Journal of Materials Science and Chemical Engineering, 2026, 14(11), 20-41
https://www.scirp.org/journal/msce
ISSN Online: 2327-6053
ISSN Print: 2327-6045

Meta-Analysis of Bio-Char, Bio-Oil, and Gas Yields of Different Types of Straw under Different Carbonization Conditions

Lianfa Li[1*], Yaxin Li[2]

[1]Taigang Technology Center, Taiyuan, China
[2]School of Chemical Engineering, Dalian University of Technology, Dalian, China
Email: *lilianfa@cshaoteng.com, lyx07@mail.dlut.edu.cn

How to cite this paper: Li, L.F. and Li, Y.X. (2026) Meta-Analysis of Bio-Char, Bio-Oil, and Gas Yields of Different Types of Straw under Different Carbonization Conditions. *Journal of Materials Science and Chemical Engineering*, **14**, 20-41.
https://doi.org/10.4236/msce.2026.1411002

Received: September 21, 2026
Accepted: November 13, 2026
Published: November 16, 2026

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Abstract

Straw is a large-scale and widely distributed agricultural biomass. On the one hand, its disposal poses challenges to local governments. On the other hand, its resource utilization is crucial for achieving agricultural carbon neutrality and the circular economy. Though some individual studies have paid attention to the carbonization mechanism of single or several types of straw, a meta-analysis study or systematic literature review on this aspect has not been reported yet. Therefore, this research aims to explore the bio-char, bio-oil, and gas yields of different types of straw under different carbonization conditions using meta-analysis. It extracts data from 11 studies, published between 2015 and 2026. Though the meta-analysis has issues with heterogeneity and publication bias due to the small sample size, it addresses a meaningful and practical topic and draws several conclusions: 1) there is a significant statistical difference in the average bio-char, bio-oil, and gas yields of the selected types of straw; 2) carbonization conditions (types of straw, temperature, heating rate, retention, and atmosphere) have impacts on the bio-char, bio-oil, and gas yields; 3) bio-char, bio-oil, and gas yields are the result of the combined effect of multiple factors representing the overall outcome. Thus, this research generates the hypothesis that it provides a practice guide for industry and research institutions to formulate targeted carbonization plans based on different types of straw, in particular by making good use of the traditional tile kiln and charcoal kiln.

Keywords

Meta-Analysis, Bio-Char, Bio-Oil, And Gas Yields, Carbonization Conditions, Pyrolysis, Forest Plot

1. Introduction

Straw is a large-scale and widely distributed agricultural biomass, and its resource utilization is crucial for achieving agricultural carbon neutrality and the circular economy. As we all know, China is an agricultural country that generates approximately 1 billion tons of various agricultural waste materials annually, such as crop stalks and weed stalks. Among these, the waste materials from major crops like rice, wheat, corn, sorghum, rapeseed, cotton, and beans account for over 85% of the total, while weed stalks make up about 10% [1]. They are a rich and renewable biomass resource, containing large amounts of cellulose, hemicellulose, and lignin. They can be carbonized to produce biochar, pyrolysis gas, and wood vinegar (containing wood tar).

Currently, the main methods of handling straw in China are open-air burning, crushing and returning to the field, and random stacking. Both open-air burning and crushing and returning to the field have caused issues. On the one hand, open-air burning and random stacking lead not only to a significant waste of biomass resources, but also to a series of environmental problems such as air pollution [2]. On the other hand, crushing and returning to the field affects crop growth and increases pest risks, which results in increased farming costs [3]. These methods restrict the sustainable development of agriculture. To address them, China has developed strategies for straw utilization, including carbonization. Bio-char, bio-oil, and gases, as core indicators for measuring the efficiency of straw carbonization, directly reflect the degree to which straw is converted into these products. Their yields are not only closely related to the composition of the straw itself (such as the contents of cellulose, hemicellulose, and lignin), but also are influenced by various process conditions such as carbonization temperature, insulation time, heating rate, and carbonization atmosphere.

Pyrolysis is a feasible technology, with a carbonization temperature range of 250˚C - 750˚C, which transforms organic material into a value-added product (such as bio-char, bio-oil, and pyrolysis gas), minimizing the problems in the combustion process of agricultural straw. It is considered one of the most interesting processes for biomass thermochemical conversion, as it is a sustainable and Earth-friendly approach. It is usually divided into flash, fast, and slow pyrolysis, and fast and slow pyrolysis have been widely applied in industry. While fast pyrolysis increases the amount of generated bio-oil and gases and produces less bio-char, slow pyrolysis produces larger portions of bio-char and gases at longer retention [4].

