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Optimal operating conditions for biofuel production from biomass and plastic waste via pyrolysis: A critical systematic review

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Abstract The increasing generation of solid waste and its inadequate management represent a major global environmental and public health challenge, particularly in Latin America. In this context, pyrolysis has emerged as an effective technological alternative for converting waste into energy. This thermochemical process, conducted in the absence of oxygen, produces valuable products such as bio-oil, syngas, and biochar, with significant energy and environmental applications. This study presents a systematic literature review aimed at identifying experimentally validated operating conditions for pyrolysis processes that favor biofuel production. Key parameters analyzed include temperature, particle size, waste type, pretreatment methods, and catalyst use. The review was conducted following PRISMA guidelines and included 64 experimental studies published between 2008 and 2024 that reported quantitative operating conditions and product yields for biomass, plastic waste, or mixed feedstocks; studies without experimental validation were excluded. The results consistently identify temperature as the most influential factor, with favorable ranges between 400 and 600 °C depending on feedstock characteristics. For lignocellulosic biomass, bio-oil yields are maximized at approximately 500 °C, whereas plastic waste exhibits higher liquid yields at lower temperatures, typically around 400 °C. Reported bio-oil yields generally range from 40–75 % for biomass and up to 90 % for selected plastic wastes, with overall conversion efficiencies commonly between 60 % and 85 %. Additionally, smaller particle sizes and pretreatments such as drying and grinding enhance conversion efficiency. The application of catalysts, particularly modified zeolites and metal-based catalysts, improves process selectivity by increasing the proportion of desirable hydrocarbons and reducing undesirable byproducts. However, these outcomes depend strongly on reactor configuration, catalyst formulation, and experimental scale, which limits the generalization of optimal operating conditions. Although no formal quantitative quality scoring was applied, methodological consistency and clarity of experimental reporting were qualitatively considered.

Keywords: systematic review, waste-to-energy conversion, pyrolysis operating parameters, catalytic pyrolysis, co-pyrolysis, bio-oil yield

1. Introduction

Mismanagement of urban and industrial solid waste is one of the most challenging environmental issues, not only for public health but also because it creates risks to ecosystems and climate. The world generated some 2.3 billion tonnes of solid waste in 2023, and waste generation is expected to increase by almost 50 per cent by 2050 unless effective strategies are put in place (Danso-Boateng et al., 2022). Much of this is still mismanaged in uncontrolled dumps (sites largely devoted to untreated rubbish and refuse), open burning (poorly controlled practices that release toxic emissions, leachates, and hazardous materials, undermining environmental and public health), and through the generation of methane (CH_4), a greenhouse gas with a substantially higher global warming potential than carbon dioxide (Kaza et al., 2018). Nearby populations become exposed and vulnerable to toxic pollutants, giving rise to the potential for both acute and chronic disease (Mishra et al., 2022).

To add to that, the problem is particularly severe in Latin America, where significant structural, institutional, and economic constraints persist in waste management systems. Less than half of municipal solid waste in Latin America is actively disposed of through controlled systems, with recycling and energy recovery representing only a small share of total waste generation (Cattani et al., 2024). High operational costs, representing up to 80% of total solid waste management expenses, further hamper the adoption of advanced technologies (Alarcón et al., 2023). There are over 5 million tonnes of municipal solid waste generated annually in Ecuador, with organic matter making up more than 50% of the total; nonetheless, the predominant waste disposal methods are landfills and uncontrolled dumping sites (Asociación de Municipalidades Ecuatorianas, 2023). In this context, waste valorization technologies must be evaluated primarily from a technical and operational performance perspective rather than from broad socio-environmental framings.

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Along these lines, waste-to-energy technologies are receiving increasing attention, with pyrolysis emerging as a technically mature and environmentally benign option. Pyrolysis enables the thermochemical conversion of biomass and plastic wastes under anoxic conditions into bio-oil, syngas, and biochar, which can serve as energy carriers or value-added products (Jha et al., 2022; Danso-Boateng et al., 2022). However, the reported performance of pyrolysis systems varies widely across the literature, even when relatively similar feedstocks or reactor designs are considered; this variability reflects the lack of standardised operational criteria and leads to uncertainty regarding optimal operating conditions.

Across the board, temperature has been found to be the most important factor influencing yield and product distribution in pyrolysis processes; by contrast, residence time, heating rate, and catalyst effects tend to play a less dominant role (Xu et al., 2025; Monguen et al., 2025). The selection of catalysts, particularly zeolites and nanostructured materials, has been shown to improve bio-oil selectivity and quality; however, reported outcomes vary widely depending on catalyst composition, loading, and activation methods (Mishra et al., 2022; Rahman et al., 2018; Shahbeik et al., 2023). In addition, operational parameters are often studied in isolation and without experimental standardisation, ultimately limiting the comparability and reproducibility of reported results.

Although a large volume of literature exists on waste pyrolysis, a comparable synthesis focusing on empirically validated optimal operating windows for biomass, plastic waste, and co-pyrolysis systems remains lacking. Such a lack of systematic integration inhibits robust trend identification and hampers the practical translation of laboratory-scale empirical data into marketable waste-to-energy applications.

