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Environment impact and bioenergy analysis on the microwave pyrolysis of WAS from food industry: Comparison of CO_2 and N_2 atmosphere

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ABSTRACT

The alarming output of waste activated sludge (WAS) from industries requires proper management routes to minimize its impact on the environment during disposal. Pyrolysis is a feasible way of processing and valorizing WAS into higher-value products of alternate use. Despite extensive research into the potential of WAS through pyrolysis, the technology's long-term viability and environmental impact have yet to be fully revealed. In addition, the environmental effects of utilizing different pyrolysis atmosphere (N_2 or CO_2) has not been studied before, although benefits of CO_2 reactivity during pyrolysis have been discovered. This study evaluates the process's environmental impact, carbon footprint, and bioenergy yield when different pyrolysis atmospheres are used. The global warming potential (GWP) for a functional unit of 1 t of dried WAS is 203.81 kg $CO_{2\ eq}$. The heat required during pyrolysis contributes the most (63.7%) towards GWP due to high energy usage, followed by the drying process (23.6%). Transportation contributes the most towards toxicity impact (59.3%) through dust, NO_x, NH_3 and SO_2 emissions. The initial moisture content of raw WAS (65%) greatly impacts overall energy consumption and environmental impact. Pyrolysis in an N_2 atmosphere will result in a higher overall bioenergy yield (833 kWh/tonne) and a lower carbon footprint (−1.09 kg CO_2/tonne). However, when CO_2 was used, the specific energy value within the biochar is higher (22.26 MJ/kg) due to enhanced carbonization. The carbon content of gas derived increased due to higher CO yield. From an energy perspective, the current setup will achieve a net positive bioenergy yield of 561 kW (CO_2) and 833 kW (N_2), where end products like biochar, bio-oil and gas can be used for power production. Despite the energy-intensive process, microwave pyrolysis has excellent potential to achieve a negative carbon footprint. The biochar used for soil amendment served as a good carbon sink. The utilization of CO_2 as carrier gases provides a pathway to utilize anthropogenic CO_2, which helps reduce global warming. This work demonstrates microwave pyrolysis as a negative emission, bioenergy-producing approach for WAS disposal and valorization.

Abbreviations: AD, Anaerobic Digestion; AP, Acidification Potential; CS, Carbon Stability; CSC, Carbon Sequestration Credits; DCB_{eq}, Dichlorobenzene Equivalent; EP, Eutrophication Potential; FU, Functional Unit; GWP, Global Warming Potential; HTP, Human Toxicity Potential; LCA, Life Cycle Assessment; PM10, Particulate Matter with Diameter <10 μm; POCP, Photo-Oxidant Formation Potential; VOCs, Volatile Organic Compounds; WAS, Waste Activated Sludge.

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1. Introduction

Waste activated sludge (WAS) generated from the wastewater treatment plant in the industry has always been a problem that needs to be dealt with. In China, it is estimated to have 5476 wastewater treatment plants producing about 39.04 million tonnes of sludge annually, while only 50% is processed (Wei et al., 2020). Conventional sludge treatment, for example, landfilled and direct land application, is not sustainable, non-environmentally friendly, and raises social concern. Countries like France, Portugal, and Spain have banned such activities (Milieu Ltd, 2010), leading to a switch from land application to sludge incineration as a waste disposal approach (>60% of sludge waste generated in the country is burnt). In Germany, an increase of 64% in thermal treatment has been recorded since the ban on landfilling in June 2005 (Roskosch and Heidecke, 2018). Nonetheless, the burning of WAS will release PAHs and ash into the atmosphere, further degrading the environment. Anaerobic digestion (AD) is a widely used method for sludge handling to produce biogas for heat and power production. The energy required for AD is much lower than the thermal treatment approach, which gives a lower carbon footprint. However, AD generates a secondary sludge that requires post-treatment and poses eutrophication and human toxicity potential if applied directly to land (Arias et al., 2021). The need to explore alternative sustainable and green pathways for sludge management and disposal is imminent. Pyrolysis has been found to be capable of processing WAS in a more environmentally friendly manner while generating higher value products of alternate use. In a review by Teoh and Li (2020), pyrolysis can reduce the sludge volume, weight and pollutants with lower global warming and toxicity potential.

Even though plenty of research has been conducted on the pyrolysis of WAS, knowledge gaps are still present. One primary concern is the wastewater source of WAS towards its reaction during pyrolysis. This is because WAS has a chemical composition that varies depending on the wastewater source, affecting the efficacy of specific management methods. WAS treatment aims for volume reduction, mass loss, biological hazard neutralization and heavy metal immobilization. To date, pyrolysis experiments have been conducted on WAS from domestic sources (Mphahlele et al., 2021), steel industry (Qin et al., 2015) and faecal-based (Krueger et al., 2021), with a less study looking into WAS from food processing industry. The composition of such source has high organic content and low toxicity level, making it different from WAS obtained from municipal or heavy industry sources. Luo et al. (2021) report that sludge with higher organic content and lower moisture will enhance the system's environmental and economic performance. Therefore, it is interesting to look into the pyrolysis of WAS from the food processing industry.

Another concern regarding the pyrolysis of WAS is its energy-intensive process. Pyrolysis is a thermal treatment method where feedstock undergoes intense heating from 400 to 650 °C. The massive amount of heat required for this process receives critics of this process being unsustainable in the long run. Microwave heating is a discovery capable of reducing heat consumption while maintaining the pyrolysis's waste conversion efficiency. Jones (2012) claims microwave heating can reduce energy consumption by 50%. In addition, microwave heating enables a higher heating rate and selectivity in improving specific product yields like H_2 proportion in the gaseous product and higher surface area in biochar (Mong et al., 2020). Hence, microwave heating is adopted in this study.

Pyrolysis atmosphere has recently received researchers' attention due to its potential to alter product qualities. Pyrolysis is commonly conducted under an inert atmosphere (N_2 gas) to avoid the oxidation of valuable organics. Recent research has shifted towards CO_2 pyrolysis, where an enhancement in thermal reaction (Kim et al., 2022) and product quality (Luo et al., 2019) has been reported. Diao et al. (2021) investigated the effect of CO_2-induced pyrolysis on biomass and reported enhancement of hydrocarbon yield as CO_2 accelerated aromatics cracks and hydrogenation of vapours. Other benefits of utilizing CO_2 were reported: 1) accelerate the degradation rate (Wang et al., 2022), 2) higher evolution of CO within the gas product, 3) suppress dehydrogenation of volatile matters, 4) modifying chemical species in bio-oil (Choi et al., 2019), 5) generate more macropores within biochar (Wang, Z. et al., 2018) and 6) present synergistic effect with Fe/Ca species within the feedstock (Cho et al., 2017). The literature reports the differences between N_2 and CO_2 atmosphere in pyrolysis, focusing mainly on the products' characteristics. There is no research work comparing the LCA of both pyrolysis atmospheres, which is the novelty of this study. Moreover, the usage of CO_2 as the pyrolysis medium suggests the possibility of utilizing the anthropogenic CO_2 in the atmosphere, potentially lowering the greenhouse gases and tackle global warming.