Meta-analysis is a statistical method that systematically integrates the results of multiple independent studies. By combining the data from multiple studies with a similar research objective or research topic, it can effectively reduce the sampling error and random error of a single study, thereby enhancing the reliability and generalizability of the research conclusions [5]. A meta-analysis study on the bio-char, bio-oil, and gas yields ("Bio-char," "Bio-oil," and "Gases" are their measurements, which will be used as variables in quantitative data analysis) of different

types of straw under different carbonization conditions has not been reported yet. This research narrows the research gap. It uses a meta-analysis method to systematically integrate relevant research data from both domestic and international sources, mainly from international sources, quantifying the effects of different types of straw (rice straw, wheat straw, corn straw, sorghum straw, rape straw, cotton straw, and soybean straw) and carbonization conditions (carbonization process, carbonization temperature, insulation time, heating rate, and carbonization atmosphere) on Bio-char, Bio-oil, and Gases. It provides a scientific basis and theoretical support for optimizing the straw carbonization process, the efficient preparation of bio-char bio-oil, and gases, and the utilization of straw resources.

2. Materials and Methods

2.1. Data Collection

The related studies were searched using the search engine or open databases, https://cn.bing.com/, https://xueshu.baidu.com/, https://www.sciencedirect.com/, and https://kns.cnki.net/. The English search keywords, including straw, carbonization rate/Bio-char, Bio-oil and Gases, pyrolysis, rice straw, wheat straw, corn straw, sorghum straw, rape straw, cotton straw, bean straw, and soybean straw were used. By using the "keyword combination search" method, different types of straw and keywords related to Bio-char, Bio-oil, and Gases/bio-char, bio-oil, and gases yields were combined to ensure that all relevant research literature was retrieved and to ensure the comprehensiveness and representativeness of the retrieved data. The first step was to conduct a preliminary search using the aforementioned databases and keywords and collect all relevant literature. The second step was to read the titles, abstracts, and full texts of the literature based on the inclusion criteria and exclusion criteria (**Table 1**) and select the relevant literature that are related to the research topic of this study (at least one type of straw with data on carbonization conditions and bio-char, bio-oil, and gas yields), following the PRISMA flow chart [6] in **Figure 1**. The final step was to extract the data on carbonization conditions and bio-char, bio-oil, and gas yields as well as the arguments on the carbonization mechanisms.

Table 1. The inclusion criteria and exclusion criteria.

Items	Inclusion criteria	Exclusion criteria
Publication date	Within 2015-2026	Published before 2015
Language	In English	In non-English
Type	Journals and research papers	Other types (such as review, news)
Full-text	Full-text accessible	Full-text inaccessible
Topics	Rice straw, wheat straw, corn straw, sorghum straw, rape straw, cotton straw, bean straw, or soybean straw used as material	Other material is used, without rice straw, wheat straw, corn straw, sorghum straw, rape straw, cotton straw, bean straw, or soybean straw as material

Continued

Key content	Including the straw carbonization experiment, clearly reporting the carbonization conditions (such as carbonization temperature, holding time, heating rate, and carbonization atmosphere, at least one of which) and the corresponding Bio-char, Bio-oil, and Gases/bio-char, bio-oil, and gases yield data.	No reports of the carbonization conditions (such as carbonization temperature, holding time, heating rate, and carbonization atmosphere, at least one of which) and the corresponding Bio-char, Bio-oil, and Gases/bio-char, bio-oil, and gases yield data. The carbonization process adopted is very complex (such as the addition of catalysts and modification treatments)