Recent reviews published between 2023 and 2024 have primarily focused on single-feedstock pyrolysis, either biomass-derived residues or plastic waste streams, with emphasis on reactor configurations, kinetic modelling, or product upgrading pathways. Critically, these reviews have not implemented a parameter-harmonised synthesis based exclusively on experimentally validated studies reporting quantitative operating conditions and product yields. In particular, recent reviews have not: (i) applied unified operational descriptors across studies to enable cross-comparability; (ii) systematically excluded modelling-only or non-experimental research when defining optimal operating windows; (iii) aligned temperature, residence time, particle size, moisture content, and catalyst use under a shared analytical framework; nor (iv) performed a structured comparison between biomass pyrolysis, plastic pyrolysis, and co-pyrolysis using the same selection and synthesis criteria. As a result, the literature currently lacks a methodologically consistent evidence base capable of identifying empirically supported operating ranges across different feedstocks. However, these studies rarely provide a direct, parameter-aligned comparison between biomass and plastic pyrolysis under equivalent operational conditions, nor do they integrate evidence from co-pyrolysis systems in a harmonised manner. As a result, current reviews fall short of elucidating how feedstock type fundamentally alters optimal operating windows, product yield distributions, and quality metrics when assessed under comparable experimental frameworks. This review explicitly addresses this gap by systematically contrasting biomass, plastic, and co-pyrolysis systems using unified operational descriptors.

Here, the present study undertakes a structured synthesis of experimentally reported results to quantitatively evaluate optimal operating conditions for pyrolysis-based waste conversion. Specifically, it analyses the influence of temperature, residence time, feedstock composition (biomass versus plastic and their blends), moisture content, particle size, and catalyst presence on product yield and quality. The objective is to delineate empirically supported operating ranges and parameter interactions that can inform reactor design, process optimisation, and the scalability of pyrolysis systems for waste-to-energy applications.

2. Materials and Methods

2.1. Search strategy and eligibility criteria

A structured bibliographic review agreed upon by the authors and based on PRISMA guidelines for systematic reviews was conducted to identify experimental studies in which optimal operating conditions for waste-to-energy conversion via pyrolysis of biomass or waste residues were determined. The literature search was performed using three major scientific databases Scopus, ScienceDirect, and Google Scholar the latter used as a complementary source to identify peer-reviewed literature and relevant bibliographic material not available in the previously mentioned databases.

Given the known limitations of Google Scholar regarding the inclusion of non-peer-reviewed material, its use was restricted to identifying potentially relevant studies not indexed in Scopus or ScienceDirect. Only documents published in peer-reviewed journals or institutional repositories with explicit experimental validation were retained. Conference abstracts, non-reviewed reports, preprints, and documents lacking a clear methodological description were excluded during the screening stage.

The search considered publications released between 2008 and 2024, a period during which researchers and companies began to develop pyrolysis technologies using diverse methodologies and technical approaches. This temporal window was selected to capture the transition from early-stage exploratory pyrolysis experiments to more mature and optimised waste-to-energy systems, ensuring the inclusion of studies employing modern reactor designs, catalytic approaches, and systematic parameter optimisation.

The studies were searched through combinations of keywords applied to titles, abstracts, and author keywords, such as: waste pyrolysis, pyrolysis operating conditions, pyrolysis parameters, bio-oil yield, catalytic pyrolysis, and co-pyrolysis, among others, using Boolean operators AND and OR. Representative search strings included: (“waste pyrolysis” OR “biomass pyrolysis” OR “plastic pyrolysis” OR “co-pyrolysis”) AND (“operating conditions” OR “process parameters” OR “temperature” OR “residence time”) AND (“bio-oil yield” OR “product distribution”). Equivalent adapted strings were applied consistently across all databases to ensure reproducibility.

2.2. Inclusion and exclusion criteria

In order to maintain a consistent and rigorous approach, only studies that satisfied the following criteria were included: (i) experimental studies of pyrolysis of biomass, plastic waste, or mixed waste streams; (ii) reports providing quantitative values for at least some of the operating parameters of interest (i.e., temperature, residence time, heating rate, particle size, feedstock composition, pretreatment, and/or catalyst use); and (iii) explicit reporting of product yields (bio-oil, biochar, and/or syngas).

In addition, only studies describing a clearly defined experimental setup (reactor type, operating protocol, and measurement methods) and presenting internally consistent yield data were considered. Studies reporting incomplete datasets were included only when key operational parameters and at least one major product yield were available and clearly interpretable.

In order to maintain quality in the selected studies, minimum experimental quality criteria were established for the selection criteria by the authors of each study. All studies must have met a minimum number of criteria: (i) provided a description of the reactor configuration and the detailed operating procedures used for each study; (ii) included at least one quantitative parameter (e.g., temperature, residence time, particle size, use of catalyst or pretreatment) that could be employed to compare the operation of the reactor to that of previous studies; (iii) provided the minimum yield (bio-oil, biochar or gas) from at least one of the studies conducted and (iv) provided an internally consistent mass or yield balance or yield report consistent with the parameters described for each study. Any study that did not have sufficient methodological transparency to allow for interpretation of the operating conditions and yield of the studies was removed from the optimisation synthesis.

Studies were excluded if they (i) were conceptual or narrative reviews, policy or normative documents, modelling or simulation studies without experimental validation, or publications that did not report sufficient quantitative data regarding process conditions and yields. Studies showing irreconcilable inconsistencies between reported operating conditions and product yields were also excluded.

Academic theses were included only when they reported original experimental data not duplicated in peer-reviewed journal articles. In cases where potential overlap with journal publications was identified, only the most complete and methodologically detailed source was retained to avoid duplication.

