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Pyrolysis of lignocellulosic, algal, plastic, and other biomass wastes for biofuel production and circular bioeconomy: A review of thermogravimetric analysis (TGA) approach

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ABSTRACT

Fossil fuels are currently the most significant energy sources. They are expected to become less available and more expensive, leading to a great demand for energy conservation and alternative energy sources. As a sustainable and renewable energy source, Biomass has piqued interest in generating bioenergy and biofuels over recent years. The thermal conversion of biomass through pyrolysis is an easy, useful, and low-cost process that can be applied to a wide variety of feedstocks. Pyrolysis characteristics of different feedstock samples can be analyzed and examined through thermogravimetric analysis (TGA). TGA has been an essential tool and widely used to investigate the thermal characteristics of a substance under heating environments, such as thermodegradation dynamics and kinetics. Studying the potential of waste biomass for generating sustainable bioenergy carves a pathway into a circular bioeconomy regime, and can help tackle our heavy reliance on nonrenewable energy sources. This study aims to give a deep insight into the wide use of TGA in aiding in the research and development of pyrolysis of different waste biomass sources. The thermal characteristics portrayed by different biomass wastes through TGA are discussed. The effects of significant pyrolysis operating parameters are also illustrated. A more comprehensive understanding of evolved products during the pyrolysis stage can be gained by combining TGA with other analytical methods. The pros and cons of using TGA are also outlined. Overall, an in-depth literature review helps identify current trends and technological improvements (i.e., integrating artificial intelligence) of TGA use with pyrolysis.

Credit author statement

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Nomenclature	
<i>Abbreviations</i>	
AI	Artificial intelligence
ANN	Artificial neural network
CPI	Comprehensive pyrolysis index
DL	Deep learning
DTG	Differential thermogravimetric
EGA	Evolved gas analysis
FTIR	Fourier-transform infrared spectroscopy
GA	Genetic algorithm
GC	Gas chromatography
HDPE	High-density polyethylene
IR	Infrared
LDPE	Low-density polyethylene
ML	Machine learning
MS	Mass spectrometry
MSE	Mean square error
MSW	Municipal solid waste
MWSD	Mixed wood sawdust
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PSW	Plastics solid waste
PVC	Polyvinyl chloride
RBF	Radial basis function
RDF	Refuse derived fuel
SDG	Sustainable Development Goals
TG	Thermogravimetric
TGA	Thermogravimetric analysis
WF-PVC	Wood flour polyvinyl chloride
WHR	Water hyacinth
WHSL	Water hyacinth stems and leaves
WoS	Web of Science
wt%	Weight loss percentage
PSO	Particle swarm optimization
Var	iables
A	Pre-exponential factor
B_i	Pyrolysis burnout index
$(\frac{dw}{dt})_{max}$	Maximum pyrolysis rate(%/min)
$(\frac{dw}{dt})_{mean}$	Average pyrolysis rate(%/min)
E_a	Activation energy
M_f	Weight loss
R_p	Maximum decomposition rate
R_y	Average decomposition rate
S	Pyrolysis characteristic index
$\Delta t_{\frac{1}{2}}$	Minimum time zone of the first half of the DTG for a particular stage/half-peak width range time
t_i	Initial devolatilization time
t_f	Burnout time
t_p	Minimum time of largest peak/DTG maximum peak time
$\Delta T_{\frac{1}{2}}$	Peak width temperature range
T_f	Burnout temperature
T_i	Initial devolatilization temperature
T_p	Pyrolysis-peak temperature/ignition temperature/DTG maximum peak temperature
P	Pyrolysis characteristic peak index
P_i	Pyrolysis index

Investigation, Writing - review & editing.

1. Introduction

Currently, the world's energy supply is primarily derived from fossil fuels, namely, oil, coal, and natural gas. On the other hand, worldwide energy demand continues to grow due to the rapid increase in the global population and as people strive for better living standards [1]. Heavy reliance on fossil fuels has led to devastating phenomena, especially climate change [2,3] and its grave impacts on public health [4]. Hence, efforts are being placed to increase energy efficiency and explore alternative energy sources. Developing and integrating renewable energies can help the world meet several goals established by the United Nations' Sustainable Development Goals (SDGs) in 2015 [5]. The 7th goal aims to provide access to affordable, reliable, sustainable, and modern energy for all; the 12th goal seeks to ensure sustainable consumption and production of resources; the 13th goal urges us to take action to combat climate change and its impacts. Using biomass, plastic, and municipal solid waste (MSW), belonging to the carbon-neutral fuels, can help realize these goals.

Biomass, such as wood, charcoal, and agricultural residues used in homes for cooking and heating purposes since ancient times and, most recently, to generate biofuels and electricity [6]. Biomass solids such as wood pellets, chips, or processed biochar [7] can be processed from biomass and burnt to produce energy. Liquid products such as bio-oils [8,9] (e.g., biodiesel) can be processed to be used as a replacement for conventional crude oil products. Biogas production [10–12], i.e., methane or syngas, can also be attained from biomass sources. These products can all be used to produce energy while achieving low carbon emissions for combustion. Biofuels can be characterized based on the types of biomasses utilized: first-, second-, third-, and fourth-generation biofuels [13,14]. First-generation biofuels are produced from edible

resources, such as sugars, starch, or vegetable oils; however, the main downside of first-generation biofuels is endangering food security. These shortcomings gave rise to second-generation biofuels, mainly from non-food crops such as lignocellulosic biomass and residues [15]. Third-generation biofuels are obtained from microorganisms such as microalgal and microbial biomass [12,16]. Lastly, fourth-generation biofuels involve genetically modified (GM) micro/organisms to enhance biofuel production [17].

Studying the potential of biomass wastes for generating sustainable bioenergy carves a pathway into a circular bioeconomy regime and can help tackle our heavy reliance on nonrenewable energy sources. The traditional linear economy model revolves around a disposal system, where products are not recycled at the end of their 'useable' life cycle. A circular bioeconomy, on the other hand, aims to achieve industrial symbiosis through the reuse of wastes or by-products from an industrial system [18,19]. Using waste products, which would have traditionally been disposed of in landfills, to generate biofuels for commercial and industrial use extends the materials' life cycle. This would provide a sustainable approach by minimizing waste and reducing environmental pollution [20].

Various biomass conversion technologies have also been developed through different thermochemical pathways to produce biofuels (Fig. 1) [21]. For instance, synthesis gas or syngas is produced through biomass gasification [22]. Biomass pyrolysis mainly produces three products: biochar, bio-oil, and synthesis gas (syngas) [23,24]. Pyrolysis is more flexible for producing biofuels than other processes such as gasification, combustion, and liquefaction [25]. Pyrolysis is an easy, functional, and low-cost process that can be applied to a wide variety of feedstocks. Pyrolysis is divided into slow, fast, and flash pyrolysis, which can also be triggered by microwave-assisted heating. This offers a wide variety of control depending on the feedstock utilized and desired preferred product. Pyrolysis also offers advantages of storing, transportation, and

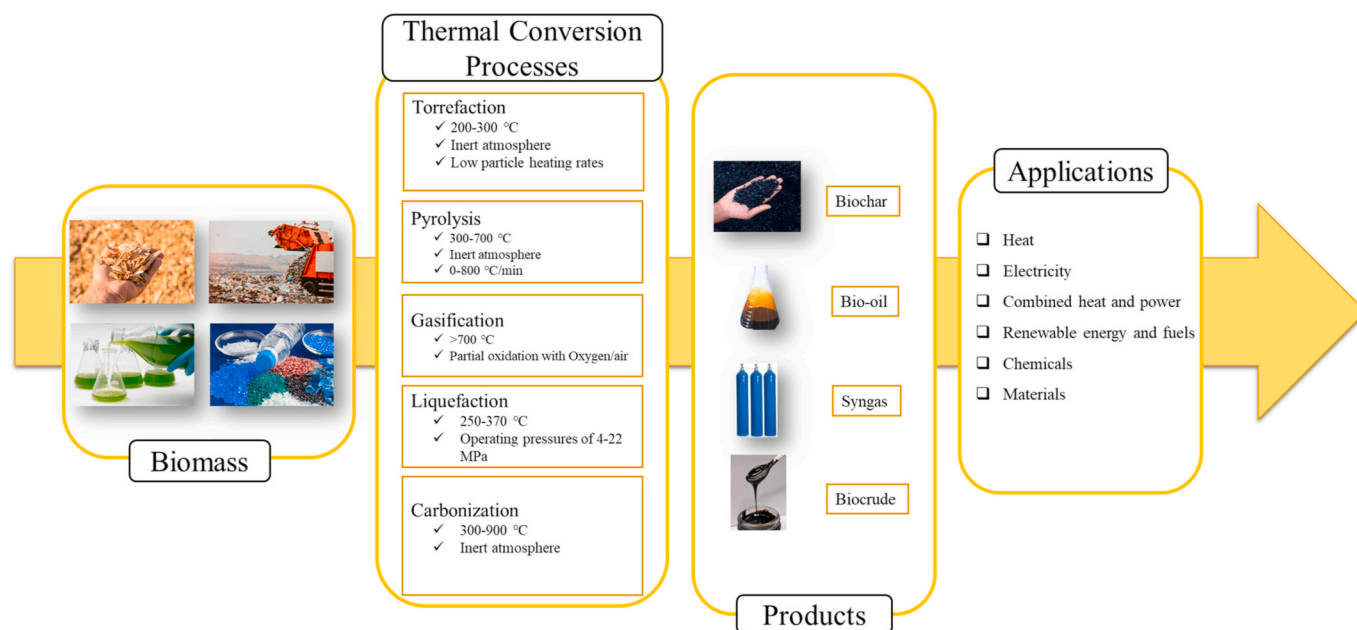


Fig. 1. Biomass waste thermochemical upgrading pathways.

pyrolyzed products can be widely used in combustion technologies, turbines, boilers, combustion engines, etc. [26].

Therefore, obtaining comprehensive knowledge on how to make the pyrolysis process of different feedstocks more efficient is very important [27]. The pyrolysis characteristics of different feedstocks can be observed, analyzed, and examined through thermogravimetric analysis (TGA) [28]. TGA has been an essential tool widely used to investigate the thermal characteristics of a substance under heating environments to figure out thermodegradation, dynamics, and even kinetics [29]. The TG analysis results are the most valuable content obtained as many studies have widely applied TGA as an analytical tool to investigate various materials. However, based on the authors' knowledge and a comprehensive literature survey, no study has focused on discussing the pyrolysis process through a TGA approach alone. Furthermore, no review paper thus far has condensed and discussed the trends and characteristics of using only TGA to study the pyrolysis process of several bioenergy

feedstocks from the recently published literature.

For this reason, this study aims to provide a deep insight into the wide use of TGA in aiding in the research and development of the pyrolysis process from different biomass, plastic, and municipal solid waste. Pyrolysis decomposition characteristics of different types of wastes through TGA are discussed. Integrating the use of TGA with other techniques such as mass spectrometry (MS) [30] and Fourier-transform infrared spectroscopy (FTIR) [30] makes it an even more valuable and powerful tool for studying decomposition characteristics of pyrolyzed samples. These integrations are also discussed. Furthermore, the challenges encountered and the perspectives of TGA for biomass pyrolysis are presented and discussed.

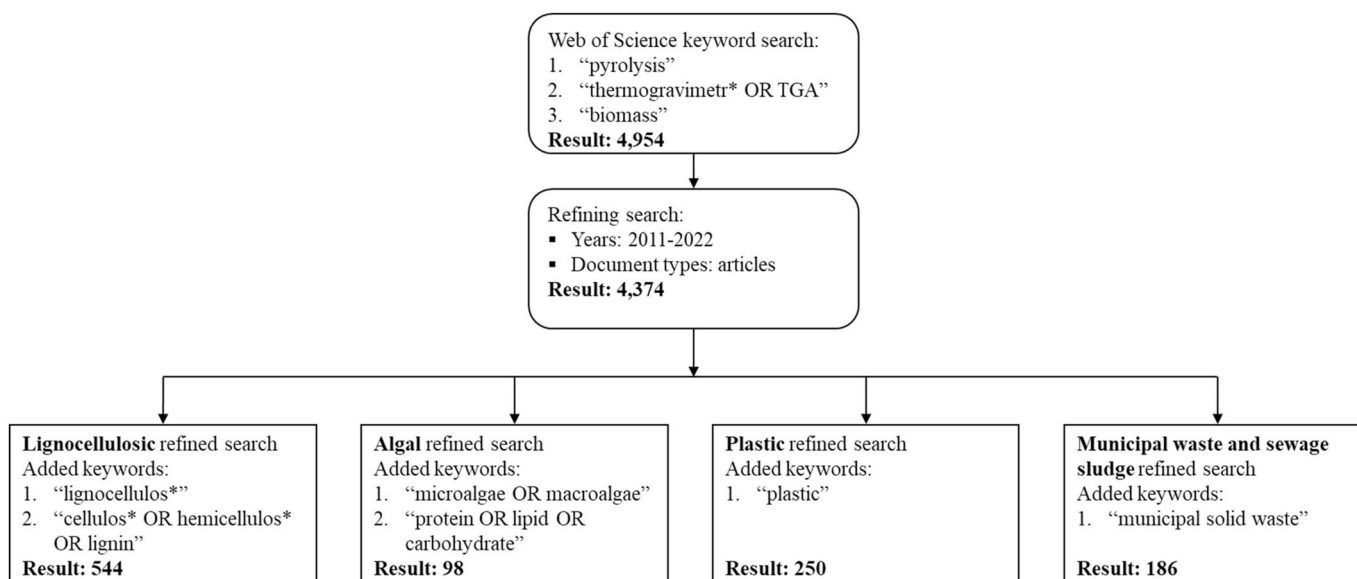


Fig. 2. Schematic of keyword search and refinement on Web of Science.