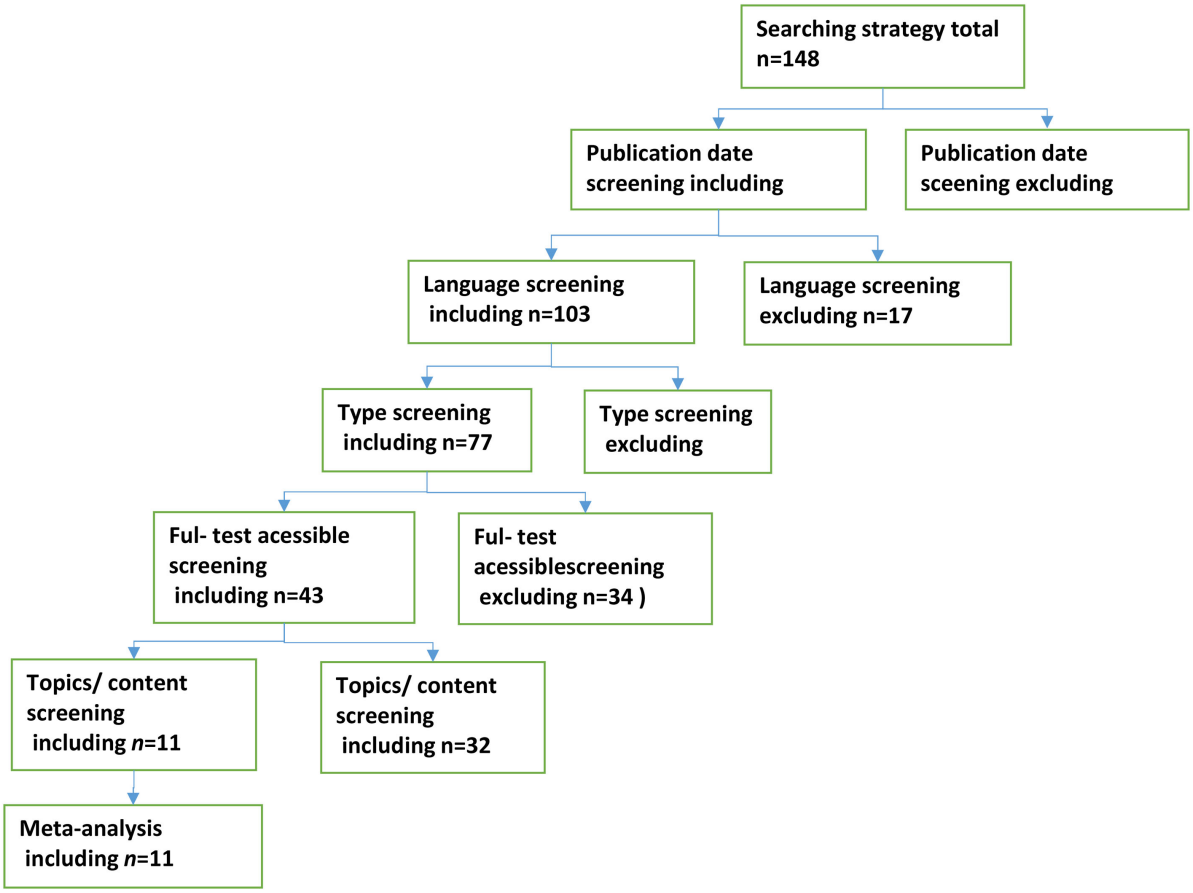


Figure 1. The PRISMA flow chart of the literature.

2.2. Data Processing and Data Analysis

A random-effects model was applied to assess the impacts of carbonization conditions (such as carbonization temperature, holding time, heating rate, and carbonization atmosphere on the yields of bio-char, bio-oil, and gases. Bio-char, Bio-oil, and Gases of straws (in percentage) with standard errors or 95% confidence interval (95% CI) were chosen as the effect size. However, some studies had reported them with standard errors, some reported them with 95% CI, and some reported them with variances. Thus, some studies lacked standard errors. To conduct the meta-analysis, 95% CI and variances were transformed into standard errors and the lacking values were filled with an imputation approach, such as Ex-

pectation-Maximization resampling and linear regression. The meta-analysis was conducted using Stata 18 software, including the forest plot, heterogeneity, and publication bias. When making the forest plots, bio-char, bio-oil, and gas yields were used as the effect-size, respectively. For per effect-size, a sensitivity analysis was conducted.

3. Results

3.1. Data Overview

In total, 11 studies were selected, covering corn straw [7] [8], sorghum straw [9] [10], wheat straw (including mixed wheat straw) [11] [12], castor straw [13], cotton straw [14], rice straw (including dry rice straw and wet basis rice straw) [15] [16], soybean straw [17]. In total, there are 113 lines of records in the original extracted dataset, covering different temperatures, holding times, heating rates, and carbonization atmospheres. A prespecified rule was applied that retains all eligible conditions, ensuring that various temperatures, holding times, heating rates, and carbonization atmospheres were covered as much as possible while accounting for within-study dependence. However, it should be noted that selecting one of 113 extracted records from each study can materially bias the pooled yields.