The pyrolysis technology has been proven feasible in transforming WAS from various wastewater sources, but such activity's environmental impact and sustainability are still of concern. LCA is commonly adopted to evaluate the environmental impact of a product or a process. A review by Ding et al. (2021) emphasizes the data quality used for LCA should meet criteria of (1) timespan – data should be within recent years, (2) Geographic scope – local, regional coverage of unit process data, (3) Accuracy – degree of variation of values in each data and (4) Repeatability. Most LCA researches focus on carbon emissions that directly relate to the global warming impact of pyrolysis. Literature mentions the possibility of pyrolysis in achieving a net negative carbon emission and a better technology for waste conversion when compared to combustion (Cheng et al., 2021). A LCA study analyses sludge management through incineration and reports that incineration without energy recovery has the highest global warming potential (GWP) of about 1700 kg $CO_{2\ eq}$/tonne of biochar produced. When energy recovery is integrated, the GWP reduces to about 700 kg $CO_{2\ eq}$/tonne of biochar produced (Barry et al., 2019). This study showcases the importance of including the application of products derived for energy recovery to improve overall environmental performance. For example, the biochar produced is employed for agriculture purposes and as a substitute for fossil fuel in energy production. A review study on pyrolysis and biochar scenario in China concludes that a reduction of 2.69 million tons of CO_2 emission can be mitigated and 3962 MWh of energy can be generated annually when both pyrolysis technology and biochar application are being employed (Kung and Mu, 2019). In a separate study, the GWP of pyrolysis reports both positive and negative GWP depending on the source of feed and end products application. Slow pyrolysis on corn stover, woody waste and sludge can potentially achieve a negative environmental footprint (−470 to 200 kg $CO_{2\ eq}$/ton of feedstock on dry weight basis), considering biochar application on land for carbon sequestration (Cheng et al., 2020). When comparing anaerobic digestion (AD) and pyrolysis in municipal solid waste treatment, the energy inputs and outputs are reported to have the most significant environmental impact (Wang et al., 2021). AD has a higher eutrophication potential (EP) when the digestate produced is used as soil conditioners, leading to N and P elements released into the environment. AD (−6.45 kg $CO_{2\ eq}$/kg) has a lower net GWP when compared to pyrolysis (−0.11 kg $CO_{2\ eq}$/kg) due to the higher energy demand for pre-treatment (drying) and pyrolysis process.

Energy balance is another critical topic in pyrolysis. The process aims to be self-sustainable (positive net energy output); however, literature records negative energy output due to excessive moisture in feedstock, energy-intensive process, and low bioenergy recovery from end-products. Pyrolysis of oil sludge from the metal industry reports that some energy is non-recoverable and records a 19–32% fractional loss (Qin et al., 2015). The microwave pyrolysis of horse manure records a negative energy profit because some product like water does not contain useful energy content (Mong et al., 2020). Some studies demonstrate the feasibility of achieving a net positive energy output. Slow pyrolysis of sludge integrated with a gas turbine for energy harvesting records a net positive energy output of 875 kWh, demonstrating the benefits of gas turbine operation (Huang et al., 2022). The report also records negative energy output for slow pyrolysis in biochar production and fast pyrolysis in bio-oil production due to the high energy requirement and low quality of products, which cannot trade-off the energy demand. From literature, most data employed in LCA studies are sources from other works, reducing the reliability of results. There are less LCA studies that analysed pyrolysis environmental impact based on self-run experimental data.

Therefore, this study aims to conduct an LCA study on the microwave pyrolysis of WAS from a food processing industry, referencing data obtained from a lab-scale experiment to evaluate the environmental impact and overall energy yield, comparing different pyrolysis atmospheres. The data employed originates from a lab setup - microwave pyrolysis reactor, where it is scaled up using a 'numbering-up' approach to mimic the operation of an industrial plant. This is the first study where different pyrolysis atmosphere of N_2 and CO_2 is evaluated through LCA. The findings will showcase the potential of microwave pyrolysis in managing WAS. The excess amount of waste can be transformed into valuable products with higher energy value, capable of being used as a green bioenergy source. The work also opens up the possibility of utilizing excess anthropogenic CO_2 and demonstrates a carbon-negative technology considering the carbon storage possibility of biochar product. This will benefit waste management facilities by having a cleaner and more sustainable technology for transforming waste.

2. Materials and method

2.1. WAS

This study utilized raw WAS sourced from a wastewater treatment plant of a local food processing and manufacturing industry – QL Figo (Johor) Sdn Bhd, Malaysia. The current plant has a daily discharge rate of approximately 1 tonne of WAS with a moisture content of ~65 wt%. The raw WAS undergoes conventional drying by an electric oven to remove water (final state of 15 wt% moisture), grind and sieve to a mesh size of 35–140 for physiochemical analysis and experiment. The elemental composition for WAS on a dried basis are Carbon-44.2 wt%, Hydrogen-6.59 wt%, Nitrogen 8 wt%, Sulphur-0.68 wt% and Oxygen-40.52 wt%. The proximate content on a dried basis are Volatile-72.3 wt%, Fixed carbon-13.02 wt%, Moisture-8 wt% and Ash-6.68% (Mong et al., 2021b). The dried WAS has a higher heating value (HHV) of 19.53 MJ/kg.

2.2. Microwave pyrolysis scenario

The lab-scale microwave pyrolysis experiment is conducted utilizing the dried, ground WAS. The experiment was conducted at 600 °C, carrier gas flow rate of CO_2 or N_2 at 1 L/min to retrieve three major end products and two minor products. A domestic microwave oven (2450 MHz) rated at 1000 W was used as the reactor to pyrolyse WAS (40 $\pm$ 0.1 g-per batch). Before the experiment commenced, the carrier gas was allowed to flow through the setup to ensure an inert environment. The microwave power was maximized and the reactor's temperature was taken through a K-type thermocouple placed within. The volatile evolved during pyrolysis was swept away by the flowing gas into a serially-connected condenser setup. The condensed liquid will be collected at the end of the condenser. The uncondensed vapour will be transferred through a silica gel and cotton wool bed to remove any moisture, which was then collected in a Tedlar gas bag. The residence time for the feedstock is 40 min. At the end of the experiment, the power supply was cut off while the carrier gas was allowed to run continuously for cooling. The solid leftover within the reactor was collected manually after the experiment. All three major products will undergo detailed characterization to analyse their properties. The experimental results record an average error of $< \pm 4\%$. The detailed experimental setup and procedure are recorded in another work (Mong et al., 2022). The product yield and energy properties are displayed in Table 1. Water and coke are assumed to have negligible energy content. The experimental data (shown in Table 1) is integrated into the LCA (Section 2.3) for an industrial-scale operation. The values were integrated using a numbering up approach where a linear relationship between feedstock and power consumption with product yield and characteristics is assumed. For instance, if the biochar experimental yield is recorded at 18%, when 1 tonne of feedstock is pyrolyzed, 0.18 tonne of biochar will be obtained.