2. Statistical overview of employing TGA for pyrolytic conversion of biomass to biofuels

An analysis was conducted using the Web of Science (WoS) database using the keywords with appropriate syntax (search operator) to conduct a deeper search: “thermogravimetr* OR TGA”, “pyrolysis”, and “biomass” (Fig. 2). The search from 2011 to 2022 resulted in 4374 published documents, indicating the extensive use of TGA over the last decade, 129 articles in 2011 vs. 581 papers in 2021. The keyword co-occurrence of the 4138 documents was also generated using VOSviewer (Fig. 3), revealing four major clusters: thermal processes, activation energy and kinetic modeling, biomass products, and feedstock properties and characterization.

3. Fundamentals of pyrolysis and TGA

3.1. Principles of pyrolysis

Pyrolysis involves the thermal degradation of various biomass (either a solid or liquid) in the absence of oxygen, producing bio-oil, biochar, and gases as fuels in a sustainable and green manner. This process is usually carried out under elevated temperatures ranging from 400 to 600 °C [31]. An inert atmosphere, mainly nitrogen or argon, is utilized. Pyrolysis is divided into three elementary modes: conventional pyrolysis (also known as slow pyrolysis), fast pyrolysis, and flash pyrolysis. Slow pyrolysis is mainly performed in fixed bed reactors, whereas fast and flash pyrolysis routes are carried out in fluidized bed reactors, vacuum reactors, or transported beds [32]. Each pyrolysis mode is defined by its operating parameters: the heating rate, temperature, residence time, and particle size, depending on the chosen parameters. This will determine the type of product obtained at the end of the pyrolysis process. Fig. 4 outlines the operational parameters

necessary for achieving each pyrolysis mode. A slow heating process over a long period results in a higher biochar yield and moderate amounts of tar byproducts. A higher heating process with a shorter time gives rise to a high liquid yield [33]. Slow pyrolysis is widely used for producing biochar under low temperatures and slow heating rates. Fast pyrolysis is used to obtain higher liquid fuel (bio-oil) yields, with lower amounts of biochar and gaseous products under rapid heating at high temperatures. In contrast, flash pyrolysis uses higher heating rates and temperatures, posing high bio-oil yield [33,34].

According to the literature, the decomposition of lignocellulosic material occurs over different temperatures. On average, hemicelluloses are from 190 to 350 °C, and cellulose is from 240 to 400 °C. Lignin decomposes over a more comprehensive temperature range than hemicelluloses and cellulose [35]. Non-lignocellulosic biomasses have a different chemical composition compared to lignocellulosic biomass. For example, algal biomass mainly constitutes proteins, lipids, and carbohydrates [36]. This composition difference is translated into different thermal decomposition profiles for algal biomass. The TGA reported by Andrade and Batista [37] suggested that most moisture would be removed between 100 and 200 °C. Lipids begin to break down at temperatures above 190 °C, whereas proteins and carbohydrates degrade between 200 and 350 °C. Chen and Chu [38] also studied the thermodegradation of carbohydrates, proteins, and lipids in microalgae using TGA. It was found that carbohydrates, proteins, and lipids thermally degrade at 164–467 °C, 209–309 °C, and 200–635 °C, respectively.

3.2. Principle of TGA

TGA is a thermal analysis technique in which the mass of a substance is observed as a function of temperature or time as the sample is subjected to controlled temperature and atmospheric environments [39].

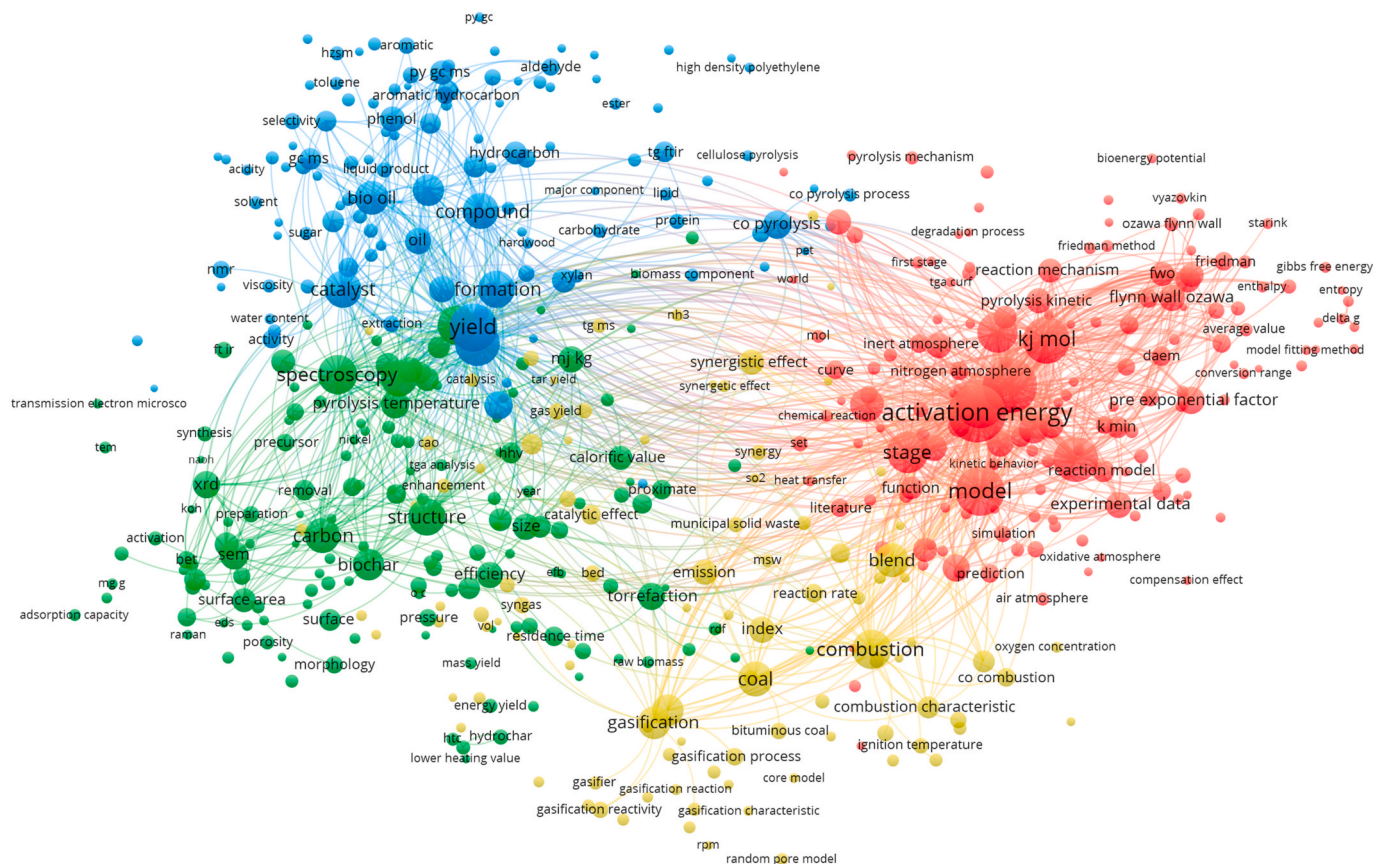


Fig. 3. VOSviewer network visualization of terms associated with pyrolysis, TGA, and biomass waste.

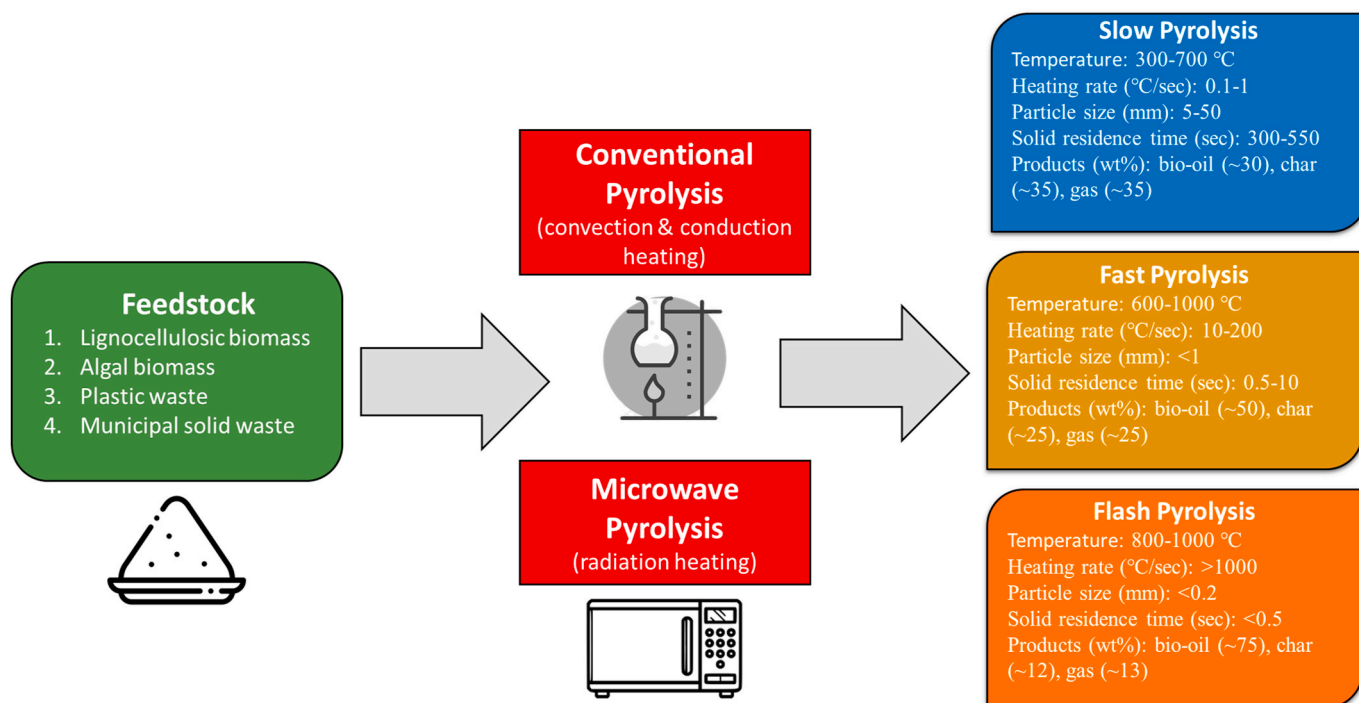


Fig. 4. Schematic of the different pyrolysis modes and their respective product yield [25,170,171].

Experimentation is conducted inside a thermogravimetric (TG) analyzer, where the sample is placed on a precision balance inside a furnace. The furnace is responsible for heating and cooling the sample during experimentation. The heating of the sample can either be in isothermal or non-isothermal conditions. A purge gas (or carrier gas), which may either be inert or reactive, flows over the sample to control the environment. In conventional TGA experiments, inert gases are widely used due to the pyrolysis nature (thermal treatment in the absence of oxygen). The literature review does not highlight any influence caused by the type of inert gas used. The most widely used inert gas

is nitrogen, but argon and helium may also be used. During experimentation, the sample mass change to temperature is observed.

Fig. 5 depicts the general components of a TG analyzer setup. The analyzer is usually connected to a computer to record results. The results obtained are generally in the form of TG curves. Examples of TGA curves are also in Fig. 5. These curves show the sample's weight loss percentage (wt%) against increasing temperature (T). As the temperature increases, the weight decreases due to mass loss, resulting from the thermal degradation of the sample. As presented, most of the decomposition occurs at lower temperatures.