2.3. Study selection and data extraction

The initial database search produced 64 experimental studies that constituted the core reference set for this review. These studies were screened for relevance based on title and abstract, and full-text analysis was subsequently performed to confirm compliance with the eligibility criteria. The study selection and screening process is presented in the PRISMA flow diagram (Figure 1).

Study selection and eligibility assessment were conducted independently by two reviewers. Discrepancies were resolved through discussion until consensus was achieved, ensuring consistency and minimising selection bias.

Systematic data extraction was conducted for the selected studies, compiling a comparative matrix of variables including feedstock type, particle size, process temperature, residence time, reactor type, pretreatment method, catalyst type and loading, and quantitative yields of bio-oil, biochar, and gaseous products. The data extraction matrix was standardised a priori to ensure uniformity across studies and to facilitate cross-comparison of operational parameters and performance indicators. Collectively, this approach facilitated comparative analysis and the identification of trends, optimal operating ranges, and recurring limitations across different waste types and pyrolysis configurations.

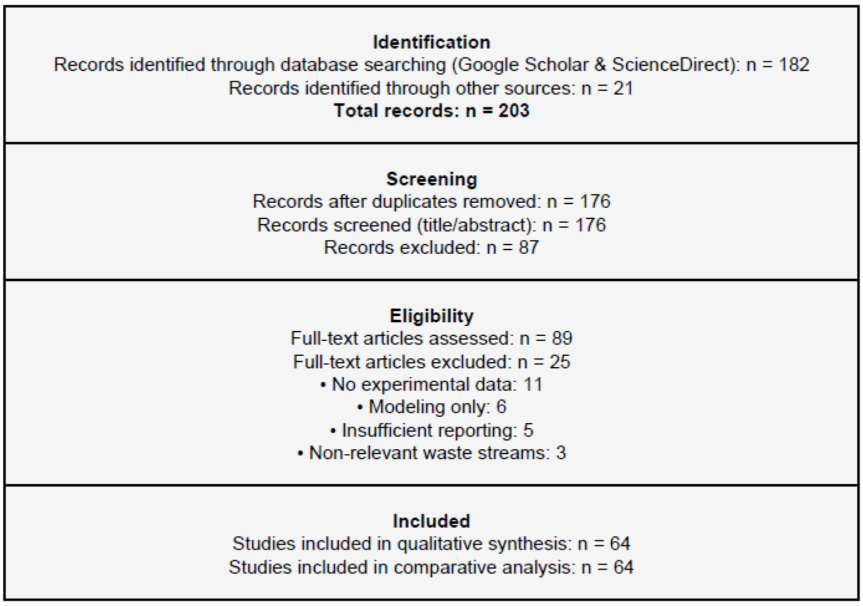
Studies with partial methodology flaws (e.g., measurement of particle size was missing, yield basis was not identified, etc.) were included for the specific dimensions for which they provided reliable information only. They were not included in the identification of parameters that define optimum operating windows, but were included in the analysis of qualitative trends so that no valid experimental data will have been lost due to inclusion of studies with methodological flaws.

2.4. Data synthesis and analysis

Extracted data were analysed using a qualitative comparative approach, based on structured narrative synthesis, to identify recurrent operational patterns and experimentally confirmed optima. Rather than conducting a statistical metaanalysis, which was precluded by heterogeneity in experimental designs and reporting formats, the synthesis focused on identifying consistent patterns, divergences, and boundary conditions across studies.

Only those studies that ranked as having met the most minimum experimental quality criteria, while simultaneously providing complete operational descriptive information, were used when determining the "optimal operating ranges" for an individual operating parameter. Incomplete methodologically reported studies were analysed separately from complete studies and were not included as part of the analysis to estimate parameter-specific optima. This methodology created operating windows that were reflective of the maximum abundance and consistent with the most robust and repeated experimental evidence available, whilst providing general observations across the literature.

This approach enabled systematic comparison of how variations in temperature, residence time, feedstock composition, and catalyst use influence product yield and quality, thereby supporting evidence-based conclusions regarding optimal operating windows and their associated limitations.



Identification
Records identified through database searching (Google Scholar & ScienceDirect): n = 182
Records identified through other sources: n = 21
Total records: n = 203

Screening
Records after duplicates removed: n = 176
Records screened (title/abstract): n = 176
Records excluded: n = 87

Eligibility
Full-text articles assessed: n = 89
Full-text articles excluded: n = 25
- No experimental data: 11
- Modeling only: 6
- Insufficient reporting: 5
- Non-relevant waste streams: 3

Included
Studies included in qualitative synthesis: n = 64
Studies included in comparative analysis: n = 64

Figura 1 PRISMA Flow Diagram.

3. Results

This section reports the evidence extracted from the reviewed studies, focusing on operational conditions and product yields. Basic conceptual descriptions are kept brief and are only used to contextualize the extracted findings.

Pyrolysis is a thermal decomposition process of waste conducted at temperatures ranging from 300 to 1000 °C under anoxic conditions (Gosgot et al., 2021). The main products of this process are solids (biochar), liquids (bio-oil), and gases (CO_2, CO, H_2, among others) (Gosgot et al., 2021; Aboelela et al., 2023).