2.3. Life cycle assessment

According to the ISO 14040 (2006) standard, LCA comprises four stages: 1) goal and scope definition, 2) life cycle inventory, 3) life cycle impact assessment and 4) interpretation. LCA is conducted to evaluate the impact of a product or process affecting the environment throughout its lifetime. The environmental impacts were assessed with referencing from Ecoinvent 2.0 and GaBi 6 databases. Reports from reputable energy-related organisations and reliable journal sources were also utilized. In the present study, the microwave pyrolysis plant is assumed to have an annual processing capacity of 14,600 tonnes and an operation hour of 7300 h. The plant is located at Kulai, Johor, Malaysia, at a nearby distance from QL Figo (Johor) Sdn. Bhd. Raw WAS was obtained directly from the industry and contained 65 wt% of moisture after the dewatering process using an on-site filter press. This brings to view that 2.43 tonne of raw WAS is required to produce 1 tonne of WAS with 15% water content after drying. The heat required for drying and pyrolysis is supplied from the power grid in electrical form.

2.3.1. Goal and scope definition

This study focuses on the environmental impact of the microwave pyrolysis process of WAS from the food processing industry. Two different pyrolysis atmospheres are being investigated, namely CO_2 and N_2. The primary purpose is to analyse the effect of product yield under different atmospheres on the environmental footprint and energy balance. The LCA adopts the cradle-to-gate approach where the system boundaries consist of WAS transportation, pre-processing stage, microwave pyrolysis and end-product retrieval stage. The details inputs and outputs of the unit processes are displayed in Fig. 1. Energy inputs in the form of electricity are assumed to be sourced from a nearby power station known as the Sultan Iskandar Combined Cycle Power Plant located in Johor, Malaysia (269.6 MW-gas fired). The following assumptions are set:

1. Raw WAS from the wastewater treatment facility is ready to be transported on-site. This study does not consider the energy required for the formation and collection of raw WAS.
2. The carbon sequential potential and bioenergy content within the derived products are numbered up from the data obtained from the lab-scaled experimental study

The functional unit is defined at 1 tonne of dried WAS used for the microwave pyrolysis process. All data presented in this LCA, including

Table 1
Experimental data on Microwave Pyrolysis of WAS under CO_2 and N_2 atmosphere.

	CO_2		N_2	
	Yield (%)	Energy (MJ/kg)	Yield (%)	Energy (MJ/kg)
Biochar	18.73	22.26	19.00	19.64
Bio-oil	34.01	18.89	34.73	18.46
Gas	19.16	8.74	25.39	9.09
Water	19.83	–	13.46	–
Coke	8.27	–	7.42	–

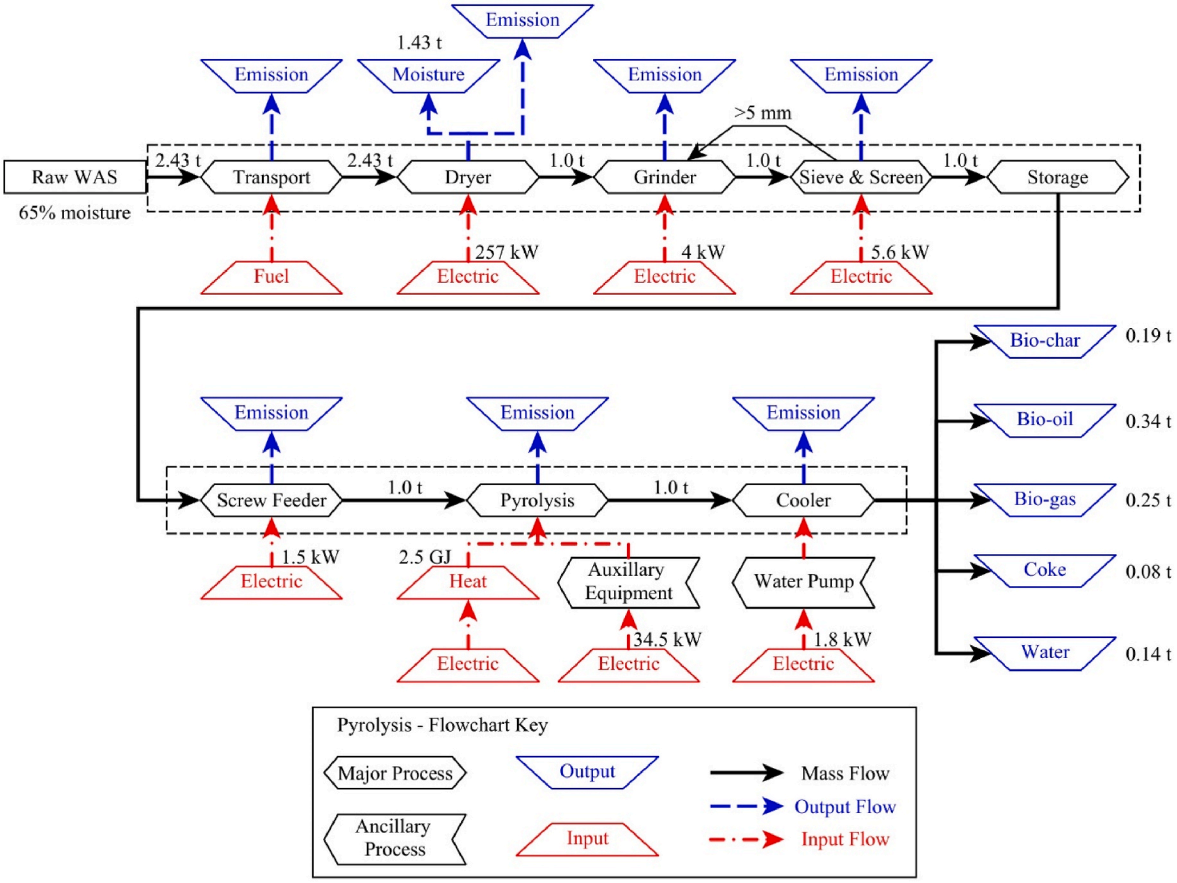

Fig. 1. System boundary for LCA of WAS pyrolysis and the associated inputs and outputs of the processes.

emission, energy consumption, and carbon footprint, are calculated based on the defined functional unit.