3.2. Forest Plot and Combined Effect Size Analysis

The forest plots in **Figures 2-4** show Bio-char of different types of straw (as for the forest plots of Bio-oil, and Gases of different types of straw, please refer to Supplementary **Figures S1-6**). There was a significant difference in their averages for corn straw, sorghum straw, wheat straw, castor straw, cotton straw, rice straw, and rape straw ($p < 0.01$), and the overall Bio-char was 33.68% with 95% CI = (24.29%, 43.08%). In terms of Bio-char, the following are the combined effect sizes: corn straw, 28.82, 95% CI = (26.24%, 31.41%), sorghum straw, 25.99%, 95% CI = (17.78%, 34.19%), wheat straw, 26.33%, 95% CI = (25.02%, 27.64%), castor straw, 50.56%, 95% CI = (48.01%, 53.11%), cotton straw, 48.89%, 95% CI = (45.77%, 52.01%), rice straw, 22.14%, 95% CI = (−4.68%, 48.97%), and soybean straw, 68.87%, 95% CI = (57.89%, 79.85%), which were obtained from the subgroup analysis. There were no reports on barley straw, rape stalk, and millet straw after re-sampling. It can be concluded that bio-char yield of soybean straw ranks the top, followed by that of castor straw, with the yields of rice straw and sorghum straw located at the bottom. It should be noted that the studies on soybean straw have a relatively small sample size (n = 1). The results might be questionable and need further exploration or simulation using ASPEN. When it comes to Bio-oil, the yield of sorghum straw ranks the top and that of cotton straw ranks at the bottom, whereas castor straw ranks the top and rice straw ranks at the bottom with respect to Gases. As with Bio-char, the results on Bio-oil and Gases might be questionable and need further exploration or simulation using ASPEN.

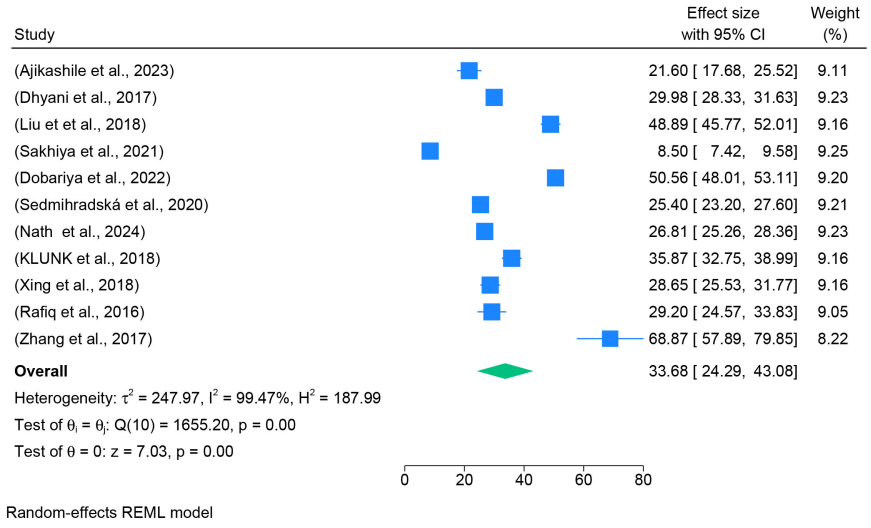


Figure 2. Overall analysis of studies on Bio-char.

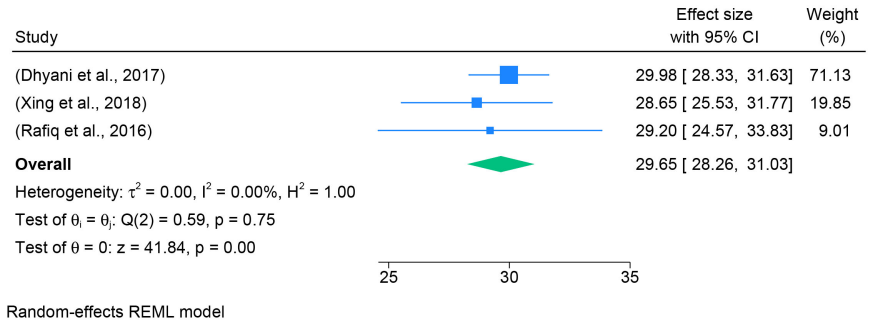


Figure 3. Sensitive analysis of studies on Bio-char.