Some Key Change processes that occur during Pyrolysis include: (1) Heat Transmittance between an Indicated Source, and (2) the initiation of pyrolysis reactions as temperature increases, leading to thermal decomposition, through which volatile compounds and carbonaceous solids are generated from biomass (Babu & Chaurasia, 2003). Considering residence time, pyrolysis processes can be classified as shown in Table 1.

3.1. Types of pyrolysis

Table 1 compares diverse types of pyrolysis according to their residence time, operating temperature, and the percentage distribution of the products generated: bio-oil, biochar, and gas. It is remarked that the greater the temperature, the quicker the process (i.e., shorter times of operation). For example, torrefaction, which is the slowest process and operates at the lowest temperatures (below 300 °C), produces biochar (approximately 75%), which makes it ideal for applications focused on soil improvement or carbon storage. In contrast, fast pyrolysis and flash pyrolysis, operating at higher temperatures and very short residence times, prioritize the production of bio-oil and gas, although in the case of flash pyrolysis, data on product yields are not reported in detail.

This behavior is explained by the thermal decomposition kinetics of biomass. In faster processes operating at higher temperatures, the formation of volatile compounds is favored, which explains the high bio-oil yields reported for fast pyrolysis (around 75%). These methods are preferable when the objective is to obtain liquid fuels as substitutes for petroleum-derived products. On the other hand, when the aim is to conserve carbon in solid form, torrefaction or slow pyrolysis are more suitable.

Thus, the choice of the pyrolysis type depends on the final purpose: energy production, carbon conservation, or the generation of chemical by-products.

Table 1 Types of pyrolysis and their characteristics.

Types of pyrolysis	Residence time	Temperature (°C)	Bio-oil	Biochar	Gas
Torrefaction	Greater than 2 hours	Less than 300	20%	75%	5%
Slow	Minutes to hours (5 to 30 minutes)	300 - 550	30%	35%	35%
Fast	From 1 to 10 seconds	425 – 600	75%	12%	13%
Flash	0.5 seconds or less	750 – 1000	-	-	-

Source: Castells & Velo (2012) and Aboelela et al. (2023).

3.2. Parameters of pyrolysis process

Among the parameters that affect pyrolysis are temperature, particle size, characteristics of the biomass or waste, pressure, and the presence of catalysts (Aboelela et al., 2023). Akhtar and Saidina (2012) mention that the operating parameters of the pyrolysis process directly influence the composition and yield of the generated products, and these parameters can be classified into (a) parameters of high influence, such as temperature and biomass type, and (b) parameters of moderate to low influence (pressure, catalysts, or the presence of minerals or metal ions, etc.).

To synthesise the evidence on “optimal conditions”, the reviewed experimental studies were standardised whenever possible by reporting yields on the basis stated by each author (dry basis, wet basis, or not specified). When the yield basis was not stated or when key operational descriptors were missing (marked as ND), the study was retained only for the yield comparison it enabled, but it was excluded from defining parameter-dependent “optimal windows”. Such cases are discussed separately to avoid biasing the optimisation synthesis.

Yield reporting heterogeneity is one of the significant methodological limitations for evaluating the available evidence. For instance, dry-basis yield versus wet-basis yield will have a drastic effect on the liquid, gas, or solid fractions estimated for each case when the moisture content of the feedstock is not stated clearly. For this reason, direct numeric comparisons between the reported yields from the studies will be done with extreme caution, and the determination of which studies provide support for optimal operating ranges will be limited to studies which have a clearly defined yield base and/or comparable yield bases across studies.

In Table 2, studies containing N.D. for particle size were not excluded because they still contribute valid evidence for temperature–yield behaviour and feedstock-dependent performance. However, they were not used to infer particle-size optima and were not weighted in any synthesis that requires complete operational descriptors.

Table 2 Optimal parameters and maximum performance obtained in the reviewed research.

Author (Year)	Feedstock	Particle size	Temp (°C)	Bio-oil (%)	Biochar (%)	Gas (%)
Penedo et al. (2008)	Cane bagasse	0.76 mm	440.81	61.28	—	—
Arteaga et al. (2012)	African palm kernel	< 1 mm	600	23.30	—	—
Mancheno et al. (2016)	Polystyrene	N.D.	400	68.55	—	—
Iglesias et al. (2020)	Eucalyptus branches	N.D.	400	—	30.80	—
Guerrero et al. (2021)	Cane bagasse + 10% catalyst	1.084 mm	500	41.00	—	—
Nawaz & Kumar (2021)	Mustard stalk	0.21–0.25 mm	500	44.69	—	—
Lara (2023)	Chestnut shell (no pretreatment)	N.D.	500	30.10	35.50	34.40
Lara (2023)	Chestnut shell (pretreatment)	N.D.	500	6.70	55.20	38.10
Ulpo et al. (2023)	Pruning + plastic waste	2–3 mm	450	73.00	—	—
Farobie et al. (2024)	40% U. lactuca + 60% PET	0.25 / 0.5 mm	500	37.91	—	—
Mendoza (2016)	Expanded polystyrene	N.D.	450	58.34	—	—
Mendoza (2016)	Polypropylene	N.D.	450	74.60	—	—
Mendoza (2016)	Low-density polyethylene	N.D.	450	34.00	—	—
Mendoza (2016)	High-density polyethylene	N.D.	500	18.20	—	—
Caicedo & Cumba (2021)	Banana industry plastic waste	N.D.	400	58.34	—	—
Villegas & Zamudio (2022)	Expanded polystyrene	6–10 mm	550	97.80	—	—

Note: N.D. means “No defined”.