2.3.2. *Life cycle inventory (LCI)*

The most time-consuming stage is data collection, which is linked to the quality of the environmental analysis results (Arias et al., 2021). All unit processes involved in the cradle-to-gate analysis were obtained from reliable sources.

i. Transportation

The raw (wet) WAS are transported from QL Figo (Johor) Sdn. Bhd. and nearby food processing industries using a 3-tonne truck running on diesel fuel. The travelling distance for each truck is estimated to be 50 km. The inputs are raw WAS and diesel fuel, while the output is the transportation of WAS to the waste management facility. Emission for the usage of diesel fuel is displayed in Table 2. The environmental impact of transportation only considers the travelling distance between the industry and the pyrolysis facility.

ii.Drying

The WAS was dried in a continuous mode through a belt-type dryer of model SBDD48600SFL, a product by SHINCCI. The power consumption is 180 kWh to remove 1 tonne of water (SHINCCI, 2019). The raw WAS with 65 wt% of water content will be dried to 15 wt% before being transferred to the next process. The unit process operates from an electricity supply by the power grid that runs on natural gas as fuel. The emission from the power grid is recorded in Table 3.

iii.Grinding

The dried WAS undergo a grinding process to break up large chunk into smaller particles (30–140 mesh size) using a hammer mill (CUM-

Table 2
Emission of truck running on environmental class 2 diesel fuel with a maximum capacity of 14 tonnes (Stripple, 2001).

Emission	kg/km
CO	9.56×10^{-4}
HC	4.58×10^{-4}
NO_x	6.02×10^{-3}
Dust	1.01×10^{-4}
CO_2	9.43×10^{-1}
SO_2	4.53×10^{-4}
CH_4	5.98×10^{-7}
N_2O	1.91×10^{-5}

Table 3
Emission from power plant using natural gas as fuel (Spath and Mann, 2000).

Emission	g/kWh
CO	0.027
NMHCs	0.01
NO_x	0.095
Particulates	0.062
CO_2	371.247
SO_x	0.002
NH_3	0.021
CH_4	0.044
CH_2O	0.009

160F -Pin type P) manufactured by ALPA Powder Tech. The hammer mill consumes electricity from the power grid, operating at a maximum rotation speed of 3200 rpm, grinding disc of 630 mm radius, power consumption of 55 kW and a maximum capacity of 4 tonnes/h (ALPA, 2021).

iv. Sieving and Screening

The ground WAS will then be sent for screening using a Disc Screener (Machinex), operating on power consumption of 5 kW with a 90% efficiency (Adams et al., 2015). The maximum load is 5 tonnes/h and the ground WAS that did not pass the screener will be sent back for the grinding process. This procedure ensures the uniformity of feedstock and will not cause blockage in the following process. The screener utilizes electricity from the power grid.

v. Feeding

The operation runs on a continuous feed process where WAS is transferred into the pyrolysis reactor through a screw feeder (LS250) manufactured by Henan Green Eco-Equipment. The delivery rate is 0.33 m^3/h, a maximum load of 4 tonnes/h and requires 1.3 kWh of electricity from the grid.

vi. Microwave Pyrolysis

The microwave pyrolysis process converts WAS at a temperature of 600 °C in an N_2 or CO_2 atmospheric condition. Electricity, WAS and carrier gas are considered as inputs and the outputs are solid char, bio-oil, non-condensable gas and water and coke. The reactor is assumed to be in a continuous mode with a throughput of 2 tonnes/h. The energy required for pyrolysis, which is supplied from the power grid to emit microwave radiation, is 2.5 GJ/h (Rajabi Hamedani et al., 2019). Other ancillary process aiding in microwave pyrolysis consumes 34.48 kWh.

vii. Cooling

The carrier gas (N_2 or CO_2) will sweep the hot volatile and vapour released during microwave pyrolysis of WAS into a cooling system manufactured by Envitech. Coldwater at 9 °C is circulated within the system to capture all condensable vapours as bio-oil. The non-condensable vapour will be collected as a gaseous product. The cooling system is assumed to be capable of quenching heated volatile originates from the reactor at 600 °C to room temperature of 25 °C. The system's cooling load is supplied by electricity from the power grid. The estimated power consumption is 1.76 kW/h (Envitech Inc, 2020).

2.3.3. Life cycle impact assessment (LCIA)

The endpoint method is employed in this LCIA. It brings out a comprehensive environmental assessment with more data integrity, weighting, modelling, and value choices (Ding et al., 2021). A total of five environmental impacts are assessed in this study, namely global warming potential (GWP), photo-oxidant formation potential (POCP), acidification potential (AP), human toxicity potential (HTP) and eutrophication potential (EP). The carbon sequestration credits (CSC) for biochar were measured by Eq. (1)

$$CSC = Y_p * CC_P * R_{C/CO_2} * CS_P \tag{1}$$

where Y_p refers to the product yield; CC_P refers to the carbon content; R_{C/CO_2} refers to the carbon to CO_2 equivalent ratio (12 kg C – 44 kg CO_2); CS_P refers to the carbon stability and the subscript P refers to the product obtained from the pyrolysis process. The CS for biochar obtained from sludge pyrolysis conditions is 0.7 (Luo et al., 2021). All impacts are measured according to the FU of 1 tonne dried WAS.

2.3.4. Interpretation

The environmental impact of microwave pyrolysis of WAS obtained through LCA was compared with those from conventional management of WAS like incineration, landfilling and recent popular approaches like AD, as sourced from other works. The environmental impacts were generalised using a FU of 1 tonne of dried WAS to have a better comparison. The pros and cons of each methods as compared to the current approach will be discussed.

2.4. Sensitivity analysis

Sensitivity analysis in LCA is essential as it evaluates the sturdiness of results and their sensitivity towards changes and uncertainties. In this work, each unit process was analysed for data uncertainty and calculations were conducted by computing the parametric difference with one parameter constant. The transportation distance was varied by reducing and expanding the area coverage of WAS collection, considering the pyrolysis facility as the midpoint. The area was reduced to a 25 km radius for a lower-end case and expanded to a 100 km radius for a higher-end case. The feedstock moisture of WAS is a parameter that varies greatly depending on the type of wastewater content, flocculation method and water removal technique. The current filter press employed in QL Figo (Johor) Sdn Bhd can retrieve WAS with a water content of 65 wt%. The variation is adjusted at 40–80 wt% of water content as the lower end (40 wt%) can be achieved using a decanter. In contrast, WAS has been reported to have 80 wt% of water content (Cheng et al., 2020).

A variation of ±15% on electrical consumption has been assumed for the microwave pyrolysis process (Wang et al., 2015). The cooling system is responsible for heat removal. The incoming vapour with a higher temperature will require more cooling load, affecting the power requirement. The upper and lower threshold of the vapour temperature is assumed to be at 500 °C and 650 °C. The grinding, feeding and screening operation utilizes equipment manufactured by specific companies. The variation in power consumption for these processes (15%) is estimated by comparing equipment manufactured by different companies with similar functionality. A similar approach has been reported in other works (Mong et al., 2021a).

2.5. Carbon footprint and energy balance analysis

The GWP, which directly relates to carbon emission and energy usage, has been discovered as the main parameter affecting the sustainability and greenery of the microwave pyrolysis process proposed in this work. It is essential to evaluate the carbon footprint of the entire process (cradle-to-grave) to obtain a more thorough insight. In fact, most LCA on pyrolysis assess the use of end-products for carbon reduction and bioenergy recovery to trade-off the energy-intensive process. This section will explain the cradle-to-grave analysis of WAS microwave pyrolysis, where the carbon footprint of each product will be calculated. The difference in product yield and properties for CO_2 and N_2 pyrolysis atmospheres will be examined, as will the impact on the overall carbon footprint and energy balance. The carbon footprint can be calculated by summarizing the CO_2 emission (energy used) and CO_2-saved (carbon storage of product).