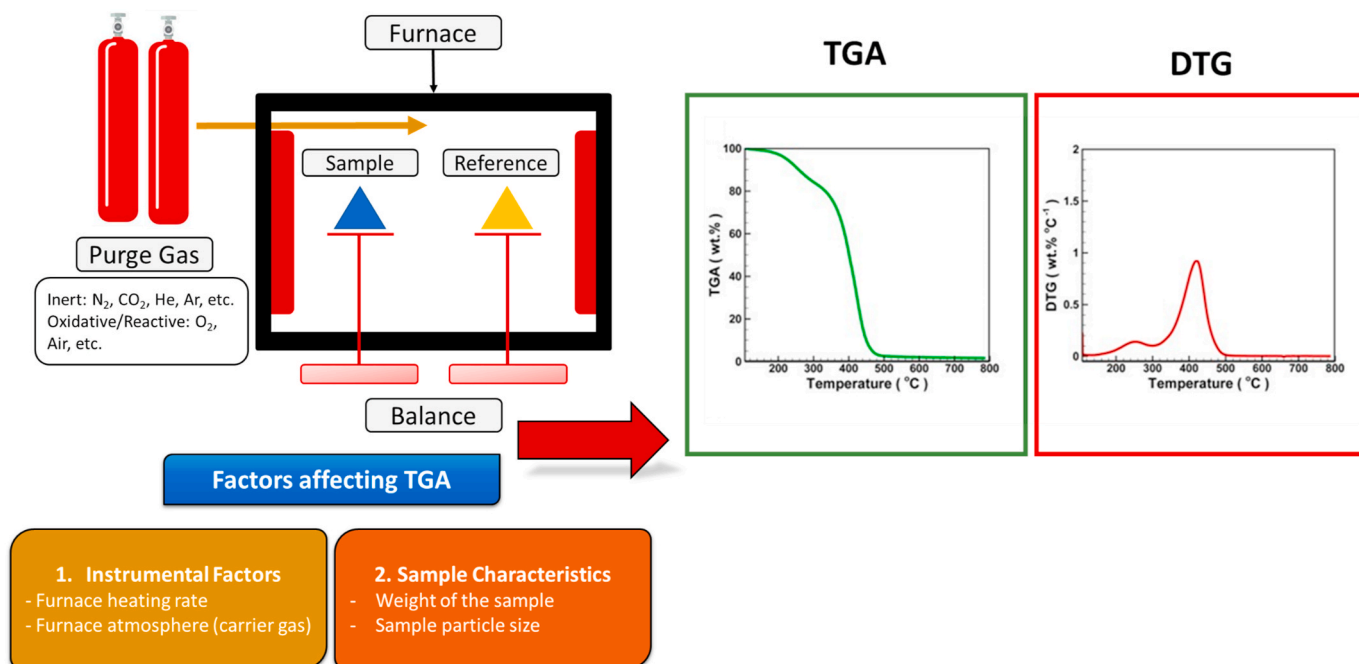


Fig. 5. Important elements and properties affecting thermogravimetric analysis [172,173].

By differentiating the TGA curves, one can obtain the differential thermogravimetric (DTG) curves. Examples of DTG curves are also depicted in Fig. 5. A DTG curve is obtained as the first derivative of the weight loss percentage (wt%) against temperature (T) or time (t). Quantitative and qualitative information can be obtained from the DTG curves. The qualitative analysis involves identifying material or differentiating between reactions. The quantitative analysis identifies the peak height and its corresponding temperature for the maximum weight loss sections of a curve [40].

4. Biomass feedstock characteristics

While bioenergy can be made from various biomass feedstocks, this study mainly focuses on the literature on lignocellulosic and algal biomass, plastics, and municipal solid wastes as the feedstocks for pyrolysis analysis. Each biomass feedstock is characterized by its chemical and physical properties. These properties influence the final product yield (biofuel) when they undergo different thermochemical conversions. Fig. 7 depicts TGA's process and application on various feedstocks and their outcomes.

4.1. Lignocellulosic biomass

Lignocellulosic biomass is abundantly available and refers to the raw materials from dry plant matter. Lignocellulosic biomass is mainly made up of cellulose (9%–80%), hemicelluloses (10%–50%), and lignin (5–35%) [41]. Lignocellulosic biomass can be placed into three major categories: waste biomass, virgin biomass, and energy crops [42]. Waste biomass is low-value by-products derived from agricultural remains (e.g., sugarcane bagasse, corn stalks, rice husks, etc.) and forestry waste materials (e.g., sawdust, logging residues, bark, shavings, chips, etc.). Virgin biomass comes from naturally occurring plant vegetation such as trees, bushes, and grass. Lastly, energy crops refer to biomass with high energy yield potential for producing second-generation biofuels (e.g., corn/maize, switchgrass, sweet sorghum, herbaceous, etc.). Other factors determining the composition of lignocellulosic biomass include its climatic conditions and the soil where it grows [43]. Therefore, qualitative and quantitative characterization of lignocellulosic biomass components is essential for its different application outlooks.

4.2. Algal biomass

Algal biomass is considered a promising feedstock for producing sustainable fuels and chemicals. Algae are divided into two major types: unicellular microalgae and multicellular macroalgae [44,45]. Nevertheless, they are both made up of proteins, lipids, and carbohydrates [46]. Algal biomass offers significant advantages for pyrolytic processes because of its high lipid content, accounting for about 20–50% of dry cell weight and up to 80% under specific conditions [47]. This high lipid content promotes a higher bio-oil yield than traditional lignocellulosic biomass.

4.3. Plastic solid waste (PSW)

Plastics have become staple materials in our lives with many versatile uses and applications. Plastics are used extensively in packaging materials, medical products, electronics, etc. [48]. On the other hand, a global pollution problem has developed with the rapid production of disposable single-use plastic. Using PSW as a source of energy production is a potential solution to this problem. The pyrolysis of PSW has become widely popular for having positive advantages towards environmental pollution and reducing carbon emissions compared to its combustion and gasification [49]. TGA is implemented to study the pyrolysis of plastics and understand their degradation reaction kinetics, which is necessary for determining important kinetic parameters for a pyrolytic reactor.

4.4. Municipal solid waste (MSW)

Another source of energy production is municipal solid waste (MSW). A survey in Taiwan in 2017 presented that around 3,130,735 tons of refuse and 4,113,808 tons of recyclable waste were generated [50]. According to the U.S. Environmental Protection Agency [51], a survey revealed that most MSW comprises materials such as paper, food waste, garden trimmings (leaves, limbs, wood, etc.), plastics, rubbers, metals, and textiles. MSW offers advantages for producing energy while reducing the quantity of material that would otherwise end up in landfills. MSW is mostly incinerated in energy plants to generate heat for producing steam to generate electricity. However, pyrolysis and gasification of MSW have become attractive alternatives to incineration. Besides, products such as refuse-derived fuels [52] and hydrogen-rich syngas [53] can be produced.

5. Important TGA characteristics

5.1. Dynamic characteristics of biomass pyrolysis

Pyrolysis can be carried out and studied through TGA with the added benefit of acquiring additional useful information that can be used to observe pyrolysis characteristics and thermal behaviors of the feedstock being used. Additionally, TGA data can be used to develop kinetic parameters to help understand reaction mechanisms. Many studies have used thermogravimetric data to create different kinetic parameters and models for explaining reaction mechanisms [54]. Obtaining more information on kinetic mechanisms is essential for describing biomass conversion of biomass during pyrolysis and gasification. This is key in designing, evaluating, and improving pyrolyzers or gasifiers [55]. Different biomass feedstocks portray different characteristics when studied through TGA. Grasping a detailed knowledge and understanding of TGA plays a crucial role in designing and operating industrial pyrolysis processes [56].

5.1.1. Lignocellulosic biomass

The thermal degradation of lignocellulosic components has been intensely studied over the years. Table 1 tabulates several studies that were carried out under TGA. Studies show that pyrolysis can be separated into four stages, as portrayed in Fig. 6a [57]: (1) moisture and light volatile components removal, (2) hemicellulose decomposition, (3) cellulose decomposition, and (4) lignin decomposition. Moisture and light volatile components are removed around temperatures <120 °C. Hemicelluloses degrade at temperatures between 220 and 325 °C [58]. Lignin and cellulose start degrading around 315–400 °C, and the remaining lignin components degrade at higher temperatures around >450 °C. In a study conducted by Chen et al. [59], the thermal degradation mechanisms of hemicelluloses, cellulose, and lignin were studied. In their study, the results from the DTG curves revealed that hemicelluloses had a maximum weight loss at 245 °C, cellulose at 355 °C, and lignin decomposed over a more comprehensive temperature range. Lignin decomposition occurred in three stages, the first max weight loss was at 254 °C, the second at 350 °C, and the third at higher temperatures of 763 °C. In another study, Stefanidis et al. [60] also investigated lignocellulosic components using TGA. Results showed that cellulose decomposed between 280 and 360 °C, and xylan (which can be used to represent hemicelluloses) decomposed between 200 and 320 °C. Lignin broke down over a wider temperature range, from 140 to 600 °C. The same observations were reported by several other studies [57,61,62].

5.1.2. Algal biomass

Table 2 lists several studies using TGA to investigate various algal feedstocks' decomposition. The pyrolytic process of algal biomass can be categorized into three stages, as shown in Fig. 6b. The first stage involves the removal of moisture and the release of light volatiles. The second stage is the main devolatilization process. One major peak is observed in

Table 1
Summary of lignocellulosic biomass studied through thermogravimetric analysis (TGA).

Type of Feedstock	Operating Conditions					Remarks	References
	Heating Rate (°C/min)	Final Temperature (°C)	Holding Time	Sample Size (mg)	Inert Gas		
One fern (<i>Pteris vittata</i> L.), Poplar wood (<i>Populus nigra</i> L.)	5	700	30 min	5–10	Ar (2 L/h)	TGA was used to determine the biomass's lignin, cellulose, and hemicellulose content. The components derived from the chemical extraction and thermogravimetric analysis process obtained positive correlations.	[39]
Microcrystalline cellulose, Birchwood xylan, Organosolv lignin	5	600 (for xylan) 800 (for lignin)	100–250 min	15–40	N ₂ (25 mL/min) Air (25 mL/min)	A modulated TGA approach provided kinetic parameters of thermal decomposition of lignocellulosic components without mathematical modeling or theoretical assumptions.	[62]
Fir wood, eucalyptus, pine bark, marine biomass (<i>Nannochloropsis gaditanamicroalgae</i>)	40	900	–	10	He (200 mL/min)	TG-MS determined pyrolysis characteristics. The thermal behavior of lignocellulosic samples depended on the amount of cellulose, hemicellulose, and lignin. NG microalgae demonstrated higher thermal stability than lignocellulosic biomass.	[129]
<i>Pinus elliottii</i> (PIE), <i>eucalyptus grandis</i> (EUG), <i>Mezilaurus itauba</i> (ITA), <i>Dipteryx odorata</i> (DIP)	10	800	–	10	N ₂ (50 cm ³ /min)	The chemical composition of different wood species was investigated. Higher extractive contents associated with lower crystallinity and lower crystalline size accelerate the degradation process and reduce wood thermal stability.	[130]
Pine wood waste (<i>Pinus insignis</i>)	15	800	–	10	O ₂ (100 mL/min)	A kinetic model was developed for oxidative pyrolysis, and the effect of oxygen was studied. Kinetic pathways were identified through the DTG curves for the solid fuel oxidative process.	[131]
Microcrystalline Cellulose, kraft lignin, xylan	10	840	–	10	–	TGA was applied to observe the pyrolytic behavior of lignocellulosic components by studying its pyrolysis products. The final solid residue of the mixed samples was accurately predicted.	[60]
Palm kernel shell (PKS), empty fruit bunches, palm mesocarp fiber	15	850	–	5	N ₂ (150 mL/min)	Thermal degradation was studied. TGA and DTG curves revealed that the maximum degradation temperatures increased after pretreatment, as a result of the catalytic effect.	[132]
Cypress wood chips, Macadamia nut shells, Australian bituminous coal	5, 10, 15, 20	100	10 min	10	N ₂ (20 mL/min)	The pyrolysis behaviors of two biomass samples and one coal sample were studied using thermogravimetric analysis. Both biomasses had distinct characteristics when compared to coal: lower-end residue, higher mass loss, and lower maximum reactivity temperature.	[133]
Palm kernel shell (PKS), cellulose, xylan, lignin	10, 20, 30, 40	800	–	15	N ₂ (70 mL/min)	TGA studied the KMS pyrolysis kinetics and behavior to achieve effective thermochemical conversion. DTG curves identified major mass-loss peaks which were related to the decomposition of hemicellulose and cellulose.	[108]
Pine wood (sawdust), rice husk, bamboo (<i>bambusa chungii</i>)	5, 10, 20	700	–	5–10	Ar (100 mL min ⁻¹)	Pyrolysis kinetics were studied under low heating rates. Using TGA results, the pyrolysis kinetic parameters and mechanisms were estimated based on the model and model-free procedures.	[134]
Oak, spruce, pine	30,	900,	15 s	3	N ₂ (40 mL/min)	The pyrolysis behavior of synthetic samples and raw biomass combinations were studied using TGA. The effect of reactor configuration was also studied.	[135]
Corn stalk	2.5, 5, 10, 20, 40	850	–	–	N ₂	Isoconversional kinetic analysis was used to interpret TGA data in order to calculate effective activation energies for lignocellulosic pyrolysis.	[136]
Rice straw, pine sawdust, Phoenix leaves	5, 10, 20, 40	900	–	10	–	Pyrolysis kinetic characteristics were studied through TGA. Increasing heating rate influenced a shift of the TG and DTG towards a high-temperature region.	[137]
Rice husk	10, 20, 30	900	–	8–10	O ₂ (40 mL/min)	TGA results were analyzed to determine kinetic parameters using Kissinger-Akahira-Sunose (KAS) and Flynn-Wall-Ozawa (FWO), both model-free isoconversional methods.	[138]
Oil-palm solid waste (shells, fibers, and kernels)	5–40	700	–	10	N ₂	Oil palm wastes were studied under thermogravimetric analysis, and a two-parallel reaction model obtained the best results when compared to experimental data.	[139]
Oil palm waste, empty fruit bunch (EFB), shells, and kernels	5, 10, 15, 20	550	20 min	–	N ₂	Non-isothermal thermogravimetry measurements were conducted, and the distributed activation energy (DAEM) was utilized to study the pyrolysis kinetic parameters	[140]
	20, 30, 40	1000	–	10			[141]