3.3. Heterogeneity and Publication Bias

The Galbraith plots in **Figure 5** show that the selected studies have some heterogeneity. The overall heterogeneity of literature on Bio-char: τ^2 = 238.73, I^2 = 99.47%, H^2 =188.51; Test of $\theta_i = \theta_j$: Q (11) =1665.52, p = 0.00. The overall heterogeneity of literature on Bio-oil: τ^2 = 286.86, I^2 = 99.86%, H^2 = 691.08; Test of $\theta_i = \theta_j$: Q (6) = 5324.44, p = 0.00. The overall heterogeneity of literature on Gases: τ^2 = 124.70, I^2 = 99.52%, H^2 = 207.292; Test of $\theta_i = \theta_j$: Q (6) = 1733.18, p = 0.00. These parameters indicate that there is substantial heterogeneity (I^2 > 50%) [18]. The key to solving it lies in identifying the source of heterogeneity. Sensitivity analysis (by the elimination method) indicates that several studies have the abnormal values. Additionally, the subgroup analysis shows that some subgroups have no heterogeneity (I^2 = 0%) (such as corn straw in the forest plot of studies on Bio-char), some subgroups have low heterogeneity (I^2 < 50%) (such as wheat straw in the forest plot of studies on Bio-char), while other subgroups still have substantial heterogeneity (I^2 > 50%) (such as rice straw in the forest plot of studies on Bio-char). Both Sensitivity analysis (by the elimination method) and the subgroup analysis show that heterogeneity mainly results from the differences in the type of

straw and the carbonization process parameters, as well as from the randomly resampling.

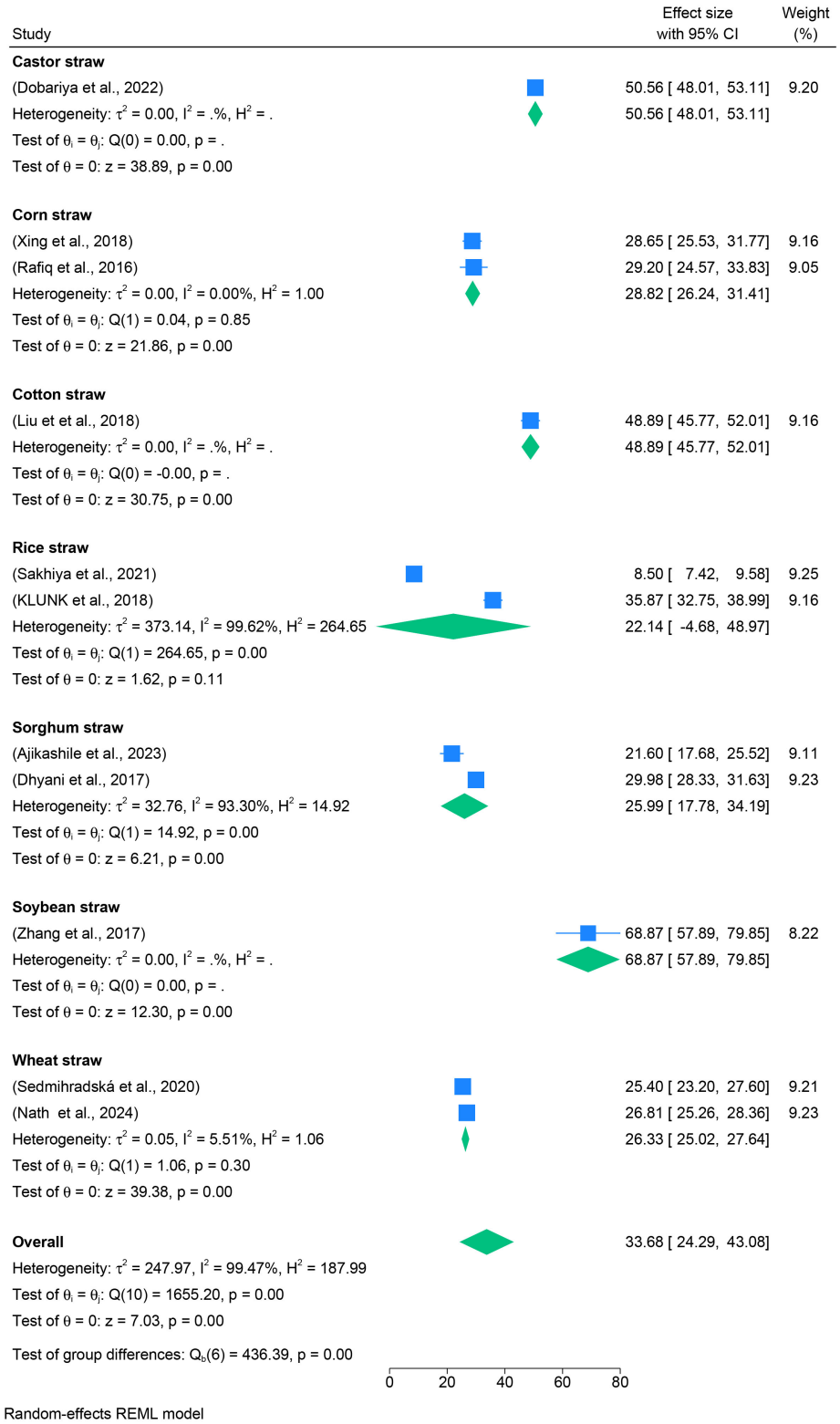
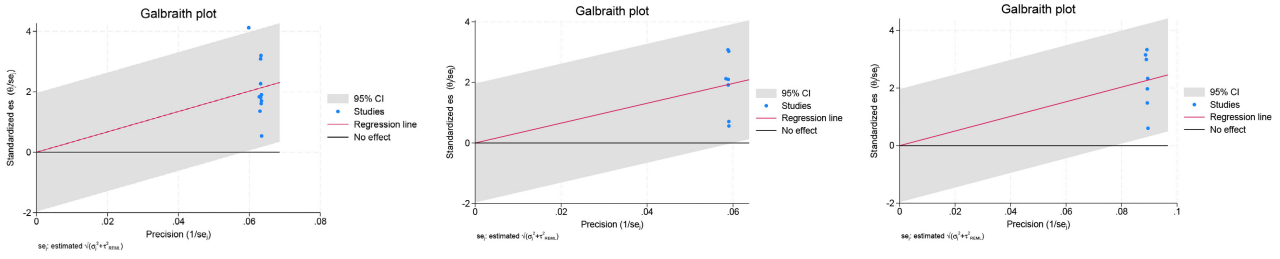