The carbon footprint of biochar and bio-oil was calculated using Eq. (1), where the carbon composition of the product obtained from characterization is used to calculate the $CO_{2\ eq}$ amount. The carbon footprint of gaseous product was calculated from the mass of respective gas fraction. For example, if the gaseous product contains 1 kg of CO and 1 kg of CH_4, then the estimated carbon footprint will be 1.57 kg CO_2 and 2.75 kg CO_2, respectively. The estimation is based on the oxidation ratio of gas. The same calculation applies for various other gas species. Gas like H_2 will be treated as zero-carbon emission. The biochar obtained will be assumed to have carbon storage potential and serve carbon sequestration purposes. According to the IBI (2018) biochar utilization in Malaysia is 28% for energy production and 72% for soil amendment;

therefore, the biochar derived in this work will follow the suggested use. Bio-oil derived from microwave pyrolysis can be utilized as liquid fuel or bio-chemical source, depending on its characteristics. The gaseous product derived contains syngas and hydrocarbon species. It is to note that when the products derived are used as bio-fuel, the carbon emission can be treated as biogenic.

The energy balance of the process will evaluate the energy content of each product. Only the products which have bioenergy potential (can be used as biofuel) will be considered. The energy balance is calculated by summarizing the energy used (from the operation) and energy produced (energy content of products). The bio-fuel products are assumed to be utilized in a gasifier/combustor for heat and power production with an efficiency of 85% (Marazza et al., 2019).

3. Results and discussion

3.1. Energy consumption

Pyrolysis experiment has always been viewed as an energy-intensive process where a massive amount of energy is required to valorize waste and biomass. The microwave pyrolysis of 1 tonne of dried WAS requires a total energy of 499.73 kWh and the proportion of energy usage is shown in Fig. 2. The microwave pyrolysis process consumed the highest energy, taking up about 73.01% of the entire process, primarily used as heat to degrade the WAS. This work further proves that energy balance is needed to justify the energy sustainability of the microwave pyrolysis process, which will be discussed in detail in the later section. Coming in second is the drying process which requires 25.73% of total energy. WAS contains water content that will increase the energy requirement of the pyrolysis process as this water needs to be minimized prior to pyrolysis (Ding et al., 2021). Others processes contribute less than 2% of the total energy usage.

3.2. Environmental impact analysis

The environmental impacts calculated for each process in the microwave pyrolysis of WAS are summarised in Fig. 3. The GWP is measured from CO_2, CO, CH_4, N_2O and NO_x emission, then multiplied using a standard value and presented as values in $CO_{2\ eq}$ (Steng). The total GWP is 203.81 kg $CO_{2\ eq}$ when 1 tonne of WAS has been successfully pyrolyzed. The greenhouse gases are mainly emitted from the pyrolysis process and the drying of WAS. The GWP of each process is correlated to the energy required, also reported by Cheng et al. (2020). The heat from the pyrolysis process contributes 63.69% of the total GWP, drying contributes 23.56%, whereas transportation contributes 8.26% from diesel consumption.

Acidification potential (AP) originates from the process that releases acidic products like SO_2, NO_x, NH_3 and unburned hydrocarbons directly into the environment. One major impact of AP is acid rain which can pollute soil and water sources. AP is measured in $SO_{2\ eq}$ value. From the microwave pyrolysis of WAS, a total of 101.2 g $SO_{2\ eq}$ is estimated to be released. Transportation is the most significant contributor to AP (64.55%) due to diesel-burning from truck use. The AP of pyrolysis (24.66%) and drying (9.12%) is lower, of which the energy is sourced from natural gas. The main reason is a higher SO_2 emission (0.453 g SO_2/km) from diesel-burning compared to the SO_2 emission (0.002g SO_2/kWh) from the power station. The AP of transportation can be reduced if all trucks used for transporting WAS were equipped with a catalytic converter in the exhaust system to capture harmful exhaust gases.

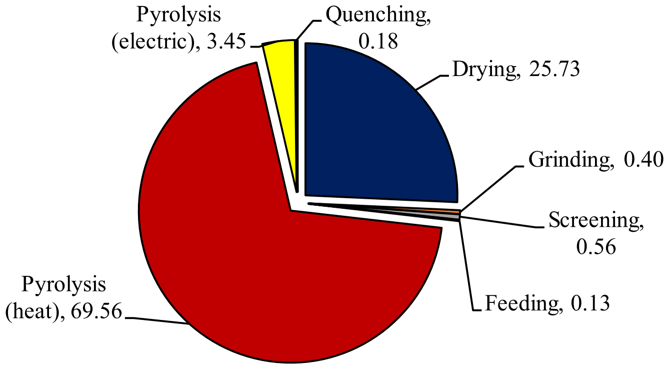

Fig. 2. Percentage of energy required for each unit process from the microwave pyrolysis of WAS (per tonne basis).

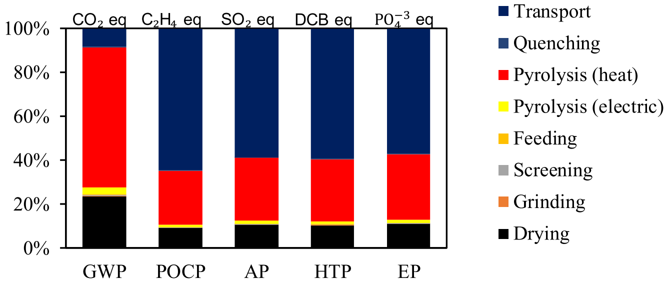

Fig. 3. The environmental effects of the various unit processes involved in the microwave pyrolysis of one tonne of dried WAS.

Eutrophication potential (EP) measures the increase in organic matter released into the environment, using $PO_4^{-3}{}_{eq}$ as a measuring unit. EP evaluates the amount of NH_3 and NO_x from the excessive level of macronutrients in the environment, which dissipates to land, water and air. In this study, a total of 22.9 g $PO_4^{-3}{}_{eq}$ is estimated to be released. Transportation (56.99%) is also the biggest contributor, followed by heat required during pyrolysis (29.92%) and drying (11.07%). Although truck use only emits NO_x (6.02 g NO_x/km) while the power grid emits both NO_x and NH_3 (0.09 g NO_x/kWh and 0.02 g NH_3/kWh), EP of transportation is still higher due to the magnitude of pollutants.

Another environmental impact that measured the impact on degrading human health from exposure to carcinogens and non-carcinogens is known as human toxicity potential (HTP). Dichlorobenzene equivalent (DCB $_{eq}$) is used as a measuring unit for HTP where pollutants like NO_x, SO_2, NH_3, dust and particulate matter with diameter <10 μm (PM10). A total of 205.1 g DCB $_{eq}$ is estimated to be released from the process. Transportation (59.27%) is the primary source of HTP, which is attributed to the dust and PM10 emissions during truck movement and NO_x and SO_2 emissions from diesel combustion.