Based on the reviewed information, it is identified that pyrolysis can be used with diverse types of materials, ranging from plant waste to xenobiotic materials such as plastics. In general, biomass can be of plant or animal origin, the former containing lignocellulosic materials, such as cellulose, hemicellulose, and lignin (Aboelela et al., 2023). However, it is important to mention that the cellulose content of the biomass must be high, while the lignin content must be low, as high lignin content reduces process efficiency (Sharma et al., 2025). Another alternative is co-pyrolysis, where diverse types of solid waste are mixed, as in the case of combining plastic polymers with biomass, which improves the liquid fraction of the process (Czajczyńska et al., 2017).

The products obtained from the pyrolysis of plastics depend on the type of raw material used. Each type of plastic, such as polyethylene (PE), polypropylene (PP), or polystyrene (PS), has a different chemical composition, which directly influences the type and proportion of products generated during the process. Operating variables must be adjusted to the specific characteristics of each polymer, as a condition that favors bio-oil production in one type of plastic may not be equally effective in another (Sharuddin et al., 2016). In the context of pyrolysis treatments applied to mixed plastics, it is important to investigate reactions that consist of diverse types of plastics in varying proportions, as this method best represents the heterogeneous nature of real plastic waste. In this case, it has been established that even minor amounts of polyethylene terephthalate (PET) within mixed plastics reduce the effectiveness of the process, particularly regarding bio-oil production (Gebre et al., 2021; Genuino et al., 2023). Hence, the design of plastic mixtures for pyrolysis should take not only into consideration the amount of each plastic present, but also the thermal and chemical compatibility of the materials to yield valuable products (e.g., bio-oil).

Co-pyrolysis is an active method for the joint valorization of biomass waste and plastic waste, thereby taking advantage of synergistic interactions when processing biomass with plastics, while improving the yield and quality of bio-oil. Research shows that by adjusting the ratios of biomass waste and plastic waste, it is possible to optimize the production of the liquid fraction and minimize undesired residual by-products through co-pyrolysis (Parra et al., 2019; Gurevich et al., 2015). In general, the bio-oil yield in fast pyrolysis of biomass ranges between 40% and 75% on a dry-weight basis, and is strongly influenced by parameters such as biomass type, particle size, heat transfer mechanism, heating rate, and residence time, which typically ranges from 1 to 10 seconds (Akhtar & Saidina, 2012).

Other aspects linked to the substrate or waste that affect process performance are pretreatments and particle size. According to the study by Lara (2023), pretreatment by drying at 105 °C allows the production of a greater quantity of bio-oil; among pretreatments, grinding and drying stand out (Gosgot et al., 2021). Regarding the analyzed studies that report particle size, the range extends between 0.21 and 10 mm. In pyrolysis processes, small-sized particles are preferred due to their uniformity and the ease with which they are heated; and depending on the type of reactor, different maximum particle sizes are established for optimal operation. For rotating cone reactors, particles should not exceed 20 mm; in fluidized bed reactors, the maximum allowed size is 2 mm, whereas in circulating fluidized bed reactors, particles must be smaller than 6 mm (Aboelela et al., 2023). Regarding pretreatments, Akhtar and Saidina (2012) pointed out that fast pyrolysis requires dry feedstock with a moisture content below 10%, and after crushing, particle size should range from 2 to 5 mm.

Furthermore, temperature is identified as the most studied variable in pyrolysis processes, as it directly influences the distribution and yield of the generated products, such as bio-oil, biochar, and gases. In the analyzed research, the evaluated temperature range lies between 400 and 600 °C, an interval considered critical for achieving efficient conversion of the feedstock. The optimal temperature varies depending on the type of material treated: for lignocellulosic biomass, numerous studies have established 500 °C as the most efficient point to produce bio-oil with high energy content and low oxygen content (Neumann et al., 2023; Zhang et al., 2022). In the case of plastic waste composed of polyethylene or polypropylene, lower temperatures around 400 °C are more favorable than higher temperatures, since lower temperatures promote the formation of lighter liquid hydrocarbons with greater economic value (López et al., 2023; Miskolczi et al., 2021). Conversely, when pyrolyzing mixtures of biomass and plastics, the most favorable temperature occurs at an intermediate level of around 450 °C, which enables constructive thermal interactions between the two feedstocks, thereby increasing liquid yields while limiting solid residue formation (Chen et al., 2022).

The temperature-dependent yield of these products should be treated as a range of conditional yields. Differences in yield reporting bases, moisture content and methods for recovering condensate between studies mean yields reported on different bases are not directly comparable to each other. The variation in these characteristics can greatly affect the measured proportion of liquid products, especially for biomass derived biomass systems where the water content can represent a substantial portion of the bio-oil.

Aboelela et al. (2023) further reinforce this observation by indicating an optimal temperature range between 400 and 500 °C to achieve high yields of bio-oil during powdered pyrolysis. Temperatures above this range favor gas formation at the expense of liquid products, while temperatures below this range do not adequately decompose polymers or lignocellulosic components. In this line, García-Núñez et al. (2023) reported that higher bio-oil yields and lower coke formation occurred when pyrolyzing agro-industrial waste at 500 °C. Lastly, researchers such as Wang et al. (2022) demonstrated that fine temperature control is necessary to avoid over-cracking volatile compounds, especially in mixed systems. It is evident that temperature not only represents the most influential variable but also the most critical factor in designing and optimizing pyrolysis processes at both laboratory and industrial scales, due to its direct influence on thermochemical reactions, vapor residence time, and product selectivity.