(continued on next page)

Table 1 (continued)

Type of Feedstock	Operating Conditions					References
	Heating Rate (°C/min)	Final Temperature (°C)	Holding Time	Sample Size (mg)	Inert Gas	
Oil-palm solid wastes, paper sludge					N ₂ (70 mL/min)	Co-pyrolysis pyrolysis and kinetic behavior of oil-palm solid wastes, paper sludge, and their blends.
Forest waste pellets	5–500	850	–	–	N ₂ (800 mL/min)	The kinetic mechanism of the sample at fast heating rates in a photo-thermal (Pt) TGA reactor was investigated. Results between Pt-TGA and commercial TGA only differed by 2.1%. [142]
Waste miscanthus grass (WMG)	20	900	–	8	N ₂ (50 mL/min)	Evolution vapors during pyrolysis were studied using TG-FTIR. The sample contained functional groups such as hydroxyl –OH groups, aromatics, ether, acidic compounds, aromatics, phenols impurities, aliphatic groups, alcohol, and ester. [143]

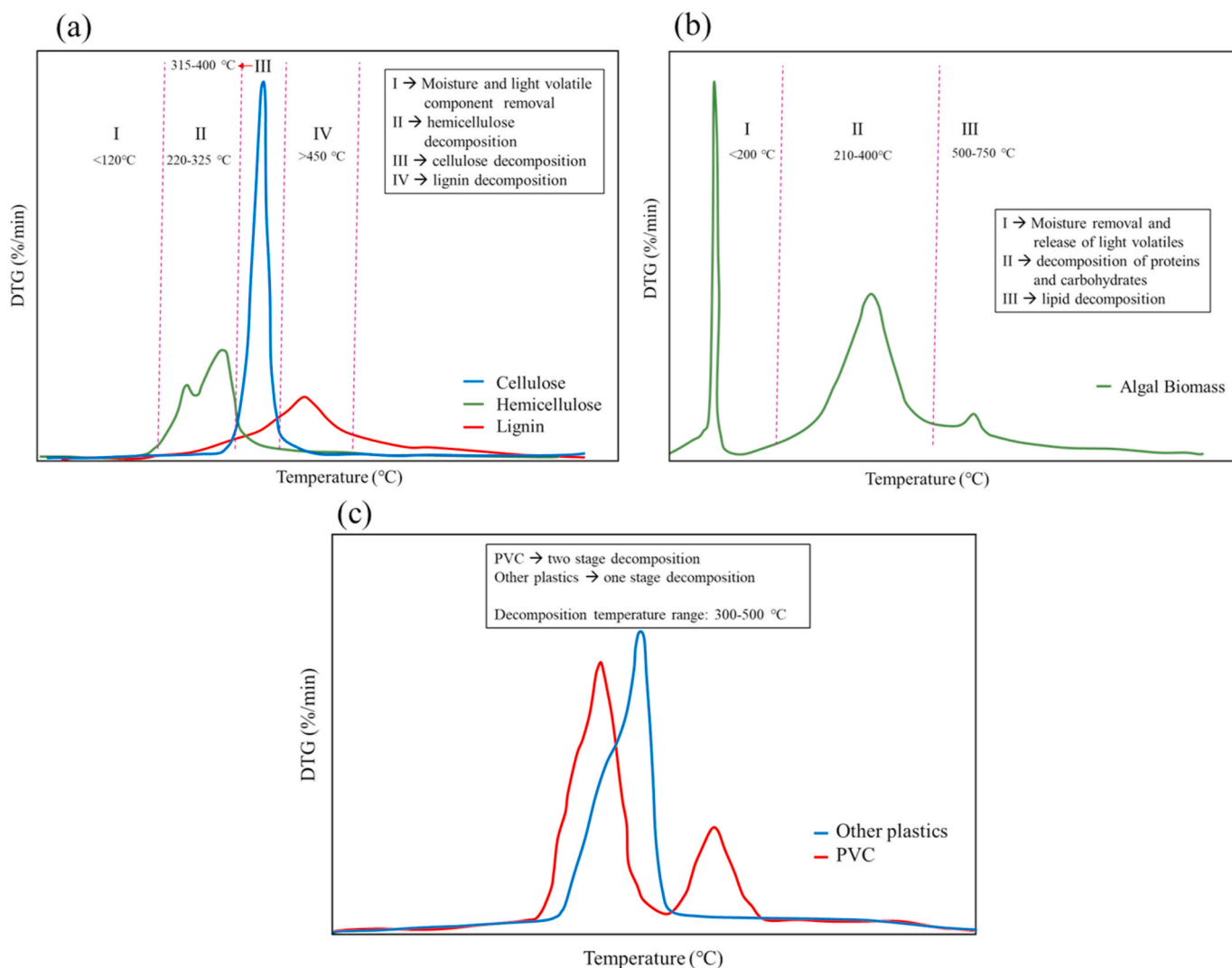


Fig. 6. (a) General decomposition curves for lignocellulosic biomass obtained from DTG, (b) general decomposition curves for algal biomass obtained from DTG, (c) general decomposition curves for plastics obtained from DTG. (License numbers: 5379350827182, 501756511, and 5379351293223)

this stage, generally representing the decomposition of proteins and carbohydrates at lower temperatures. Within the third stage, a second peak appears due to lipid decomposition. Bothwell Nyoni [63] studied the thermal behavior of the algal components of *Scenedesmus microalgae*. Their results showed that carbohydrates and proteins decomposed together between 210 and 400 °C, whereas lipids decomposed between

temperatures of 500 and 750 °C. It was mentioned that decomposition behavior changed significantly when the heating rate increased. Chen et al. [64] studied the thermal behavior of *Scenedesmus obliquus* CNW-N and reported similar characteristics. A large peak around 200–430 °C accounted for the breakdown of proteins and carbohydrates, whereas a smaller peak (439–530 °C) was attributed to the decomposition of lipids.

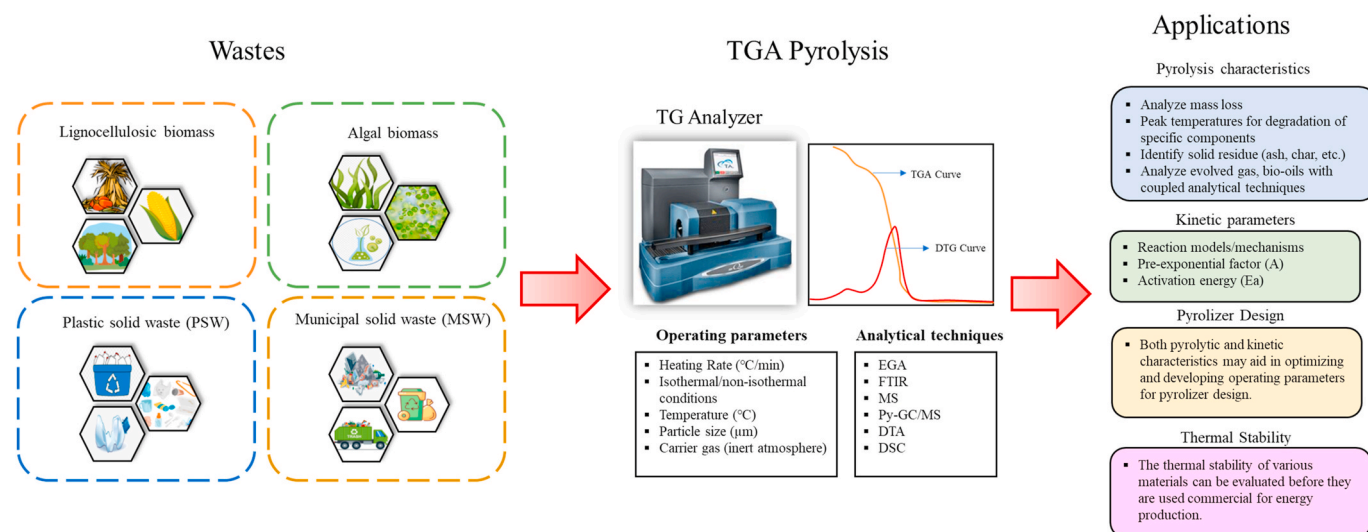


Fig. 7. Applications of TGA in pyrolysis research.

This study also reported that the weight percentage of individual components influenced the intensity of the peaks. *S. obliquus* is a protein-rich microalga (30.38 wt%); therefore, the first peak was quite high. On the other hand, its lipid content is quite low (4.66 wt%), resulting in a significantly smaller peak in the DTG curves. Rizzo et al. [65] also observed similar pyrolytic characteristics and thermal behavior. It can be presumed that proteins and carbohydrates have low thermal stability, whereas lipids have high thermal stability [66]. Lastly, in the fourth stage, at higher temperatures, slow weight loss is observed for algal biomass, attributed to the slow decomposition of carbonaceous matter and solid residue.

5.1.3. Plastics solid waste (PSW)

According to the UN environment program [67], of the seven billion tons of plastic generated globally, only about 10% is recycled. Understanding plastic waste degradation mechanisms can help better design pyrolytic reactors to minimize plastic waste and recycle value-added materials [49]. Since most plastics are solid and dry, the initial stage of moisture removal of pyrolysis is missing, and most plastics devolatilize in one phase. Table 3 shows several studies conducted on plastic decomposition using TGA. Zheng and Tao [68] studied the thermal decomposition of low-density polyethylene (LDPE) between 400 and 500 °C. The solid residue produced was very low, and its single DTG peak was very intense. Kumar and Singh [69] performed TGA on high-density polyethylene (HDPE) using various temperatures to observe thermal stability and degradation. Results of the DTG curve revealed one peak between 380 and 470 °C, meaning that HDPE decomposed in one step. In another study conducted by Brems et al. [70], the cracking of polyethylene terephthalate (PET) and polystyrene (PS) at different heating rates was investigated through TGA. The pyrolysis stage for PET was between 380 and 470 °C, and for PS, it was between 395 and 459 °C. PET resulted in the carbonaceous residue of about 10 wt%; but for PS, it was 2 wt%, regardless of the heating rate. These two plastics decomposed in one step since only one peak emerged in the DTG curves. Fig. 6c shows the DTG decomposition characteristics of most of the plastics studied under TGA.

Most plastics generally portray a narrower decomposition range than other biomass waste [71]. However, polymer polyvinyl chloride (PVC), which only accounts for a very small percentage of PSW [72], shows different characteristics. Fang et al. [73] studied the thermal degradation of wood-flour-PVC composites (WF-PVC). In this study, the primary elements of WF-PVC were investigated. Pure PVC results revealed two distinct peaks in the DTG curves, as shown in Fig. 6c. It was assumed that HCl elimination was reflected within the first peak, whereas the thermal

degradation of the carbon chain of PVC was represented in the second peak. In the study by Gunasee et al. [74], the degradation characteristics of PP, PS, and PVC polymers were explored by studying both TGA and DTG curves. The plastics PP and PS degraded over a small range and portrayed a single-step decomposition. This characteristic was presumably attributed to the plastics' homogenous structure. However, for PVC, this study also observed two distinct steps in its DTG curves, peaking at 309 °C and 450 °C. Similar pyrolytic behavior for PVC was observed by Blazevska-Gilev [75]. Zhou et al. [76] studied the pyrolysis behavior of chlorinated polyvinyl chloride (CPVC) and compared it to normal polyvinyl chloride (PVC). TG and DTG curves revealed that both plastics decomposed in two stages and portrayed similar pyrolysis characteristics. Gunasee et al. [74] explained that PVC decomposition characteristics could be attributed to the difference in macromolecular structure and pyrolysis mechanisms compared to the other plastics. In this study, it was noticed that fiberglass was highly present in the solid residue of the cases with PCV, possibly contributing to the nature of the decomposition curves observed. However, Huang et al. [77] proposed that in the first stage of PVC decomposition, the main reaction consisted of dehydrochlorination, which led to the release of HCl and the formation of conjugated polyene. In the second stage, the cyclization reactions of the conjugated polyene led to the formation of aromatic hydrocarbons such as benzene, chlorobenzene, homologues, and char. In summary, most waste plastics (PET, PP, PS) decompose in a single-stage decomposition process. However, PVC portrays a two-step decomposition process.

