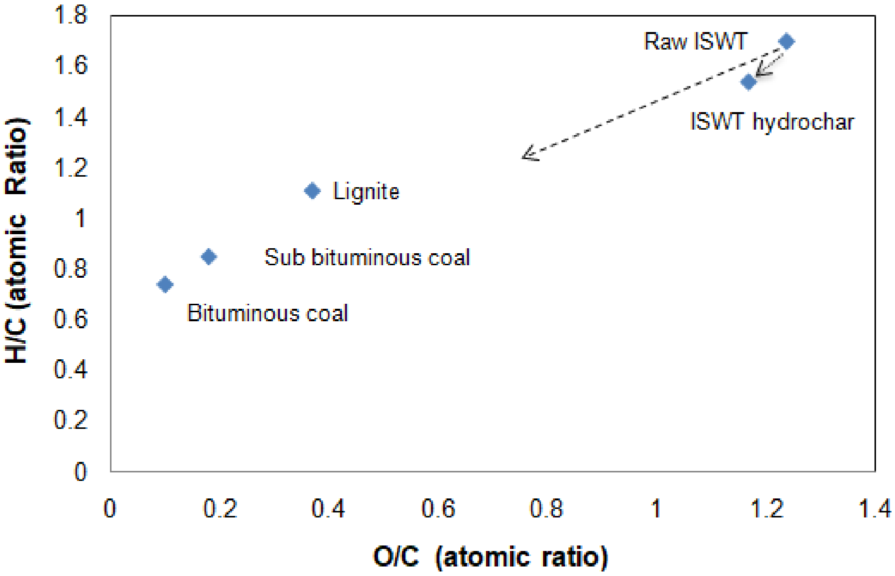

Figure 3. Three common fuels (lignite, sub-bituminous coal, and bituminous coal) are shown in the Van Krevelen diagram along with raw materials and hydrochar (Source: Authors)

Surface structure and mechanism analysis

The SEM (surface structure and mechanism) images show the raw materials structure which changes in high temperature. Primarily, the raw samples have a distinct shape because of their intact texture. The surface morphology and material properties of ISST-raw materials and ISST-hydrochar have changed, as shown in the SEM images (Figure. 4).

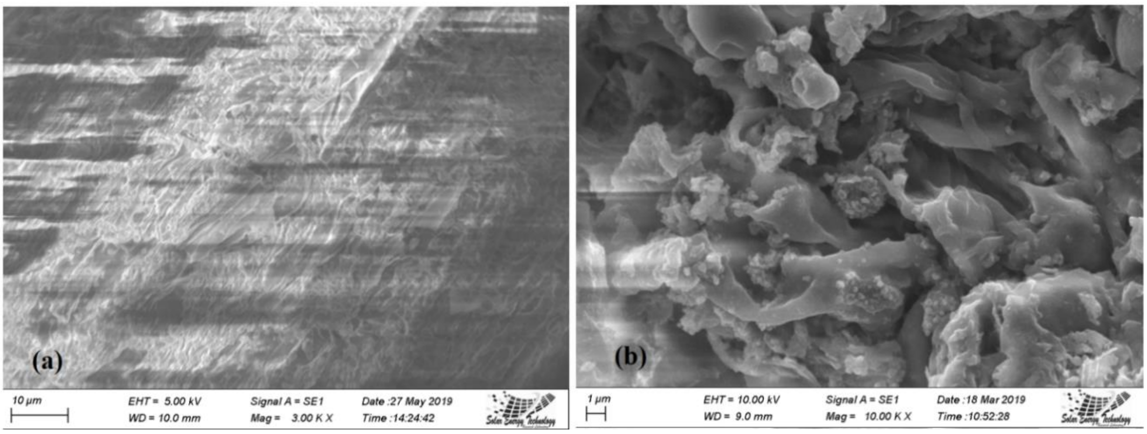

Figure 4. SEM images of (a) ISST raw materials and (b) ISST-hydrochar (Source: Authors)

As anticipated, a significant distinction was observed. As seen in figure 4 (a), ISST-raw demonstrated a typical cellular structure of carbon-rich biomass. Many pores were found and they ranged in size from 5 to 25 mm. However, the biomass structure broke separately for the HTC process. In the hydrochar sample, as shown in figure 4(b), some microscopic pores are generated by the exhaust of gas.