Catalysts are a crucial variable that significantly affects efficiency and selectivity in pyrolysis processes, as reported by Guerrero et al. (2021). The presence of catalysts increases bio-oil production through modification of thermal decomposition pathways that favor liquid compound formation while reducing gas and solid by-products. Catalysts reduce the activation energy of depolymerization and thermal cracking reactions, improving operation at lower temperatures and shorter reaction times. This enhances both efficiency and conversion rates of biomass or plastic waste into liquid products with higher commercial value, such as bio-oils (Aboelela et al., 2023).

Several recent studies also suggest that acidic or zeolitic catalysts (e.g., HZSM-5, Al-MCM-41, and metal-modified zeolites) improve bio-oil quality by decreasing oxygen content and increasing aromatic hydrocarbon fractions (Li et al., 2023; Singh & Ruj, 2022). For example, Wang et al. (2023) showed that using HZSM-5 during the pyrolysis of lignocellulosic waste resulted in an increase of approximately 35% in aromatic compound yield at temperatures as low as 400 °C. Rashid et al. (2022) additionally identified that metallic catalysts, such as Ni/Al_2O_3 and Fe–Zn–Zr catalysts, not only promote bio-oil deoxygenation but also reduce coke formation, thereby extending reactor lifespan. Moreover, catalyst use enables greater selectivity toward specific bio-oil fractions, such as liquid fuels or industrial chemical precursors, depending on catalyst structure and acid–base properties. This enhances process performance and supports adaptability to diverse feedstocks. Thus, proper catalyst design and selection represent a key area for advancing waste-to-energy technologies through pyrolysis (Sudalaimuthu et al., 2024).

In addition to yield, bio-oil quality is also an important consideration influenced by feedstock type and operating conditions. When plastics are used as feedstock, bio-oils tend to be richer in long-chain hydrocarbons, exhibit higher calorific values, and possess properties closer to conventional fuels, making them suitable for energy and petrochemical applications. In contrast, biomass-derived bio-oils contain higher proportions of oxygenated compounds, which implies lower thermal stability and the need for further upgrading treatments, such as hydrogenation. In co-pyrolysis systems, interactions between biomass and plastics have been shown to improve oil quality by reducing oxygen content and increasing the yield of desirable liquid fractions. These synergies not only enhance process efficiency but also provide a technologically promising route for sustainable management of mixed wastes, contributing to a circular, low-carbon economy. In summary, it is identified that increasing specific process parameters favors the formation of particular products (Table 3).

Table 3 Parameters and generated products.

Parameters	Biochar	Bio oil	Gas
Temperature (Increases)	Decreases	Increases until a given value	Increases
Heating Rate (Increases)	Decreases	Increases	Increases
Particle size (Increases)	Increases	Increases	Decreases
Residence Time (Increases)	Decreases	Increases	Increases

Source: Adapted from Tamagno et al. (2025).

Depending on the type of product to be obtained, operating conditions can be modified to achieve optimum yields. Experimental evidence suggests that biochar yields are favored under the following conditions: lower temperatures, slow heating rates, shorter residence times, and larger particle sizes; whereas optimal bio-oil yields are obtained at temperatures close to 500 °C, with fast heating rates, relatively longer residence times, and particle sizes smaller than 2 mm (Tamagno et al., 2025).

4. Discussion

The reported results of the reviewed studies are consistent with pyrolysis being a flexible, robust, and effective means of converting solid wastes into biofuels, with temperature identified as the key factor influencing both yield and the nature of the resulting fractions in the majority of cases. Specific optima are observed to vary; however, as an overarching trend, bio-oils are reported to reach peak yields within the 400–600 °C range. This range is closely linked to the composition of the biomass being thermally treated. For example, when lignocellulosic residues are subjected to pyrolytic conditions, the most favorable temperatures for bio-oil production are around 500 °C (e.g., Neumann et al., 2023; Zhang et al., 2022), whereas in the case of plastic wastes, particularly polyethylene and polypropylene, the optimal temperatures reported in this study are around 400 °C (López et al., 2023; Miskolczi et al., 2021). However, the apparent "optimal temperature" should be interpreted as conditional upon reactor hydrodynamics and the heat-transfer regime: studies conducted in fluidized beds, fixed beds, and batch reactors are not thermally equivalent, and reported optima can shift when vapor residence time, quench efficiency, and secondary cracking are not controlled or not reported. This finding further underlines the versatility of pyrolysis and the role of temperature as a controllable design variable for biofuels derived by this means.

Concerning factors other than temperature, and more closely related to feedstock preparation for pyrolysis, particle size and pretreatments play a decisive role in process efficiency and the extent of devolatilization. If, for example, feedstocks are processed at particle sizes below 2 mm, heat transfer within the reacting material is improved, thereby ensuring more efficient devolatilization, especially in fluidized bed reactors, as reported by Aboelela et al. (2023) and Akhtar and Saidina (2012). Drying pretreatments, for instance, favor improved bio-oil yields by eliminating moisture prior to reactor entry, which would otherwise consume energy during vaporization or be lost through condensation in downstream heat traces, as reported by Lara (2023) for chestnut shell pyrolysis. Nevertheless, the magnitude of these effects is inconsistent across studies because "particle size" often co-varies with reactor type and heating rate: for example, the same nominal size can behave differently depending on bed mixing, internal diffusion limitations, and whether the system is heat-transfer- or kinetics-limited. Similarly, pretreatments may improve apparent yields by reducing water in the condensate, but they can also alter the extent of secondary reactions and the measured mass balance depending on the condensation system and analytical methods employed. This latter finding emphasizes the importance of upstream feedstock preparation in the overall energy recovery process from waste biomass.