5.1.4. Municipal solid waste (MSW)

MSW mainly contains yard waste, paper and cardboard, fruit and vegetable waste peels, food waste, plastics, and textiles. Yard, fruit and vegetable wastes can be categorized as lignocellulosic biomass; therefore, they are mainly cellulose, hemicelluloses, and lignin. They portray similar thermal decomposition behavior discussed in Section 5.1.1, whereas the thermal decompositions of plastic components follow the pyrolytic characteristics discussed in Section 5.1.3.

Table 4 provides a summary of various types of MSW studied using TGA. Li et al. [78] investigated the pyrolysis characteristics of eight different combustible MSW components (Chinese cabbage, orange peel, poplar wood, paper, PE, PS, PVC, and polyester fabric) using DTG curves. The pyrolysis degradation of the lignocellulosic components was similar: cellulose was broken down between 300 and 400 °C and only had one peak, but hemicelluloses broke down mainly between 210 and 400 °C and displayed two distinct peaks. Finally, lignin decomposition occurred over a more extensive temperature range. Mass loss was mainly

Table 2
Summary of algal biomass studied through thermogravimetric analysis (TGA).

Type of Feedstock	Operating Conditions					Remarks	Ref.
	Heating Rate (°C/min)	Final Temperature (°C)	Holding Time	Sample Size (mg)	Inert Gas		
<i>Parachlorella kessleri</i> HY6	5, 10, 20	700	–	7	N ₂ (100 mL/min)	TGA coupled with other techniques demonstrated that microalgae degraded in three important steps.	[144]
<i>Chlorella</i> sp., <i>Chlamydomonas reinhardtii</i> algae	3 (°C/min)	1000	–	5–15	N ₂ (20 mL/min)	Algal chemical decomposition transitions from the sample mass loss with temperature was studied using TGA, and compared with the literature.	[145]
<i>Sargassum fluitans</i> , <i>S. natans</i> (morphotypes I and VIII)	10	800	–	–	N ₂ (100 mL/min)	Thermal decomposition characteristics were studied. The char contents of the samples were identified.	[146]
<i>Tetradismus obliquus</i> , <i>Tetradismus dimorphus</i> , <i>Chlorella sorokiniana</i> , <i>Chlorella</i> sp.	10	800	3 h	5	N ₂ (100 mL/min)	DTG data was obtained by using TGA data. The maximum decomposition of the biomass samples was represented by a devolatilization curve that occurred around 270–310 °C.	[147]
<i>Spirulina</i>	5, 10, 20, 30, 40, 50	850	5 min	10	N ₂	The kinetic and thermodynamic analysis of the pyrolysis of <i>Spirulina</i> and one peak was observed for each heating rate which indicated that it is protein-rich and decomposes very easily.	[91]
<i>Spirulina plantensis</i> , <i>Chlorella pyrenoidosa</i>	10, 13, 16, 19, 22, 25, 39, 35, 40	700	–	5	N ₂ (60 mL/min)	The kinetic parameters for isothermal pyrolysis were estimated via TGA. The competitive reactions involved in the isothermal pyrolysis model were also identified.	[148]
<i>Enteromorpha compressa</i>	5, 10, 30	1000	–	–	N ₂ (30 mL/min)	The kinetic study of the pyrolysis of the algal biomass was performed with TGA by observing and measuring its weight loss. Maximum decomposition occurred between 493 and 923 K.	[149]
<i>Nannochloropsis</i> sp.	35	750	–	3	N ₂	TGA was used to identify three main decomposition steps, <180 °C dehydration, 180–540 °C devolatilization, and >540 °C corresponding to slow decomposition of solid residue)	[150]
<i>Coleastrum</i> , <i>Actinostrium</i> , <i>Diatom</i> and <i>Mucidosphaerium pulchellum</i>	20	800	–	5–10	Ar (75 mL/min)	The thermal decomposition behavior of the biomass was confirmed using TGA. Data showed that about 50% of the initial biomass was pyrolyzed at 500 °C.	[151]
<i>Chlorella vulgaris</i>	5, 10, 20	800	–	10	N ₂ (100 mL/min)	Algal biomass sample experienced the greatest mass loss at 296 °C. Algal biomass obtained the highest bio-oil yield (32.69 wt%) compared to other samples.	[152]
<i>Chlamydomonas reinhardtii</i> , cell wall mutant <i>C. reinhardtii</i> CW15 + , <i>Chlorella vulgaris</i>	100	900	10 min	5	He (50 mL/min)	The study under TGA resulted in three stages of decomposition, mainly identified as (1) dehydration, (2) devolatilization, and (3) the decomposition of carbonaceous solids. Pyrolytic decomposition occurred between 270 and 500 °C, and most mas was lost between 350 and 360 °C.	[153]
<i>Chlorella vulgaris</i> (CV), <i>Dunaliella salina</i> (DS) and <i>Haematococcus pluvialis</i> (HP)	5, 10, 20, 30, 40, 50	850	5 min	12	N ₂	Increasing heating rates caused the TG/DTG curves to shift towards higher temperatures without affecting decomposition behavior. TGA data were used to develop the key parameters for the kinetic study.	[154]
<i>Enteromorpha prolifera</i>	10, 20, 30, 40, 50	700	–	10	N ₂ (50 cm ³ /min)	Pyrolytic and kinetic behavior of <i>E. prolifera</i> were investigated. Three stages of decomposition were identified: (1) light volatile compounds decomposed, (2) main pyrolysis stage, and (3) solid residuals were slowly pyrolyzed.	[155]

triggered around 280–400 °C. For paper, since it is primarily made up of cellulose, it only showed one peak in its DTG curve, about 300–400 °C. For PP and PS, their DTG temperature peaks were observed at 477 °C and 413 °C, respectively. Similar to what was discussed previously, PVC was decomposed in two stages, mainly between 250–380 °C and 400–550 °C. Lastly, for polyester fabric, DTG curves revealed that the principal mass loss occurred within a narrow temperature range of 375–475 °C with a temperature peak at 438 °C.

Gunasee et al. [74] compared single MSW components of packaging paper, hygienic paper, cardboard, PVC, polypropylene, PS, branches, leaves, grass, and a combination of polypropylene, branches, and cardboard. Hygienic paper and cardboard were categorized as cellulosic-based materials and degraded between 210 and 230 °C, within the cellulose degradation range. In their results, packaging paper degraded differently from other cellulosic-based materials (hygienic paper and cardboard) and displayed two peaks in the DTG curve at 362 °C and 486 °C. The first peak was credited to cellulosic degradation

like those of hygienic paper and cardboard. However, the second peak resulted from the degradation of calcium carbonate, a common additive in packing paper.

In another study conducted by Ansah et al. [79], residential MSW comprising PET plastic, wood, paper, and cotton textile, were studied. The main pyrolysis stage for PET occurred between 360 and 480 °C. Meanwhile, paper, wood, and textile decomposed at a lower temperature range of 220–380 °C, within the range of lignocellulosic materials. Plastic waste had the highest weight loss of 18.5 wt%, followed by paper and textiles (10.8 wt%), and then wood (9.9 wt%).

Several MSW components were studied individually in many of the studies reviewed, which is the main challenge to the thermochemical treatment of mixed MSW in real-life applications.

In summary, it can be observed that every feedstock portrays different decomposition characteristics, and the general DTG decomposition curves are displayed in Fig. 6. Lignocellulosic biomass decomposes over four stages, algal biomass decomposes in three stages,

Table 3
Summary of Plastic Solid Waste (PSW) studied through thermogravimetric analysis (TGA).

Type of Feedstock	Operating Conditions				Inert Gas	Remarks	Ref.
	Heating Rate (°C/min)	Final Temperature (°C)	Holding Time	Sample Size (mg)			
LDPE	5, 10, 20, 40, 60	600	–	5–10	Ar (20 mL/min)	The solid residue produced was very low, and its single DTG peak was very intense. LDPE showed faster thermal weight loss compared to cellulose.	[68]
HDPE	20	600	–	–	Air (40 mL/min)	The thermal stability and degradation of waste HDPE in various temperature ranges were studied via TGA. HDPE degradation started from 390 to 490 °C.	[69]
PET, PS	15, 50, 100	–	–	–	N ₂ (50 mL/min)	The pyrolysis stage for PET was between 380 and 470 °C, and PS was between 395 and 459 °C. PET resulted in the carbonaceous residue of about 10 wt%; while for PS, it was 2 wt%.	[70]
WPE, WP: mixture of PE, PS, and PET	5, 10, 15, 20	973.15 K (≈700.25 °C)	–	13	Ar (60 mL/min)	TG curves remained the same regardless of the variation of the heating rate. TG curves also show the plastic samples decomposed into gaseous products during pyrolysis.	[92]
PET	10, 20, 40, 60	800	–	10	N ₂ (60 mL/min)	For PET plastic, the active pyrolysis stage was between 360 and 480 °C. This temperature range was significantly higher than other biomass-derived components also studied.	[79]
LDPE	20	600	–	5	N ₂ (50 mL/min)	Thermal decomposition of LDPE happened between the temperature of 400–500 °C. No solid residue was formed from the complete degradation of LDPE.	[156]
LDPE, HDPE, PS, PP	5, 10, 15, 20	600	–	10–12	N ₂ (60 cm ³ /min)	The pyrolysis of each polymer was a single-step process with a range of 300–500 °C. The thermal stability of the polymers investigated in this study was ranked as follows: PS < PP < LDPE < HDPE.	[157]
HDPE, virgin LDPE, PP, mixtures of LDPE/PP	10	600	–	20	N ₂ (60 mL/min)	TGA studies revealed that the degradation of individual polymers portrayed similar thermal behavior. HDPE degraded between 452 and 489 °C, LDPE between 437 and 486 °C, and PP between 378 and 456 °C. The use of a catalyst lowered the degradation temperature.	[158]
HDPE and PS	10	1073 K (≈799.85 °C)	5 min	10	N ₂ (50 mL/min)	The decomposition of PS was between 623 and 723 K, while for HDPE, it was between 663 and 768 K. The temperature peak and decomposition intensity for HDPE were higher than that of PS.	[71]
PVC, WF-PVC	10	800	–	–	N ₂	Pure PVC was tested under TGA conditions, and two peaks were observed in the STG curves. It was assumed that HCl-elimination occurred within the first peak, while the thermal degradation of the carbon chain of PVC occurred in the second peak.	[73]
PVC, PS, PP	20	1000	5 min	10–20	Ar (50 mL/min)	Two steps were involved in the degradation of PVC, with peaks on the DTG curves observed at 309 °C and 450 °C. PP and PS decomposed in a small temperature range; they both portrayed a single-stage degradation.	[74]

LDPE, Low density polyethylene pellet; HDPE, High density polyethylene; PET, Polyethylene terephthalate; PS, Polystyrene; WPE, Waste polyethylene; WP, waste plastics; PE, polyethylene; PP, Polypropylene; PVC, Polyvinyl chloride; WF-PVC, wood-flour-polyvinyl chloride composites.

and most plastics decompose in a single stage, except for PVC, which portrayed two decomposition stages. As for MSW, the characteristics of the previous biomass can be used to explain its decomposition since MSW is made up of many lignocellulosic and plastic materials.

5.2. Temperature

5.2.1. Isothermal vs non-isothermal conditions

TGA through isothermal and non-isothermal conditions is commonly used to develop kinetic information of pyrolysis. The mass change of a sample is observed through TGA as a function of time during isothermal pyrolysis or temperature during non-isothermal pyrolysis [80]. A TG analyzer exposes a sample to a selected and controlled temperature profile in an inert atmosphere. During non-isothermal conditions, the temperature increases at a fixed heating rate from a lower temperature to a higher temperature. Thermograms developed from TGA data show mass loss in terms of temperature change. According to the reviewed articles that studied pyrolysis through TGA, the temperature is generally raised from room temperature to temperatures as high as 1000 °C at different heating rates. On the other hand, the isothermal condition occurs when a sample is subjected to a constant temperature and held for a particular period. In this case, thermograms portray mass loss according to changes in time since the temperature is kept constant throughout the pyrolysis process. Both conditions are useful in deriving kinetic parameters (e.g., pre-exponential factor (*A*), activation energy (*E_a*), etc.). Different models can be used depending on whether

isothermal or non-isothermal conditions are used. Li et al. [81] studied waste wood biomass and observed its pyrolytic characteristics and non-isothermal kinetics. Based on the obtained results, an improved Coats-Redfern method was derived. Wang and Zhao [82] utilized isothermal and non-isothermal conditions for pyrolysis of plastic waste (perfusion tubes) to compare the kinetic parameters. In a study by Cano-Pleite et al. [83], microalgae pyrolysis was conducted under isothermal and non-isothermal conditions. Kinetic parameters for isothermal pyrolysis were identified using TGA, whereas isothermal microalgae pyrolysis was investigated using a macro-TGA bubbling fluidized bed.