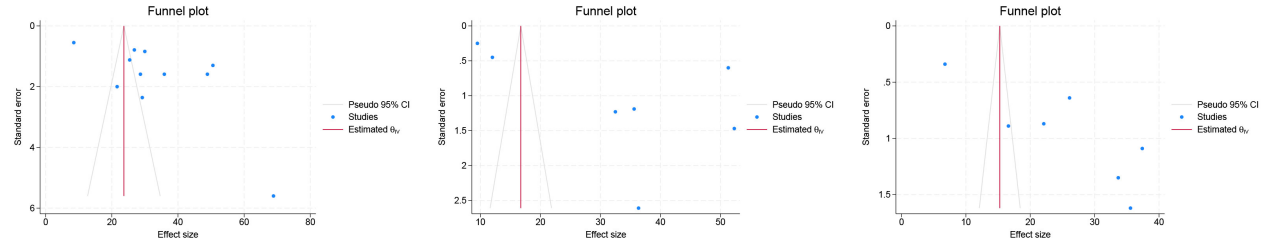
Figure 4. Sub-group analysis of studies on Bio-char.

Funnel plots and Egger's tests are often used to evaluate publication bias [18]. Funnel plots in Figure 6 show that the selected studies have some publication bias. On the other hand, the Egger tests in Table 2 suggest rejecting the null hypothesis of "funnel plot symmetry" (the funnel-plot asymmetry) and suggest the presence of a small-study effect in the data distribution (most $p < 0.05$ [18]). The publication biases in the funnel plots are affected by the small resample size. Small sample-size studies are more prone to the exaggeration of effect sizes. Such a systematic difference is not equivalent to publication bias. To address the issue, future research needs to enlarge the resample size.



(a) (b) (c)

Figure 5. Galbraith plots: (a) Bio-char, (b) Bio-oil, and (c) Gases.



(a) (b) (c)

Figure 6. Funnel plots: (a) Bio-char, (b) Bio-oil, and (c) Gases.

Table 2. Egger test.

Effect size	z	$p > \|z\|$
Bio-char	3.17	0.015
Bio-oil	1.14	0.2525
Gases	3.25	0.001

3.4. The Influence of Carbonization Conditions on Bio-Char, Bio-Oil, and Gases

Several studies have proved that carbonization conditions (types of straw, temperature, heating rate, retention, and atmosphere) have impacts on yields of Bio-char, Bio-oil, and Gases. This meta-analysis systematically confirmed the impacts (visualized in Figures 7-12).