Photo-oxidant formation potential (POCP) measures the chances of photo-oxidant formation from the volatile organic compounds (VOCs) emitted into the atmosphere (Li et al., 2015). POCP will impose the risk of smog formation that will degrade the human respiratory system. Ozone can also be form when VOCs react with NO_x in the presence of sunlight. The measuring unit for POCP is $C_2H_{6\ eq}$. Of all unit processes, transportation contributes the largest portion (58.67%), followed by pyrolysis (28.74%) and drying (10.63%). Petroleum diesel contains paraffins, cyclo-paraffins and some aromatics that release VOCs during combustion (Chin and Batterman, 2012).

3.3. Sensitivity analysis

Sensitivity analysis for this work is done on every unit process to evaluate the effect of the value's discrepancy on GWP. Fig. 4 displays the changes incur due to varying input parameters on each unit process. Overall, GWP varies from 169.81 kg $CO_{2\ eq}$ to 265.04 kg $CO_{2\ eq}$ for every tonne of WAS processed. Moisture or water content of WAS, one of the significant parameters during drying, imposes the most extensive GWP variation. Compared to the baseline scenario (water at 65 wt%), a reduction of 25% moisture in the raw WAS will reduce 16.68% of GWP, but an increase of 15% moisture will spike the GWP by 30%. This

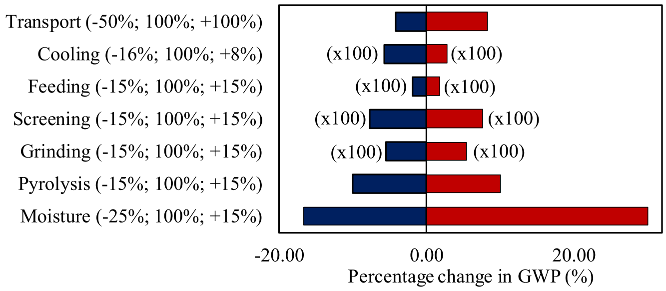

Fig. 4. Dependence of various unit processes on GWP per tonne of dried WAS. Changes in operating parameters as a percentage of the baseline (the unit for each process on the y-axis is determined by its operating variable). A unit process uses kWh, while feedstock moisture is measured in wt.%.

significant difference displays the benefits of receiving raw WAS with low water content from the wastewater industry on the overall environmental footprint of the process. The discovery is well aligned with the reports by Cheng et al. (2021), where GWP emission is closely linked with moisture content, heat and electricity usage. Since Malaysia receives a good amount of solar energy all year round (solar irradiance of 400–600 MJ/m^2) (Mekhilef et al., 2012), a possible scenario of sun-drying the raw WAS could be done. This will further reduce the dependency of GWP on the drying operation. Nonetheless, consideration needs to be included regarding the on-site area, the potential of natural decomposition during sun-dry and the possibility of organic leaching on the soil.

The microwave pyrolysis process, which is the primary process, will induce a GWP difference of ±10.03% on the entire operation, when the electrical consumption is altered by ±15%. Transportation comes in third place where the distance for WAS transfer is considered. For the best-case scenario of only sourcing WAS from QL Figo (Johor) Sdn Bhd to the processing plant, trucks are only required to travel a short distance (~25 km) as the plant is located near the food processing industry. The GWP of this scenario can be reduced by 4.13%. However, the current wastewater facility of QL Figo (Johor) Sdn Bhd only generates 1 tonne of sludge daily, which means that additional WAS needs to be sourced from other wastewater plants. For the worst-case scenario, assuming that sufficient WAS can be collected from industries located within a 100 km radius, an additional 8.24% of GWP will be incurred.

It is interesting to observe that although the core process of the plant is microwave pyrolysis, its effect on GWP is lower when compared with the drying process. A conclusion can be drawn that the GWP of the facility is feedstock-dependent rather than process-dependent. Feedstock with higher water content will impose a larger GWP, directly reducing the environmental benefits of the process. Other auxiliary processes like grinding, screening, feeding and cooling have a much lower effect on GWP. If the plant is able to obtain highly efficient equipment for the ancillary process, a total of 2.06% of GWP can be further reduced.

3.4. *Carbon footprint and energy balance*

From the characteristics of the product obtained, it is proposed that the biochar will be used as solid fuel (28%) and soil amendment (72%). The portion of biochar used for soil amendment will be assumed to have carbon storage potential. Due to the good heating value, the bio-oil and gas products are treated as fuel sources for heat and power generation.

Table 4 shows the potential of sequestrating maximum CO_2 and producing maximum bioenergy yield from the end-products derived. Microwave pyrolysis under N_2 atmosphere has a higher CO_2 sequential potential as compared to CO_2 atmosphere. From Table 1, although the bio-oil has the highest yield (34%) as compared to biochar and gas, the CO_2 sequential potential is low. This is due to the carbon content of the products where bio-oil derived from CO_2 and N_2 atmosphere has 24.85% and 21.71% of carbon, respectively. Unlike the biochar yield, even at low yield (19%), it has greater CO_2 sequential potential due to denser carbon composition (57.4%-CO_2 & 58.3%-N_2). For the gas product, N_2 atmosphere (25.39%) has a higher yield than CO_2 (19.16%), but the higher CO proportion (52 vol%) for gas derived from CO_2 atmosphere gives a higher CO_2 sequential potential. The higher CO proportion is due to the reaction between CO_2 and the volatiles evolved, which lowers tar formation (Mong et al., 2022). The reactive carrier gas – CO_2 also functions as both oxygen donor and expediting agent for random bond scission to generate CO during pyrolysis (Choi et al., 2018). The effect of Boudouard reaction ($C + CO_2 \rightarrow 2CO$) (Song et al., 2020) might be present within an energy-intensive microwave reactor in the formation of CO. Nonetheless, the intensity of the Boudouard reaction may not be high as the typical reaction temperature is at 700 °C. In contrast, the current operating temperature is at 600 °C. This scenario is also evident from the experimental report by Jung et al. (2020), where CO formation increases substantially at >600 °C for CO_2 atmosphere when compared with N_2.

Table 4
The potential CO_2 sequestration potential and bioenergy yield from the microwave pyrolysis of WAS under CO_2 and N_2 atmosphere.