5.2.2. Effect of heating rate

The heating rate is usually defined as the amount of heat transferred per unit time in a material. In TGA, the heating rate is expressed in terms of °C/min or K/min. A few studies observed that increasing heating rates delayed overall thermal degradation [84,85]. Increasing the heating rates caused the material to reach the temperature in a shorter time, in turn, leading to the shift of the ignition, peak, and burnout temperatures towards higher values. This is a result of a larger temperature gradient that is developed between the inside and the outside of the material. Moreover, a higher heating rate influences a slower decomposition process. Higher temperatures are less effective than lower temperatures. Lower heating rates allow the biomass samples to be heated gradually, giving rise to more efficient heat transfer within the material [86]. TG analyzers can run high heating rates (e.g., 500 °C/min). However, to

Table 4
Summary of Municipal Solid Wastes (MSW) studied through thermogravimetric analysis (TGA).

Type of Feedstock	Operating Conditions					Remarks	Ref.
	Heating Rate (°C/min)	Final Temperature (°C)	Holding Time	Sample Size (mg)	Inert Gas		
Polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), hygienic paper (HP), cardboard (CB), packaging paper (PK), pine wood leaves (LV), branches (BR), and grass (GR)	20	1000	5 min	10–20	Ar, air (21% O ₂ /79% N ₂)	Synergistic effects during pyrolysis of MSW were investigated through a TGA model. The MSW mixture devolatilized in two major stages (375 and 481 °C) under pyrolysis. The first peak can be attributed to the devolatilization of carbohydrates in lignocellulosic and cellulose-based materials, while the second was due to PP and lignin degradation.	[74]
Chinese cabbage, orange peel, poplar wood, paper, PE, PS, PVC, polyester fabric	10	1000	–	–	N ₂ (100 mL/min)	Mass loss of the lignocellulosic components was mainly between 200 and 400 °C. For polyester fabrics, the mass loss occurred between 375 and 475 °C. PVC decomposed in two stages: (1) 250–380 °C and (2) 380–500 °C.	[78]
Food (46.4%), fruit waste (4.7%), wood, paper (18.2%), and polyvinyl chloride (PVC) (30.75%)	20, 30, 40	950	–	6 ± 0.2	N ₂ (80 mL/min)	The decomposition of SMW samples was divided into four stages. Major mass loss was due to the decomposition of cellulose and hemicellulose 300–390 °C. Chlorine emissions were due to PVC (235–578 °C), lignin, and remaining PVC hydrocarbons produced a peak in the stage.	[159]
Polyvinyl chloride (PVC), lignin, cotton, rubber, cabbage, and printing paper	5	800	–	8–12	N ₂ (20 mL/min)	The thermal decomposition of six components was investigated under a steam atmosphere using TGA-MS. The TG and DTG curves were used to compare pyrolysis within N ₂ and steam atmosphere. Steam had little effect in the lower temperatures, and remarkable differences were observed as temperature increased.	[160]
Textile waste (waste jeans)	10	800	–	7–10	N ₂ (60 mL/min)	Thermal and chemical decomposition of waste jeans samples were studied. The main decompositions of samples were as follows: untreated (322–466 °C), heavy metal-free (22–467 °C), and regenerated cellulose (350–475 °C)	[161]
High-ash anaerobic sewage sludge	10, 25, 50, 90	951.85	–	10	N ₂ (100 mL/min)	The mass-loss rate was the highest, around 398–953 K. pyrolytic behavior was divided into three reaction zones: (1) dehydration (<398 K), (2) devolatilization (398–953 K), and (3) decomposition of char and inorganic material (>953 K).	[162]
Dacron (a synthetic polyester fiber), spent tire, printing paper, rice, and polyethylene (PE)	5, 10, 20, 30	1193 K (≈920 °C)	–	10	N ₂ (100 mL/min)	Pyrolysis of components in N ₂ and CO ₂ gasification were studied with varying heating rates using TGA. Pyrolysis in CO ₂ and N ₂ portrayed similar characteristics; however, CO ₂ pyrolysis shifted the reaction to higher temperatures.	[163]
Paper, poplar wood, polyethylene (PE), polyethylene terephthalate (PET), rice, and rubber	5, 10, 20	1273 K (≈999.85 °C)	–	10	N ₂ (100 mL/min)	Experimental TGA data were compared to results obtained from a Weibull model. The Weibull model was able to produce TG and DTG curves very accurately for the components under study.	[164]

minimize the temperature gradient within the sample, most laboratory-scale studies are conducted using low heating rates (e.g., 5–50 °C/min) [87]. The heating rate can also influence the resolution of the thermogram. Choosing slower heating rates usually results in a higher resolution of the curves.

Chen et al. [88] studied moso bamboo at four heating rates of 5, 10, 20, and 30 °C/min. Their results revealed that increasing heating rate caused the onset and offset temperatures of the main devolatilization stage to shift towards higher temperatures. A recent study by Elorf et al. [89] investigated the pyrolysis of olive waste. The TGA curves were shown at the heating rates of 10, 20, and 40 °C/min, where the DTG curves revealed that the pyrolysis region and peak temperatures shifted slightly towards higher temperatures. The peak temperatures for 10, 20, and 40 °C/min were 328, 330, and 333 °C, respectively. Similar trends were observed for tobacco waste studied through TGA at 5, 10, 20, and 40 °C/min [90]. It was observed that, with increasing heating rate, the

maximum decomposition rates and temperatures shifted to higher regions. El-Sayed and Khairv [84] studied the thermal degradation of biomass samples (wheat straw, wheat dust, and corn cob) with TGA at 10, 15, and 20 K/min. Their results also revealed that increasing heating rate affected ignition, peak, and burnout temperatures. Higher heating rates were less effective than lower heating rates, leading to slower decomposition processes at higher temperatures. These observations were also held for other biomass samples. Vasudev et al. [91] studied the microalgae *Spirulina* at heating rates of 5, 10, 20, 30, 40, and 50 °C/min. DTG curves revealed that the main pyrolysis stage shifted towards higher temperatures with increasing heating rates. DTG peak weight loss intensity also increased with rising heating rates. Pan et al. [92] investigated plastic waste under varying heating rates. The DTG curves of pure and waste polyethylene (PE) portrayed a significant shift towards higher temperatures when the heating rate increased. Additionally, the peak values for PE also increase with rising heating rates.

In conclusion, choosing between isothermal and non-isothermal conditions depends on the type of model chosen to study the feedstock that would be utilized. Mass loss in isothermal heating curves (constant temperature) is shown in terms of time, whereas in non-isothermal heating (changing temperatures), the mass loss is shown in terms of temperature. Additionally, most studies usually choose non-isothermal conditions since studies are carried out at different heating rates.

5.3. Effect of particle size

Biomass size reduction and densification have been the commonly used pretreatment techniques. Increasing material bulk density and energy density can pose cheaper transportation costs [93], which is very beneficial when dealing with large amounts of biomass. However, the study's feedstock sample size is usually in milligrams (mg) when conducting TGA experiments, which implies, in turn, that the particle size of the feedstock must also be relatively small. To attain a small particle size, suitable laboratory-grade grinders are used for biomass size reduction. The type of material, initial particle size, sample size, and the required final particle size all influence the grind time of a sample [94]. Sieves can be used to filter desired sizes from the final ground samples. Smaller particles, namely, the minus material, will pass through the sieve, whereas large particles, so-called the plus material, will remain.

Literature suggests that biomass particle size mainly affects the process of kinetics. Feedstock particle size and heating rate are important parameters that directly influence the pyrolysis kinetics and the process's total energy requirement. It was also noted that particle size has a similar influence to that of increasing heating rate. Suriapparao and Vinu [95] discussed that as the feedstock sample's particle size increased, the volatile matter and fixed carbon increased, but the ash content decreased. High ash content was a noticeable characteristic with particle sizes typically <100 μm. Suriapparao and Vinu [95] also investigated the effects of particle size on the pyrolysis of mixed wood sawdust (MWSD). The particle sizes were between 26.5 and 925 μm, and the heating rate was 20 °C/min. Their results revealed that mass loss increased with increasing particle size during the main pyrolysis stage, whereas the opposite was observed during post-pyrolysis. As for pyrolysis temperatures, there was a slight shift towards higher temperatures as the particle size increased. Additionally, an interesting trend was observed as the particle size increased, the activation energies decreased in slow heating rates, but they actually increased with even slower heating rates. A recent study by Xiao et al. [96] investigated different factors affecting pyrolysis kinetic characteristics of different lignocellulosic biomasses. For pine sawdust and rice straw samples, the initial and final pyrolysis temperatures did not change for smaller particle sizes (0.150–1.180 mm and 1.109–0.120 mm); however, for larger particles (0.250–0.380 mm), the pyrolysis temperatures increased. In contrast, smaller particle size for Phoenix leaves samples portrayed higher final pyrolysis temperatures. Mlonka-Mędrala et al. [94] also investigated the effect of particle size distribution on the pyrolysis of biomass samples. This study also observed that the larger particle sizes (0.425 mm) of energy crop and straw samples influenced the DTG curves of the pyrolysis process to shift towards higher temperatures.

5.4. Characteristic indices

Specific characteristic indexes are used in tandem with kinetic models and TGA results. These are fairly easy and quick to calculate and aid in identifying the thermal properties of the biomass feedstock. These indexes are classified as pyrolysis-peak Temperature (T_p) and pyrolysis index (P_i), pyrolysis burnout index (B_i), pyrolysis characteristic peak index (P), and comprehensive pyrolysis index (CPI). Each characteristic can be calculated based on the data of TG and DTG curves developed for biomass samples. Fig. 8 visually represents some of the characteristic variables necessary to calculate various pyrolysis indices. Each is briefly described in the following sections.

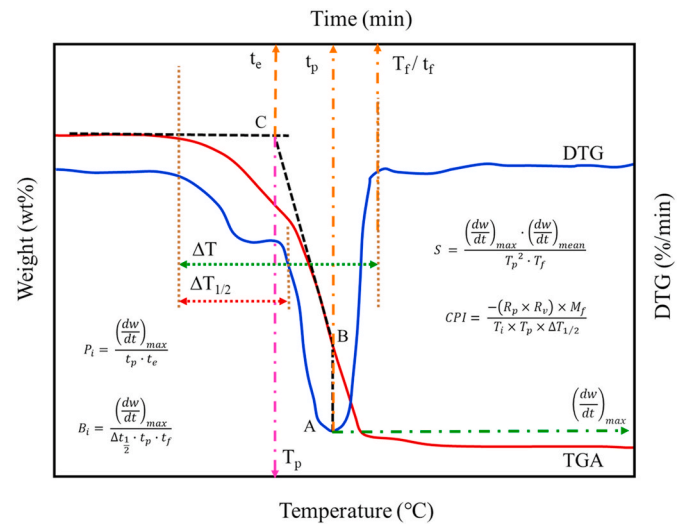


Fig. 8. Visual representation of the characteristic variables necessary to calculate various pyrolysis indices [97,101].

5.4.1. Pyrolysis index (P_i) and pyrolysis-peak temperature (T_p)

The pyrolysis index denotes the pyrolysis capacity for each particular pyrolysis stage or peak. Physically, the higher the P_i value, the easier it is for the biomass to pyrolyze, making it easier to identify a sample's pyrolysis capacity. This index is defined mathematically by the following equation:

$$P_i = \frac{(\frac{dw}{dt})_{max}}{t_p \cdot t_e} \quad (1)$$

where $(\frac{dw}{dt})_{max}$ is the maximum pyrolysis rate (%/min), t_p is the time (min) of the largest peak (maximum degradation rate), and t_e is associated with the pyrolysis-peak temperature (T_p). Paniagua et al. [97] determined characteristic indexes during the study of poplar energy crops. In this study, lower T_p values were recommended. This would result in the pyrolysis phase requiring a lower energy expenditure, leading to a larger P_i during the active phase. Kanca [98] studied the effect of TGA's mixing ratio of cotton waste-based biofuel and lignite-based fossil fuel. This study found that the ignition temperatures decreased with increasing cotton waste proportions of blends.

5.4.2. Pyrolysis burnout index (B_i)

The pyrolysis burnout index (B_i) evaluates the biomass burnout performance. A B_i value denotes a higher burnout efficiency for the biomass sample. This index is similar to the pyrolysis index (P_i); however, B_i index does not take into consideration the pyrolysis-peak temperature (T_p) and prioritizes the end of the peak. This index value can be calculated as follows:

$$B_i = \frac{(\frac{dw}{dt})_{max}}{\Delta t_{\frac{1}{2}} \cdot t_p \cdot t_f} \quad (2)$$

where $(\frac{dw}{dt})_{max}$ is the maximum pyrolysis rate (%/min), $\Delta t_{1/2}$ is the time (min) is the time zone of the first half of the DTG for a particular stage, t_p is the time (min) of the largest peak (maximum degradation rate), and t_f is the time at which the end of the peak takes place (burnout time). Paniagua et al. [97] determined that the B_i index provided higher importance to the final part of each pyrolysis stage even though it neglected the pyrolysis-peak temperature. Kanca [98] determined that the burnout temperatures of cotton waste were higher than Yeni Caltex lignite.