Supplementary Table S1 indicates that fixed carbon (FC) has a positive rela-

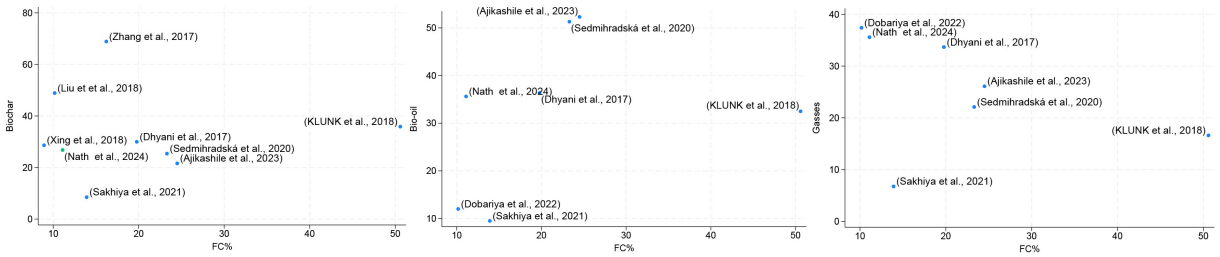
tionship with Bio-char and Bio-oil. However, the relationship between FC and Gases is negative, and volatile matter in all types of straws has a positive relationship with Bio-char, while a negative relationship with Bio-oil and Gases. The relationships are not significant because of the small sample size in the resampling (volatile matter → Bio-char: $p = 0.735 > 0.05$, volatile matter → Bio-oil: $p = 0.699 > 0.05$ and volatile matter → Gases: $p = 0.784 > 0.05$). The finding here is supported by several existing studies. According to Hassan & Strezov (2025) [19], FC and volatile matter in all types of straws, hemicellulose, cellulose, and lignin also have impacts on bio-char formation mechanism. The relationship between hemicellulose (or, cellulose and lignin) and Bio-char, Bio-oil, and Gases needs more exploration. Additionally, Liu *et al.* (2018) [20] state that the carbon yields of cotton straw rice, wheat, corn, and rapeseed are approximately 37.87%, 37.38%, 34.42%, 34.39%, and 32.74%, respectively. The FC of cotton straw rice, wheat, corn, rapeseed, and Bio-char are approximately 10.17%, 10.06%, 9.93%, 8.93%, and 7.49%, respectively (see Supplementary **Table S2**). This means that the carbon yields (Bio-char) of cotton of the tested straws are positively related to FC.

Supplementary **Table S3** indicates that heating rate has a positive relationship with Gases and Bio-oil while a negative relationship with Bio-char. The relationships are not significant ($p > 0.05$), and the sample size needs to be enlarged to explore whether there is a significant relationship between the variables. Heating rate is often related to the types of pyrolysis (mainly including slow pyrolysis, fast pyrolysis, and flash pyrolysis) [21]. Several scholars, such as Loc *et al.* [4], Nath *et al.* [11], and Elshareef *et al.* [22], have summarized their findings, as shown in Supplementary **Table S4**. It can be derived that heating rate has a positive relationship with Bio-oil. Normally, the high heating rate, the more Gases and the less Bio-char; however, in flash pyrolysis, the yield of gases decreases.

Supplementary **Table S5** indicates that retention has a positive relationship with Gases and Bio-oil while a negative relationship with Bio-char. The longer retention, the more Gases and Bio-oil, and the less Bio-char. The relationships are not significant ($p > 0.05$). Similar to heating rate, retention is associated with the types of pyrolysis. The slow pyrolysis has relatively longer retention. Thus, the findings here are supported by Loc *et al.* [4], Nath *et al.* [11], and Elshareef *et al.* [22]. A longer pyrolysis time (retention) increases the system's reaction rate, promoting biomass carbonization and influencing the yield of bio-char, bio-oil, and gases [23]. Depending on the pyrolysis method, either fast pyrolysis or slow pyrolysis, retention (either seconds in fast pyrolysis or hours in slow pyrolysis) has impacts on biomass carbonization and influences bio-char yield and properties. This study observes the relationship between the yields of bio-char, bio-oil, and gas, either positive or negative, however, not significant. It should be noted that to maximize bio-char yield, a longer retention and slower heating rate are needed, as well as a suitable temperature (300˚C - 500˚C), according to Loc *et al.* [4].