Pyrolysis Atmosphere	CO_2		N_2	
	CO_2 sequential (kg CO_2/tonne)	Energy (kWh/tonne)	CO_2 sequential (kg CO_2/tonne)	Energy (kWh/tonne)
Biochar (Fuel)	77.35	274.97	113.83	259.20
Biochar (C-store)	198.91	831.87	204.90	784.14
Bio-oil (Fuel)	80.301	391.59	92.41	544.47
Gas (Fuel)	244.63	394.38	226.17	529.87
SUM	601.19	1892.83	637.33	2117.69

The ideal energy derived from the bio-products obtained is 1892.83 kWh/tonne and 2117.69 kWh/tonne for CO_2 and N_2 scenarios. The actual value will be lower as not all products will be used as fuel sources and there will be inefficiency during the product-to-energy conversion process. Generally, biochar and bio-oil contain good energy density characteristics (>18 MJ/kg). The biochar has an HHV of 22.26 MJ/kg and 19.64 MJ/kg for CO_2 and N_2 scenarios, respectively. Although the HHV is much lower as compared to coal (>40 MJ/kg), the dried, carbon-dense biochar is still a valuable solid fuel, having higher HHV than those of sludge-derived biochar (10 MJ/kg) (Ghodke et al., 2021). The HHV of bio-oil from WAS (18.89 MJ/kg-CO_2 and 18.46 MJ/kg-N_2) is not as high as common fossil-derived oil due to high oxygen composition (45–50%). Conventional fuel like diesel has a heating value of 42 MJ/kg, while sludge-derived liquid fuel has a heating value of 16–27 MJ/kg (Ghodke et al., 2021).

Fig. 5 display the energy balance for the microwave pyrolysis of WAS under CO_2 and N_2 atmosphere. Bioenergy can be derived from the 28% of biochar with a heating value of 22.26 MJ/kg (CO_2) and 19.64 MJ/kg (N_2), bio-oil with a heating value of 18.89 MJ/kg (CO_2) and 18.46 MJ/kg (N_2) and gaseous product with a heating value of 8.74 MJ/kg (CO_2) and 9.09 MJ/kg (N_2). The biochar obtained in CO_2 atmosphere has a higher energy content. CO_2 causes carbonization of C, which lowers the C proportion in carboxylate species and increases the aromatic C portion within the biochar, giving it greater thermal stability (Wang et al., 2022). Similar findings on retrieving biochar with a higher energy value in CO_2 pyrolysis than N_2 have been reported elsewhere (Lee et al., 2021). The net positive energy output of 561 kW (CO_2) and 833 kW (N_2) can be achieved when bioenergy is harvested from microwave pyrolysis. The lower energy derived from CO_2 pyrolysis is also attributed to the properties of bio-oil and gas products. Although CO_2 can produce biochar with better quality (higher energy value), the N_2 atmosphere can yield a higher energy profit. The discovery is due to the reactivity of carrier gas used, where CO_2 will react with volatiles evolved during pyrolysis, further catalysing the breakdown of major compounds into

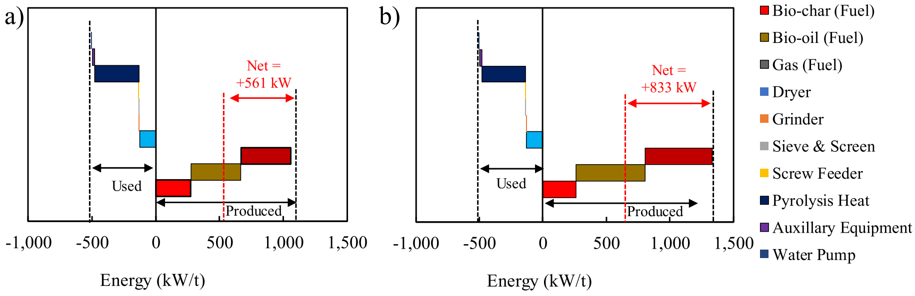

Fig. 5. Energy balance for the microwave pyrolysis of WAS for a) CO_2 and b) N_2 atmosphere.

smaller molecules. Gaseous product from the N_2 atmosphere attains a higher energy value as larger hydrocarbon molecules are present. Similar findings are reported elsewhere (Jung et al., 2020). The bio-oil from CO_2 pyrolysis has a lower heating value due to the presence of water within the liquid yield, which is formed from the water-gas shift reaction ($CO_2+H_2 \rightarrow CO + H_2O$). The pyrolysis atmosphere with a high CO_2 concentration may react with the hydrogen molecules forming CO and water (Wang et al., 2018).

The carbon footprint analysis for the microwave pyrolysis of WAS is shown in Fig. 6. The only product with carbon sequestration potential is the derived biochar, while other products such as bio-oil and gas are considered not to possess carbon sequestration potential. This is due to the proposed application of such products as biofuel sources, which will be combusted for heat and power generation. The CO_2 generated from this process is treated as biogenic. Biochar attained a dense carbon structure from the decomposition process that releases moisture, volatile and organic compounds. After pyrolysis, the leftover solid has a stable carbon structure that does not decompose easily under normal atmospheric conditions, serving as a good carbon storage product. Fig. 6(a) shows that microwave pyrolysis under CO_2 conditions will yield a net positive carbon footprint after considering the carbon sequestration of biochar. On the other hand, N_2 demonstrates a greener carbon footprint with a net emission of -1.09 kg CO_2. A net negative value indicates that the microwave pyrolysis process is considered a carbon-negative technology if the derived biochar is utilized for carbon storage purposes. It is worthwhile to note that the analysis portrayed in this study did not consider the anthropogenic CO_2 saving originates from the CO_2 used as carrier gas. If this were to be included, the carbon footprint of CO_2 condition would be lower and possibly achieve a net negative carbon emission. From another perspective, the avoided fossil fuel impact of using bio-products for heat and power generation is also not considered in this calculation. Many studies calculated the avoided fossil fuel impact to show the 'superiority' of particular green technology. However, it is not portrayed in this work to emphasize the 'real' impact of each unit process.

3.5. Comparison with other WAS management methods

The environmental impacts of WAS microwave pyrolysis are compared with other sludge management methods like landfilling, anaerobic digestion, incineration and different pyrolysis approach. The difference in environmental impact is tabulated in Table 5. Compared with conventional methods like landfilling, pyrolysis is definitely a greener approach. Landfilling 1 tonne of WAS will cause a GWP of more than 17 times (Usapein and Chavalparit, 2015) compared to the microwave pyrolysis method in this work. The AP and EP of landfilling are also alarming due to the landfill gases and toxic leachate released directly into the environment. Implementing WAS as fertilizers and soil amendments has a lower GWP as the process requires less energy input. Most GWP originates from the natural decomposition of WAS, releasing a handful of greenhouse gases. Utilizing WAS as fertilizers have a higher EP when compared with landfilling (Usapein and Chavalparit, 2015). One main reason is that landfills are usually isolated from fertile and agricultural land; hence, pollution can be confined to a particular region. However, using WAS as fertilizer signifies exposure to agricultural land and freshwater sources, increasing the chances of nutrients and toxic compounds entering these sources.