5.4.3. Pyrolysis characteristic index (S)

The pyrolysis characteristic index (S) assesses the pyrolysis

performance and denotes the energy required to pyrolyze the biomass sample. It is inferred that a higher (*S*) value translates to a better pyrolysis property of the biomass. Since several vital parameters are considered in this index, it gives a reasonably comprehensive evaluation that can be regarded as a reference for practical operation. The pyrolysis characteristic index (*S*) can be calculated using the following equation:

$$S = \frac{\left(\frac{dw}{dt}\right)_{max} \cdot \left(\frac{dw}{dt}\right)_{mean}}{T_p^2 \cdot T_f} \quad (3)$$

where $\left(\frac{dw}{dt}\right)_{max}$ is the maximum pyrolysis rate (%/min), $\left(\frac{dw}{dt}\right)_{mean}$ is the average pyrolysis rate, T_p is the pyrolysis-peak temperature (ignition temperature), and T_f is the temperature value at the end of the peak (burnout temperature). Paniagua et al. [97] compared *S* values for different biomass samples and concluded that values obtained were lower during pyrolysis.

5.4.4. Comprehensive pyrolysis performance

The pyrolysis performance of biomass can be evaluated using the following parameters: initial devolatilization time (t_i), DTG maximum peak time (t_p), half-peak width range time ($\Delta t_{1/2}$), weight loss M_f ($M_f = m_0 - m_\infty$), and comprehensive pyrolysis index (CPI). By definition, a larger CPI translates to a better pyrolysis performance. More information concerning CPI can be found in studies by Huang et al. [99], Bi et al. [100], and Zhang et al. [101]. CPI can be calculated as follows:

$$CPI = \frac{-(R_p \times R_v) \times M_f}{T_i \times T_p \times \Delta T_{1/2}} \quad (4)$$

where R_p is the maximum decomposition rate, R_v is the average decomposition rate, M_f is weight loss ($M_f = m_0 - m_\infty$), T_i is the initial devolatilization temperature, T_p is DTG maximum peak temperature, and $\Delta T_{1/2}$ is peak width temperature range (when $R/R_p = 1/2$). Huang et al. [99] studied the pyrolytic bioenergy potential of water hyacinth (WHR), stems and leaves (WHS) by analyzing their physiochemical properties. This study found that the rise in the R_p , R_v , and CPI values at high heating rates improved the pyrolysis performance. Zhang et al. [101] studied cattle manure's gaseous products and pyrolytic performance using TGA, FTIR, and Py-GC/MS. Performance comparisons of manure pyrolysis in N_2 and CO_2 atmospheres. This study concluded that the total CPI of the CO_2 atmosphere was higher compared to the N_2 atmosphere, since pyrolysis was more vigorous in the CO_2 atmosphere.

Ultimately, pyrolysis indices are important tools for obtaining biomass feedstock thermal properties from thermogravimetric data. The pyrolysis index (P_i) helps identify a feedstock's pyrolysis capacity, and the pyrolysis burnout index (B_i) evaluates a biomass burnout performance. The pyrolysis characteristic index (*S*) assesses the energy

required to pyrolyze the feedstock, and the comprehensive pyrolysis performance evaluates the pyrolysis performance.

6. TGA coupled with other analysis techniques

Thermogravimetric analysis may be helpful, but it does not offer sufficiently qualitative information on biomass transformation during analysis [102]. Coupling TGA with other techniques has become widely popular and provides more versatility for analysis. Since TGA alone is primarily applicable for mass changes, it must be coupled with other analysis techniques to study different characteristics, such as phase transition, heat transfer, or other physical changes independent of mass changes. Widely used analytical techniques with TGA include TGA-FTIR, Py-GC/MS, TGA-MS, EGA, etc. Fig. 9 summarizes the most established and new technological developments of TGA for pyrolysis studies.

6.1. TGA-FTIR

During thermal analysis, gases are released directly from the sample and cannot be easily identified in TGA. Therefore, TGA can be paired with Fourier transform infrared (FTIR) spectroscopy, commonly called TGA-FTIR, as a powerful analytical technique to tackle this challenge. This combined technique allows for simultaneous weight loss measurement through thermogravimetry and the identification of functional groups and light molecular weight gases that evolve during pyrolysis, such as CO_2 , CO, NO, etc., through FTIR. TGA-FTIR produces a typical spectral output known as an absorbance spectra plot. This tool aids in the identification and quantitative characterization (speciation) of various volatile products. It can also provide insight into the kinetics involved during pyrolysis and help develop models to predict pyrolysis products and kinetics of biomass [103].

Singh et al. [104] used TGA-FTIR to analyze the pyrolysis of biomass wood waste, waste materials, waste tires, waste plastic, and refused derived fuel (RDF). Evolved gases from the waste materials were characterized through the wide spectrum of qualitative data produced by TGA-FTIR. Tian et al. [105] also used TGA-FTIR to study evolved gas and its kinetic behavior during the pyrolysis of waste tea. CO_2 was the major gas released during the thermal degradation of waste tea. Other evolved gases such as H_2O , CH_3COOH , and C_6H_5OH were also detected. Fasina and Littlefield [106] studied the decomposition of pecan shells. TGA found that pecan shells decomposed in four stages, and FTIR analysis identified CO_2 , CO, acetic acid, and ethanol as the major gases released during their decomposition. Wang et al. [107] studied the decomposition of corncob with and without catalyst through TGA-FTIR. Light gases like CO_2 , CO, H_2O , and CH_4 were identified. Complex compounds like

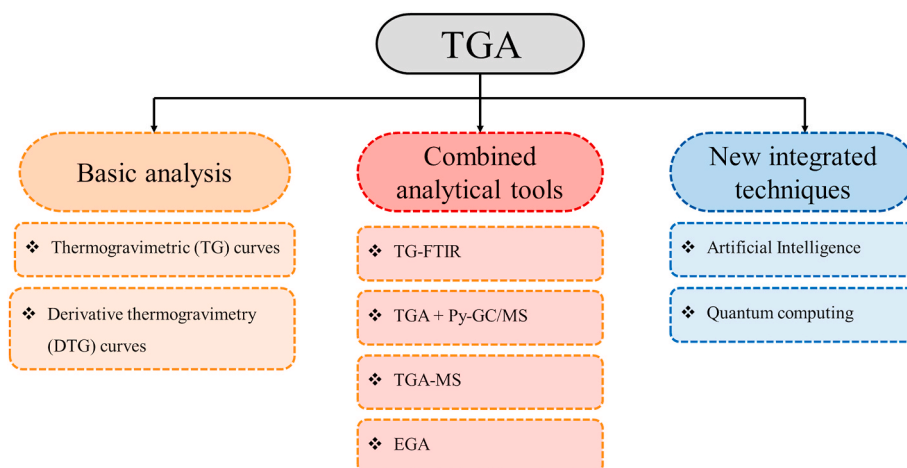


Fig. 9. Overview of the most established and new technological developments of TGA for pyrolysis studies.

hydrocarbons, phenols, acids, and carbonyl compounds were grouped since they were hard to distinguish within the IR spectra. Ma et al. [108] also used TGA-FTIR to study the degradation of palm kernel shells and identify volatile components during their decomposition. According to FTIR spectra, the prominent volatile components detected included CO₂, aldehydes, ketones, organic acids, alkanes, and phenols.

6.2. Pyrolysis-GC/MS (Py-GC/MS)

Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) can also be coupled with thermogravimetric analysis to investigate the thermal decomposition of biomass. Py-GC/MS is a powerful analytical tool that is used to decompose samples into smaller molecules that can be separated by gas chromatography, which are then identified using mass spectrometry. It is widely used for the detection of polymers. Compared to FTIR, which categorizes some identified compounds into groups, Py-GC/MS can identify specific molecules during pyrolysis decomposition. Gao et al. [109] analyzed the pyrolysis and combustion of pine sawdust through TGA-FTIR and Py-GC/MS. Py-GC/MS aided in categorizing the composition and structure of evolving gas in the pyrolysis of pine sawdust. Their results revealed that the evolved gas mainly consisted of small molar gases, acetaldehyde, acetic acid, and formic and acetic anhydrides. Zheng et al. [68] utilized both TGA and Py-GC/MS to investigate the catalytic thermal decomposition of biomass, synthetic polymers, and cellulose mixtures. Magdziarz et al. [110] explored the pyrolysis process of pine hydrochars through TGA and Py-GC/MS. Py-GC/MS identified aromatics, cyclic and aliphatic hydrocarbons, phenols and their derivatives, furan derivatives, and oxygen compounds (acids, ketones, aldehydes, etc.). Carbon oxides were the main types of compounds from the decomposition of hydrochars.

6.3. Thermogravimetric analysis with mass spectrometry (TGA-MS)

Thermogravimetric mass spectrometry (TG-MS) is useful for studying reaction features. TGA coupled with MS offers real-time detection and analysis of evolved gases from biomass pyrolysis or combustion [102]. MS is an analytical method used to quantify the mass-to-charge ratio of ions that can be represented in a mass spectrum. A characteristic fragmentation pattern can classify atoms or molecules by correlating identified masses with known masses. Magdziarz and Werle [111] analyzed the pyrolysis and combustion processes of three different kinds of sewage sludge by TGA-MS. TGA revealed that the main devolatilization stage occurred at 200–540 °C, and was related to the decomposition of proteins and soluble polysaccharides. On the other hand, MS analyzed the gaseous products of the pyrolysis process and identified H₂, CO, CO₂, and CH₄ as the main evolution products. Another study analyzed non-condensable gases produced during catalytic and non-catalytic pyrolysis of coffee ground residues via TGA-MS [112]. The main gases identified were oxygen-containing species (mainly H₂O), followed by CO and CO₂. Qiao et al. [113] studied various chitin biomass substrates, and the distribution of evolved gases was investigated with TGA and MS. The mass spectra identified light gases like NH₃, H₂O, CO, and CO₂. Salema et al. [114] also investigated the pyrolysis process of biomass blends of oil palm shells, empty fruit bunch, and sawdust with thermogravimetric mass spectrometry. The mass spectra identified the main evolved gaseous compounds as CO₂, CH₄, CH₃OH, C₃H₆, and CH₂O₂, which varied in intensity with increasing temperatures.

6.4. Evolved gas analysis (EGA)

Evolved gas analysis (EGA) can be used to investigate the gas evolved during the decomposition of biomass samples. EGA can be carried out by the combination of thermogravimetry with other analytical techniques, such as FTIR, MS, or combined GC/MS [115]. The combination of these techniques provides “on-line” information on the evolved species for

inorganic and organic compounds and products from the decomposition reactions during thermal analysis [116]. From all these combinations with thermogravimetry, the literature suggests that mass spectrometry (MS) was the most suitable for biomass EGA [116,117].

7. Advantages, challenges, and future perspectives

7.1. Advantages of TGA

TGA has been widely recognized as a practical tool for thermal analysis and gaining more knowledge about various thermal characteristics of various biomass materials. TGA offers many advantages, as depicted in Fig. 10. A vast array of different biomass feedstocks can be studied via TGA. This analytical technique accurately measures a biomass sample's mass loss over time under different heating rates and atmospheric conditions [28]. TGA is simple to operate, offers strong repeatability, and is highly precise. According to the literature, TG analyzers only require a relatively small sample for analysis, usually <20 mg for most biomass samples. TGA data can also be used to estimate kinetic parameters [118], such as pre-exponential factor (A), activation energy (E_a), etc., which help understand reaction mechanisms. Grasping a detailed knowledge and understanding of TGA and gaining kinetic parameters play a crucial role in designing and operating pyrolysis processes in the industry [56]. As discussed in Section 6, TGA can be coupled with other analysis techniques to study other pyrolysis products that cannot be learned through TGA alone. By coupling TGA with FTIR [104], MS [102], combined GC/MS [109], and EGA [115], more information about the thermal behavior or evolved gas produced during the decomposition process of the biomass sample can be studied. This analytical tool provides a quick and efficient understanding of biomass characteristics before a specific material is chosen for energy production on an industrial scale. Understanding the physical and chemical properties of biomass on a small scale can be cost-effective and helpful for determining the potential of the material for energy production on a commercial/industrial scale.