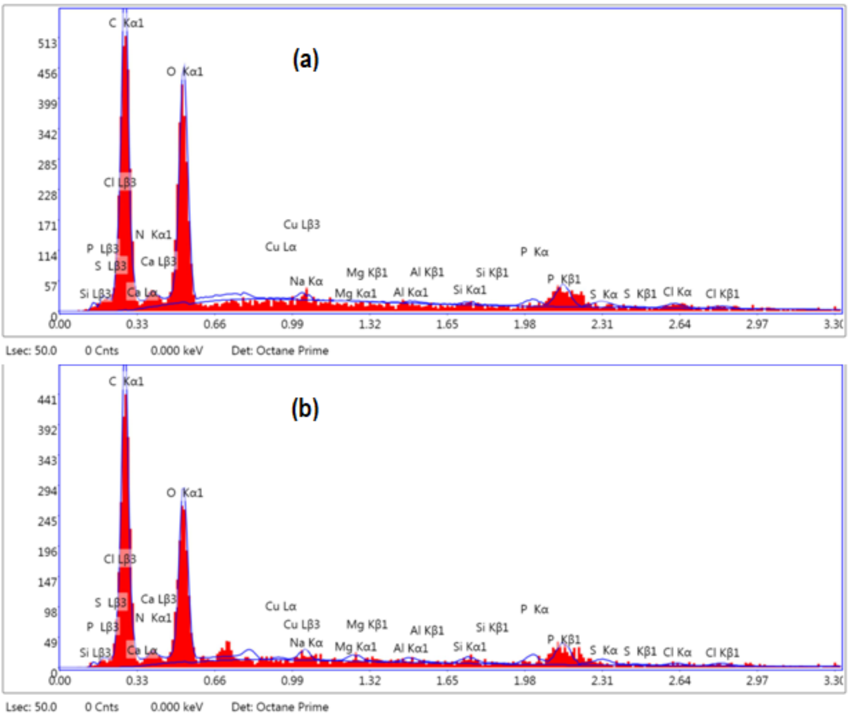

Figure 5. Representative EDX spectra obtained (a) Raw ISST and (b) ISST hydrochar in optimized condition (Source: Authors).

The analytical method of energy-dispersive X-ray spectroscopy (EDX) is employed to evaluate a sample's chemical structure or conduct an elemental investigation. It depends on the connection of an X-ray sparking source. Its ability to characterize things is largely a result of the basic concept that each component has a distinct atomic structure that allows for a distinct set of peaks.

The main electron beam is generated using a tungsten filament. Additionally, it is centered on the sample's surface to encourage the radiation of distinctive X-rays from it. In this study, elemental scanning or EDX served to find the minerals arranged on the external layers of raw materials and hydrochar. Here, a 5kV electron beam was deployed to generate the EDX information. Some peaks in the 0–20 keV range were found as shown (Figure 5) and energy correlates with K-shells. The advantage of this method is its ability to make possible qualitative and semi-quantitative atomic structure composition on different sample regions.

Carbon, nitrogen, calcium, potassium, sulfur, silicon, magnesium, etc., are the key elements of (ISST) raw materials and hydrochar. From Figure 5, it can be seen that carbon dominated the hydrochar rather than raw material. In ISST-raw and according to mass percentage, carbon is the significant element. After that, compared to other elements oxygen had a higher percentage. ISST-HC showed better quality than ISST-raw as fuel because of presenting higher oxygen content in ISST-raw. So, ISST-HC is enriched with nutrients than raw materials of ISST.

FTIR analysis

FTIR images of raw materials (ISST) and ISST-hydrochar products at optimized conditions are shown (Figure 6). Some differences were observed in Figure 6, confirming the occurrence of chemical transformation during HTC. FTIR images with wave numbers between 4000 and 500 cm^{-1} were used to examine the chemical groups found in ISST-raw and hydrochar. The specific wavelengths provide information about the existence of bonding for atoms with different groups of functions.