Incineration, another conventional method in WAS management, presents itself as a very energy-intensive process. When used as a substitute for fossil fuel in energy production, WAS records a favourable GWP of -2951 kg $CO_{2\ eq}$ because CO_2 emitted from waste incineration is biogenic (Usapein and Chavalparit, 2015). However, the AP of 180 kg $SO_{2\ eq}$ due to NO_x and SO_2 emission when the ash produced is landfilled impose greater environmental damage when compared with the current study of 0.1012 kg $SO_{2\ eq}$. In a separate study, sewage sludge with 95% water content was dried and incinerated in a cement kiln for heat and power production and consumed a very high amount of energy (about 500 times higher than the current study) (Abuşoğlu et al., 2017). However, a negative scoring for GWP is reported, which is attributed to the avoided fossil fuel used for power generation, resulting in lesser greenhouse gas emissions. Anaerobic digestion has been widely employed in wastewater treatment plants for WAS treatment to produce biogas for heat and power generation. However, the production of secondary sludge still requires post-treatment. An LCA study of AD on WAS compared the post-treatment of secondary sludge through composting and incineration. Overall, AD emits lower GWP as compared to the current study of microwave pyrolysis, but the post-treatment technology imposed higher AP, EP and HTP (Arias et al., 2021). The production of

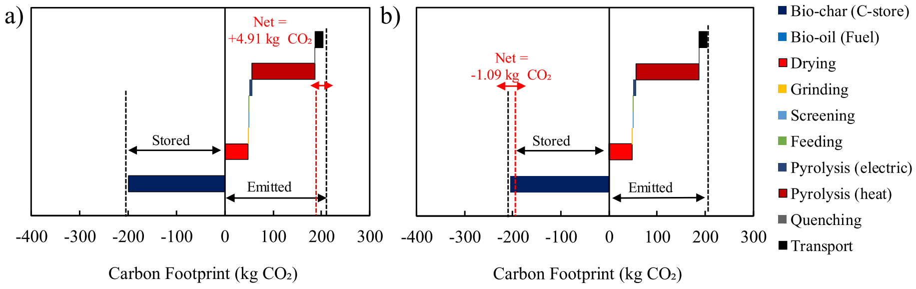

Fig. 6. Carbon footprint analysis for each unit process involved and carbon storage potential of the derived product for a) CO_2 and b) N_2 atmosphere.

Table 5
Comparison of different processing methods for WAS (reference unit, 1 tonne).

	Energy Consumption (kWh)	GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4^3 eq)	HTP (DCB eq)	POCP (C_2H_4 eq)	Reference
Microwave pyrolysis of WAS	499.7339	203.8149	0.101182	0.022888	0.20506	0.006991	This work
Sewage Sludge Incineration (95%-water content)	249,631.1	–	–	–	–	–	Abuşoğlu et al. (2017)
Landfill	–	3552	148	9.6	–	–	Usapein & Chavalparit (2015)
Conventional fuel substitute in cement kiln		−2951	180	0.2			Usapein & Chavalparit (2015)
Fertilizer	–	197	2.91	12.2	–	–	Usapein & Chavalparit (2015)
Pyrolysis (70%-water content)	–	1147	–	–	–	–	Luo et al. (2021)
Anaerobic digestion and composting	−78.67	40.82	0.48	25.77	115.62	–	Arias et al. (2021)
Anaerobic digestion and incineration	329.05	160.5	0.77	0.2	4.17	–	Arias et al. (2021)

secondary sludge cause AD to have a higher toxicity level than pyrolysis.

An LCA pyrolysis study done on municipal sludge in China presents a wide range of GWP (674.6 to −32.5 kg CO_2 $_{eq}$) depending on the sludge's moisture content. The findings support the results obtained in this work, showcasing the feasibility of achieving a negative carbon footprint from pyrolysis of WAS. Nonetheless, the GWP reported in this study is much lower than the work of (Luo et al., 2021), which would probably be attributed to microwave heating technology. In short, pyrolysis presents itself as a 'greener' technology with a lower environmental impact than other currently used approaches. Despite the energy-intensive process, the bioenergy generation potential of pyrolysis can break even or achieve a positive energy generation. Moreover, the bioproducts derived can replace fossil fuels and be used for carbon sequestration purposes, further reducing the carbon footprint of the process.

3.6. Limitations of the study and future work

The microwave pyrolysis plant analysed in this study utilizes data from equipment manufacturers, databases and scaled-up from laboratory retrieved values. Therefore, an actual microwave pyrolysis facility requires a certain margin of error when using the data presented in this work. In addition, the current study analyses a specific feedstock – WAS from the food processing industry and limited the usage of data on WAS from different sources. Further study should be conducted by employing WAS from various wastewater sources to evaluate the sensitivity of this model to changes. It is also encouraging to integrate other sustainability assessment tools to assess the exergy, economics and emergy for a more thorough evaluation of the sustainability of such technology.

Microwave pyrolysis is still being developed to penetrate the industrial scale setup. The current drawback would be upscaling the microwave reactor to be capable of:

1. Effectively transferring and processing the feedstock (batch or continuous feed)
2. Direct microwaves radiation generated from magnetron onto the feedstock while preventing microwave leakage
3. Ensure robustness of setup to be totally sealed (inert environment and no volatile leakage)

The main advantage of microwave heating is that heating feedstock from the inside out (volumetric heating) will prevent uneven heating allowing for lesser pre-treatment on the feedstock. Besides, water or moisture within the feedstock will not affect the pyrolysis process as microwave radiation will be able to dry the feedstock rapidly due to the microwave absorbability index (dielectric constant) of water molecules.

4. Conclusion

The study presents an LCA on microwave pyrolysis of WAS under CO_2 and N_2 atmospheres, where its environmental impact, energy balance and carbon footprint are analysed. Drying is the most prominent process affecting the overall GWP, demonstrating the importance of having an effective mechanism for water removal. An increase of 15% moisture content of the raw WAS will contribute to an overall increase in 30% of GWP. Transportation contributes to the entire process's toxicity level as diesel fuel releases SO_2, NO_x, hydrocarbon, dust, and PM10 during combustion. A catalytic converter is vital to mitigate this risk. The end-products formed under CO_2 and N_2 conditions vary and induce changes in microwave pyrolysis's energy sustainability and carbon emission. N_2 atmosphere yields a higher energy profit (+833 kW) and a negative carbon footprint (−1.09 kg CO_2 $_{eq}$) signifies microwave pyrolysis's feasibility. Despite the finding that the CO_2 atmosphere can only achieve a positive carbon footprint (4.91 kg CO_2 $_{eq}$), the utilization of CO_2 within the process enables the utilization of excess CO_2, paving the way toward a carbon-negative process. In short, microwave pyrolysis has been demonstrated as a feasible, green and energy sustainable pathway for WAS valorization, producing biochar, bio-oil and gas with bioenergy content. Future work can be done to analyse the exergy, economics and emergy of the process or even utilize different feedstock to test the sensitivity of the current model.

Credit author statement

Guo Ren Mong: Writing – original draft preparation, Data curation, Funding acquisition. Chin Seng Liew: Conceptualization. William Woei Fong Chong: Writing, Editing. Siti Aminah Mohd Nor: Conceptualization, Resources. Jo-Han Ng: Methodology, Formal analysis. Rubia Idris: Validation, Review & Editing, Meng Choung Chiong: Review & Editing. Jun Wei Lim: Conceptualization. Zainul Akmar Zakaria: Review & Editing. Kok Sin Woon: Methodology, Formal analysis.

Declaration of competing interest

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

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