The vapor fraction produced during pyrolysis can also be enhanced in both quantity and quality through the use of catalysts during the reaction itself. Reported zeolitic catalysts include HZSM-5 and Al-MCM-41, which catalyze deoxygenation reactions during biomass pyrolysis, resulting in catalyzed bio-oils with lower oxygen content and higher aromatic hydrocarbon fractions (Li et al., 2023; Singh and Ruj, 2022). Metal-based catalysts, such as Ni/Al_2O_3 or Fe–Zn–Zr systems, mitigate coke formation while extending reactor lifespan (Rashid et al., 2022). That said, the extent of catalytic effects is highly variable, as expected in the reviewed literature, and strongly reflects reactor configuration, catalyst loading, and utilization strategies. Critically, this variability is not merely “literature noise” but reflects physical and thermodynamic constraints: catalysts may promote desirable deoxygenation and aromatization reactions, yet they can also intensify cracking and gas formation when vapor contact times are long or catalyst-to-biomass ratios are high. Moreover, catalytic performance is scale-sensitive pressure drop, catalyst deactivation by ash or alkali metals, and heat management become dominant factors at pilot and industrial scales, meaning that laboratory-scale improvements in selectivity may not translate directly without engineered regeneration and robust solids-handling systems.

Another relevant phenomenon concerns the co-pyrolysis of lignocellulosic biomass with plastic waste. Several studies report improvements in liquid yield when adopting blended feedstocks, with biomass plastic mixtures yielding significantly higher liquid fractions, as discussed by Farobie et al. (2024) and Parra et al. (2019). This biomass plastic interaction represents one of the most technically complex aspects and constitutes a key novelty of the present synthesis, as it is governed by coupled reaction pathways rather than simple additive behavior. In co-pyrolysis, hydrogen-rich polymers (e.g., PE, PP, PS) can act as hydrogen donors, partially suppressing the formation of oxygenated fragments from lignocellulosic biomass and shifting the product distribution toward less oxygenated liquids, consistent with the improved liquid yields reported in blended systems. At the same time, the magnitude and even direction of this “synergy” depends strongly on (i) polymer identity and fraction, (ii) mixing intimacy and particle contact, (iii) vapor residence time and quench rate, and (iv) reactor configuration (batch versus continuous; fixed bed versus fluidized bed). Consequently, direct comparisons across studies are only defensible when these descriptors are properly aligned.

However, this synergy does not hold universally. Several studies report that mixing even small amounts of poly(ethylene terephthalate) (PET) with municipal solid waste prior to liquefaction is counterproductive, due to PET’s highly oxygenated structure and low resistance to thermal degradation, which leads to only modest or negligible increases in bio-oil yield (Gebre et al., 2021; Genuino et al., 2023). A key inconsistency emerging from the reviewed evidence is that PET-containing blends often underperform, even when other plastics enhance liquid yields. This behavior can be explained by PET’s oxygenated backbone and its tendency to generate oxygen-rich intermediates that increase acidity and promote char or coke formation, thereby reducing recoverable liquid yields and accelerating catalyst deactivation when catalysts are employed. Importantly, these limitations are amplified by scale and reactor choice: in systems with longer vapor residence times or inadequate quenching, PET-derived vapors are more prone to secondary reactions such as repolymerization and coking, whereas short-residence systems with rapid condensation may partially mitigate these effects. Therefore, the benefits of co-pyrolysis cannot be generalized and must be interpreted as conditional upon polymer composition particularly PET content as well as residence-time temperature history and reactor-scale constraints.

Overall, the discussion indicates that reported “optima” and “synergies” in co-pyrolysis should be framed as reactor- and scale-dependent operating windows rather than universal setpoints. Future evidence synthesis would benefit from (a) harmonized reporting of yield bases (dry or wet), (b) explicit specification of vapor residence time and quench conditions, and (c) clear scale descriptors (laboratory, bench, or pilot), in order to distinguish intrinsic chemical effects from transport- and scale-driven artifacts.

4.1. Limitations and inconsistencies in the literature

Even though a considerable experimental literature exists on the technique of pyrolysis, several methodological shortcomings arise. Many works discuss the influence of operating parameters individually, often under laboratory-scale conditions and across widely different reactor types, heating rates, and vapor residence times; therefore, yield values and reported optimal conditions are not always strictly comparable. This limitation is directly reflected in the results of the present review, where reported optimal temperatures (e.g., 400–500 °C for plastics versus ~500 °C for lignocellulosic biomass) can only be interpreted as conditional ranges rather than absolute optima, due to the lack of alignment in reactor configuration and vapor-phase handling across studies. Inconsistent reporting of important parameters such as heating rate, catalyst-to-feed ratio, or vapor residence time further complicates comparison and synthesis across studies, and contributes to seemingly contradictory performance results. For example, variations in reported bio-oil yields for similar feedstocks could not always be attributed to intrinsic material properties, but rather to unreported differences in quench efficiency or secondary cracking conditions.