7.2. Challenges of TGA

Although thermogravimetric analysis offers many advantages, it also comes with its fair share of challenges. These challenges were outlined concisely in Fig. 10. TGA cannot study the thermal process of a sample which does not undergo mass change, such as melting, the transition from one crystalline form to another, glass transition temperatures, etc. However, most biomass feedstock samples undergo significant mass loss, so this is not much of an issue. As mentioned earlier, TGA offers high accuracy and reliable results; therefore, experiments and conditions must be selected carefully. So TGA results can be consistent, and the representative of actual large-scale scenarios are more realistic. However, the process is sensitive, and one must be careful with the sample size. A small sample size is usually selected (~2–50 mg). This sample size also means that very little product is obtained at the end of the degradation process. This means TGA is not practical for producing pyrolysis products, but it's a powerful tool for studying biomass characteristics. TG analyzers require calibration and must be cross-checked with measurement results from a reference or literature value. Additionally, describing thermal behavior and determining reaction mechanisms solely on mass change can be pretty limiting. Other pyrolysis products, e.g., evolved gases, bio-oils, residues, etc., cannot be analyzed by TGA either. Hence, TGA needs to be coupled with other techniques to better understand biomass's pyrolysis characteristics. Results obtained from combined TGA and thermal analysis techniques are not very straightforward. Careful analysis and knowledge are needed to interpret the data. Furthermore, some TG analyzers are expensive equipment, and laboratories or researchers may not have immediate access to these devices.

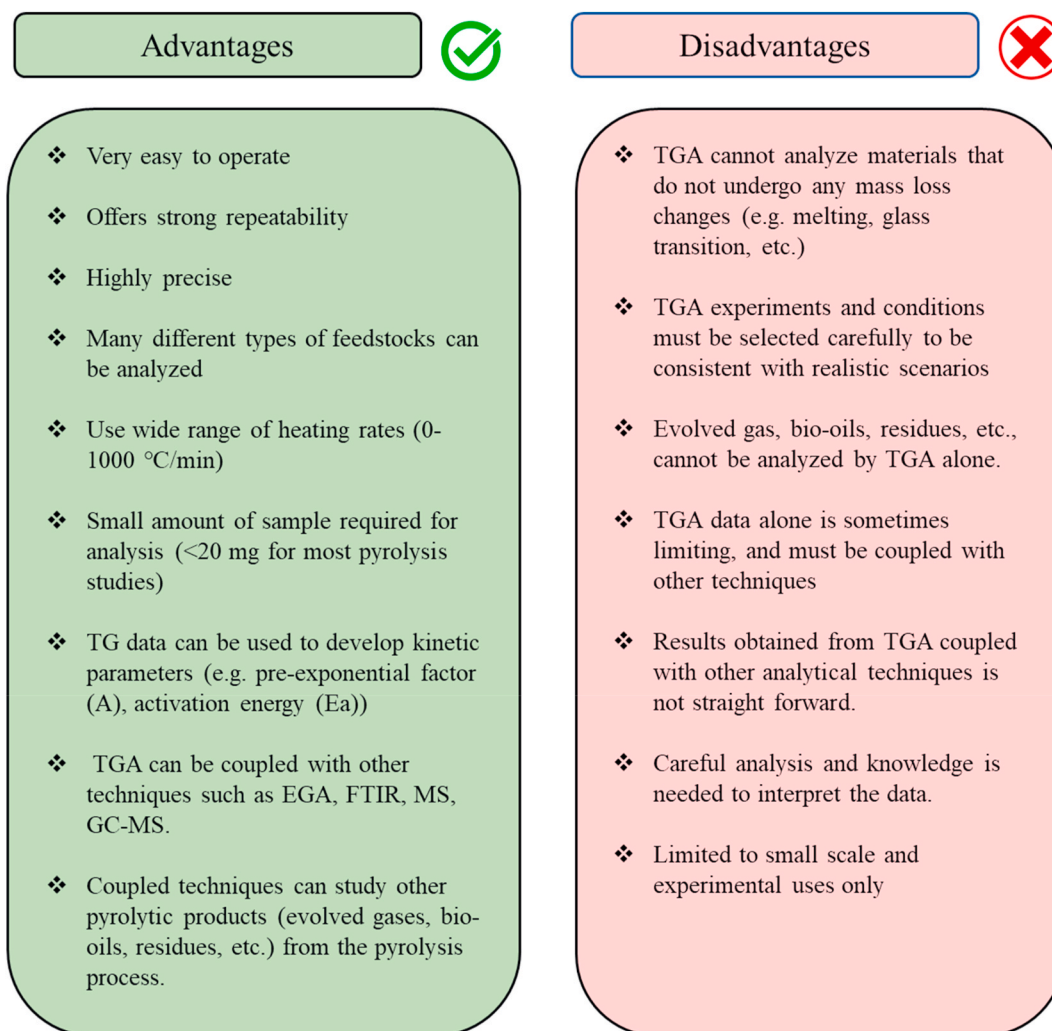


Fig. 10. Summary of the advantages and disadvantages of thermogravimetric analysis.

7.3. Biomass feedstock constraints

Biomass pyrolysis of various kinds of biomass wastes is a promising path for breaking our dependence on fossil fuels and their derived petrochemical products. Biomass is abundantly available, entirely sustainable, and can be converted into various biofuels [119]. However, current constraints include biomass production, harvesting, drying, and storage costs. Other factors may consist of these biomass materials' regional and seasonal availability. Using biomass wastes is an alternative pathway for energy production from something that would otherwise end up in landfills. But they also come with some challenges [120]. Some waste products are localized, and availability might fluctuate over time. Consistent long-term feedstock supply may pose a big issue. The transportation cost must also be considered, mainly since biomass waste sources are usually scattered and must be collected. Additionally, biomass pretreatment may result in additional costs.

An abundant array of potential biomass sources also makes it difficult to choose an appropriate feedstock for pyrolysis, since many of these biomasses are made up of different properties and characteristics. TGA has provided a way to investigate the thermal characteristics of various kinds of biomass waste, which can also help develop kinetic models and parameters to obtain fitting operating parameters for industrial/commercial scale pyrolyzers.

7.4. Future prospects and integration with artificial intelligence

Artificial intelligence (AI) has been rapidly developing and making its way into different research fields, most recently in bioenergy. AI is praised for being very accurate, capable of improvement, efficient, cost-effective, and can handle massive data sets. AI is a broad field with many different subfields, termed machine learning (ML), genetic algorithms (GA), artificial neural networks (ANN), deep learning (DL), etc. These techniques have provided remarkable modeling efficiency and can reproduce experimental data [121].

AI provides many applications in bioenergy. Table 5 provides a summary of AI technologies that have been applied in bioenergy applications. Liao and Yao [122] categorized them into four main sectors: (1) prediction of biomass performance indicators for rapid screening and selection of biomass; (2) prediction of process-based performance indicators of biomass conversion; (3) prediction of biofuel properties for optimal utilization of bioenergy; and (4) optimization for supply chain design and planning from both technical and sustainability perspectives. AI has been applied to pyrolysis studies for predicting product yields and properties based on operating conditions and feedstock characterization data [123]. Kinetic parameters can also be determined by using AI models. Sunphorka et al. [124] applied three ANN models were utilized to construct an association between biomass constituents and kinetic parameters (i.e., pre-exponential factor (k_0), activation energy (Ea), and reaction order (n)) of biomass. Fazilat et al. [125] used experimental data obtained from TGA to model back propagation ANN and

Table 5
Summary of AI technology for bioenergy application.

Technique	Input variables	Output variables	AI application	Remarks	Ref.
Levenberg Marquardt backpropagation algorithm	Mass percentage composition of cellulose, hemicellulose, and lignin	Kinetic parameters of log (K), log(E), and log(n)	Pre-exponential factor, reaction order, and kinetic parameters were identified and correlated using an ANN model.	ANN produced results portrayed a high correlation with TGA data.	[124]
adaptive-neuro-fuzzy-interference system (ANFIS), radial basis function (RBF), Mean square errors (MSE)	–	–	MSE was used to successfully predict the thermal degradation behavior of NY6/FK blends.	The modeling approach concluded that artificial intelligence techniques are an effective tool for predicting kinetic parameters of the thermal degradation process of MY6/FK blends.	[125]
ANN model	Lignocellulosic components (cellulose, lignin, hemicellulose), particle heating rate (β)	Kinetic parameters (log (K), log(E), log(n))	The complex and nonlinear correlations between the kinetic parameters and the heating conditions/biomass chemical compositions were studied.	The performance of the ANN model was more effective than that of the EC model. The ANN model was able to more effectively predict log(K) and log(E).	[126]
ANN model, Extreme learning machine with wavelet transform algorithm (ELM-WT)	Biodiesel volume percentage in fuel, EPS content, load fraction (%), engine speed (rpm)	- Exergy of: fuel, exhaust, transfer to cooling water, transfer to ambient, to destruction, and efficiency - sustainability index	A new model predictive strategy investigated the exergetic performance of direct injection engines running utilizing different renewable and non-renewable fuels.	The ELM-WT approach portrayed faster learning speeds compared to traditional feed-forward network learning algorithms.	[165]
ANN, support vector machine (SVM)	–	–	Predictive models were implemented to study the distribution of products and bio-oil heating from biomass pyrolysis.	Both the ANN and SVM models could successfully evaluate the yield of the pyrolytic products and bio-oil heating value.	[166]
Scaled conjugate gradient (SCG) and Levenberg–Marquardt (LM) algorithm	–	–	The pyrolysis of rice husk was examined using a predictive model strategy to identify the thermal degradation mechanism.	A nonlinear model was able to more effectively describe the rice husk degradation compared to a linear model.	[167]
Shuffled complex evolution global optimum algorithm	–	–	The shuffled complex evolution optimization algorithm, together with kinetic parameters, was used to observe the interactions of hemicellulose and cellulose.	The thermal interaction of isolated hemicellulose and cellulose could be ignored, and this was shown due to the good agreement between the predicted results and the experimental data.	[168]
Feed forward based single layer and multi-layer perception (SLP-MLP) neural network, particle swarm optimization (PSO), Monte Carlo simulation (MC)	Blend ratio, temperature, and heating temperature	TGA (%) data	An ANN was used to predict the TGA values of the co-combustion of pine sawdust and lignite coal.	The ANN was very successful in predicting TG data.	[169]

feed-forward ANDIS to predict the thermal degradation kinetics of nylon6/feather keratin blends. Xing et al. [126] compared ANN models with empirical correlational and random forest models to develop and predict the kinetic parameters based on biomass chemical compositions and heating conditions of the single-step kinetic model. The results showed that the ANN and random forest models could provide accurate predictions.

Machine learning, a type of AI, can be able to aid in the prediction of TGA curves. This allows researchers to predict different biomass feed-stock thermodegradation dynamics easily. Chen et al. [85] studied cellulose, hemicelluloses, and lignin thermodegradation through TGA under several heating rates. Particle swarm optimization (PSO) was used to optimize an independent parallel reaction kinetic model. The pyrolysis kinetics of lignocellulosic components were predicted by using pseudo-reactions. Sezer et al. [127] developed an ANN to predict the instantaneous combustion index for a biomass combustion process using 24 thermogravimetric experiments. The results between experimental and predicted values were reasonable, with an $R^2 > 0.99$. These integrations can carve a pathway for other uses and implementation of machine learning. Quantum computing [128] has also been rising in popularity for its use in the bioenergy sector. For the foreseeable future, quantum computing can be coupled with machine learning for predicting biomass kinetics.

The application of AI in the bioenergy field is anticipated to increase, stemming from its multiple advantages. With this new era of advanced

technological computing, the development and implementation of AI is very promising and may play a crucial role in optimizing and developing parameters for large-scale bioenergy systems.

8. Conclusions

This paper has presented a review of the application of thermogravimetric analysis (TGA) in aiding in the research and development of pyrolysis. Gaining a deeper insight into the characteristics of biomass waste's pyrolysis process is crucial for its conversion into biofuels. Using waste products from either industrial or municipal sources helps reduce waste and achieve a circular bioeconomy. TGA is conducive to optimizing parameters, pyrolyzer design, biomass valorization, and evaluating material thermal stability. It is also an essential analytical tool for determining thermodegradation dynamics and kinetics of different biomass wastes. The thermal degradation of lignocellulosic biomass through thermogravimetry occurs in four stages. Algal biomass degrades in three stages. Most plastics portray a one-step decomposition stage, except for PVC, which has a two-step decomposition stage. The effects of pyrolysis's operating parameters such as heating rate, temperature, isothermal/non-isothermal conditions, and particle size were explored. Isothermal or non-isothermal conditions are chosen based on the kinetic model needed for a study. They are also important for deriving kinetic parameters. A slow heating rate provides better-distributed heating in the sample and results in a higher resolution of the TGA/DTG curves.

Particle size mainly influences the pyrolysis kinetics. Pyrolysis capacity of pyrolysis stages, burnout performance, energy requirement, and pyrolysis performance are important feedstock thermal properties that are evaluated through characteristic indices. Furthermore, TGA alone is limited to only observing thermal degradation. TGA can be coupled with other analytical techniques, like FTIR, MS, GC/MS, and EGA, for studying other evolved gases and other pyrolytic characteristics. Integrating artificial intelligence into the mix delivers a promising road alongside TGA techniques for optimizing and developing parameters for bioenergy production.

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.

Data availability

The data that has been used is confidential.

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