In Figure 6, in both cases, a strong peak is detected in 1581.63 in the raw sample and a slightly lower frequency is evident in the processed sample. It indicates C=C stretching in the aromatic skeletal present in lignin. The peaks at 1056.99 and 1033.83 cm^{-1} are possibly because of C-O stretching in hemicellulose ester which has somewhat increased frequency in hydrochar (C. F. Liu et al., 2006). Several weak peaks found in 1315.45, 1276.88, 1230.58, 1207.44, and 1153.43 may represent C-O stretching due to vibration in the lignin and hemicellulose esters. The peaks at lower frequencies at 671.23, 601.79, and 540.07 indicate a halogen compound C-Br bond. Apart from this, the distinctive cellulose band is observed in the region of 1160–900 cm^{-1}, the small peak of hemicellulose is found at 1730, and the lignin band in the region of 1550–1300 cm^{-1} (Raspolli Galletti et al., 2015).

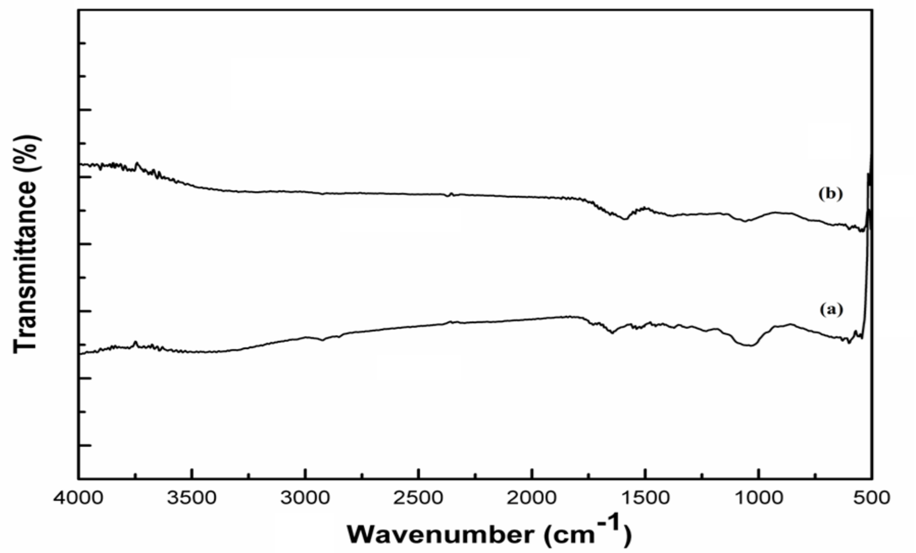

Figure 6. FTIR spectra of raw ISST (a) and HC ISST (b) derived at optimized conditions (Source: Authors)

Conclusion

In this study, hydrochar was produced from *Sphagneticola trilobata* through a hydrothermal carbonization process. Different times and temperatures were used to get the highest yield. The optimized conditions for hydrochar production were 182.16 °C temperature and 2.12 hours for reaction time and in that scenario, the yield% of the hydrochar was 51.42%. After analysis of hydrochar, it can be seen that its calorific value rose from the calorific value of 13.68 MJ/Kg to 17.03 MJ/Kg of *Sphagneticola trilobata* biomass. The energy content of hydrochar was increased in comparison with raw biomass. The oxygen, sulfur (S), and ash contents were reduced while the amount of carbon was higher than the green biomass. The novelty of this research is waste management, ecosystem restoration and bioenergy production. It can therefore be concluded our proposed method is an excellent one for enhancing the properties of invasive species' biomass when converted to hydrochar for use as an energy source. Converting bioenergy from invasive species is cost effective and invasive species can be wasteful because they damage ecosystems, lower biodiversity, and sometimes require expensive management measures to stop their spread.

Authors' contributions

MAtI: Conceptualization, resources, project administration; IJ: data curation, investigation, writing; PPD: writing original draft preparation; BHH: review and editing, visualization and investigation; ZL: review and editing, visualization and investigation; MAI: Conceptualization, methodology, funding acquisition, software, supervision.

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Availability of data and materials

All the data has been incorporated into the manuscript.

Declarations

Ethical Approval

Not applicable

Competing interests

The authors declare no competing interest

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