Moreover, most studies reported in the literature remain at a laboratory or pilot scale, with limited discussion of the challenges associated with process scale-up. This gap is evident in the reviewed studies on catalytic pyrolysis and co-pyrolysis, where improvements in liquid yield or quality are often demonstrated at bench scale, without adequately addressing catalyst deactivation, pressure drop, or solids-handling constraints that dominate at larger scales. At larger scales, heat and mass transfer limitations, catalyst deactivation, feedstock heterogeneity, and operational stability become far more critical issues, which are often insufficiently addressed in the literature. As a result, several trends identified in this review, particularly those related to catalyst-enhanced bio-oil quality and biomass–plastic synergistic effects, should be interpreted cautiously when extrapolating beyond laboratory conditions.

Additionally, the gap between laboratory research and industrial implementation represents a major hurdle to the widespread adoption of pyrolysis as a waste-to-energy solution. Overall, it is clear that pyrolysis is a technically feasible route for obtaining energy from solid waste, as well as an environmentally favorable one, but that improvements are needed in standardization practices and in the integration of experimental findings with process engineering and industrial feasibility analyses. Harmonized protocols, systematic comparison of catalyst systems, and pilot-scale investigations should feature more prominently in future studies.

In contrast, the limitations of the present study are primarily associated with the heterogeneity and incompleteness of the available data rather than with its own experimental design. As discussed in the Results section, several studies lacked full reporting of key operational parameters (e.g., particle size or yield basis), which restricted their inclusion in the identification of parameter-dependent optimal operating windows. To mitigate this, such studies were analysed only for the dimensions they reliably informed (e.g., temperature–yield relationships) and were excluded from syntheses requiring complete descriptors. Consequently, while this review provides a structured comparison of trends and conditional optima, it does not claim to establish universal operating setpoints, but rather evidence-based ranges contingent upon reactor type, feedstock composition, and scale.

5. Conclusions

This review shows that pyrolysis is a technically appropriate and environmentally sound method for the energy recovery of urban, industrial, and agricultural solid waste. Under an anoxic environment and within a temperature range of 400–600 °C, pyrolysis enhances the value of its main products bio-oil, biochar, and syngas thereby supporting waste valorisation and improved resource-use efficiency within a circular economy framework.

Rather than identifying a single universal optimum, this review demonstrates that temperature remains the dominant controlling parameter in pyrolysis, but its optimal range is strongly conditional on feedstock type and reactor configuration. For lignocellulosic biomass, the reviewed evidence consistently indicates that temperatures around 500 °C favour bio-oil production under controlled conditions, whereas plastic-derived feedstocks tend to achieve higher liquid-to-solid ratios at comparatively lower temperatures, typically between 400 and 450 °C. Reported high liquid yields for plastics should therefore be interpreted as context-dependent outcomes, influenced by polymer composition, reactor design, and vapour-phase handling, rather than as generalisable performance benchmarks. Co-pyrolysis of biomass and plastic wastes shows potential to improve liquid yields and fuel properties; however, the magnitude and direction of such synergies depend on mixture composition, especially the presence of oxygenated polymers, and on residence time temperature histories.

The results further indicate that, from a technical and industrial perspective, feedstock preparation (including particle size reduction and drying), reactor configuration, and catalyst selection exert a significant influence on process efficiency. Zeolitic and metal-based catalysts, particularly those containing Ni or Fe, have been shown to promote deoxygenation reactions and suppress undesirable gas formation under specific conditions. Nevertheless, the review highlights that catalytic benefits are highly sensitive to catalyst loading, deactivation mechanisms, and scale-related constraints, which limits direct extrapolation from laboratory results to industrial applications. Although liquid bio-oil yields exceeding 70% have been reported under specific fast pyrolysis conditions, these values correspond to controlled experimental scenarios and should not be interpreted as representative performance benchmarks for all feedstocks, reactor configurations, or scales of operation.

The main contribution of this review lies in its systematic identification of conditional operating windows, rather than absolute optima, across biomass, plastic, and co-pyrolysis systems. By harmonising experimental evidence and explicitly accounting for incomplete reporting, this study provides a structured framework for interpreting variability in reported yields and performance trends. Practically, this contribution supports the design of future experimental studies, facilitates more consistent comparison of pyrolysis performance across feedstocks, and provides a methodological basis for bridging laboratory research with pilot-scale and industrial development.

Future work should therefore focus on refining optimisation strategies to facilitate the transfer of laboratory-scale findings to practical implementation. Key priorities include the standardisation of experimental protocols, explicit reporting of vapour residence time and yield bases, evaluation of long-term catalyst stability, pilot-scale validation under realistic feedstock heterogeneity, and integrated techno-economic and life-cycle assessments. Consequently, the present review should be interpreted as providing evidence-based operating ranges and methodological guidance rather than prescriptive design values for industrial deployment. The evidence synthesised in this review offers a robust foundation for both experimental design and applied development, supporting informed decision-making by researchers, industry stakeholders, and policymakers in addressing the urgent need for sustainable management of mixed waste streams through low-emission waste-to-energy pathways.

6. Declarations

6.1. Ethical considerations

Not applicable.

6.2. Use of artificial intelligence (AI)

The authors declare that no generative artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript.

6.3. Conflict of interest

The authors declare no conflicts of interest.

6.4. Funding

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