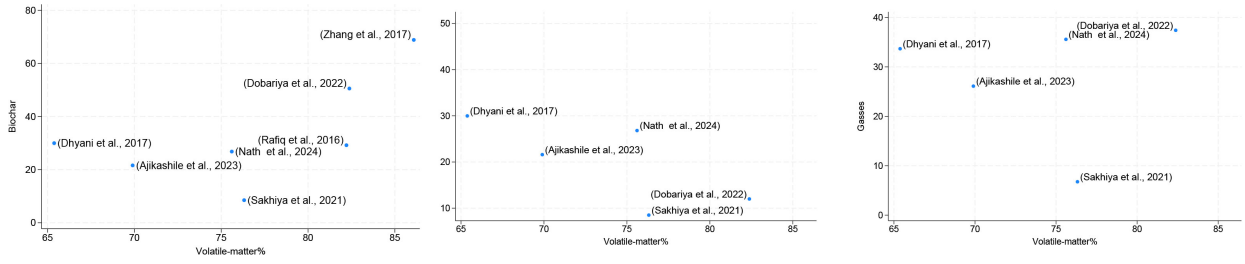
Supplementary Table S6 indicates that temperature has a positive relationship (but not significant) with Bio-oil (r = 0.03, p = 0.414 > 0.05) and a significant negative relationship with Bio-char (r = −0.07, p = 0.001 < 0.05) and Gases (r = −0.05, p = 0.031 < 0.05). The higher the temperature, the more Bio-oil and the less Bio-char and Gases. These findings here are consistent with those in previous studies. According to Sakhiya *et al.* [15], the yields of pyrolysis products are influenced by temperature, heating rate, retention, flow rate of inert gas, biomass type, and particle size. Pyrolysis temperature plays an important role in the pyrolysis process. Higher temperature, together with longer retention, increases the pyrolysis process [7] [24]. The bio-oil yield is proved to be maximized by several studies, such as Tagade *et al.* [25], with a relatively higher heating rate (>200˚C/s), relatively higher temperature (T > 500˚C), and shorter retention, which is often referred to as fast pyrolysis. In contrast, slow pyrolysis maximizes bio-char yield at a lower heating rate (5 - 15˚C/min), in the temperature range of 300˚C - 600˚C, and with longer retention (60 - 180 min) [26].

Supplementary Table S7 indicates that an inert atmosphere has a positive relationship with Bio-oil (r = 6.97) while a negative relationship with Bio-char (r =-0.88) and Gases (r = −5.59). The relationships are not significant (three p > 0.05); whether they are significant or not needs further exploration with a larger the sample size. The effect of the inert atmosphere is He > N_2 > CO_2. Atmosphere and temperature are thought to be the predominant factors influencing bio-char properties [27]. A CO_2 atmosphere plays a role in producing high-quality bio-char with nutritional elements(N/P/K), compared with an N_2 atmosphere [28]. However, the effect of atmosphere on bio-char production is mostly neglected [29].



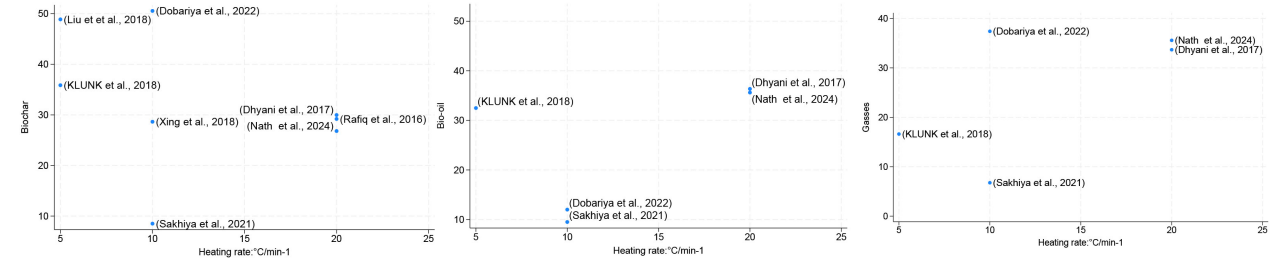
(a) (b) (c)

Figure 7. Relationship between FC and the yields of (a) Bio-char, (b) Bio-oil, and (c) Gases.



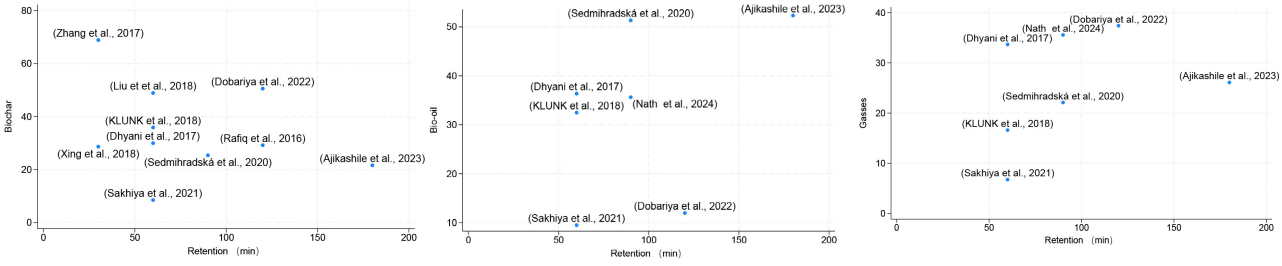
(a) (b) (c)

Figure 8. Relationship between volatile matter and the yields of (a) Bio-char, (b) Bio-oil, and (c) Gases.



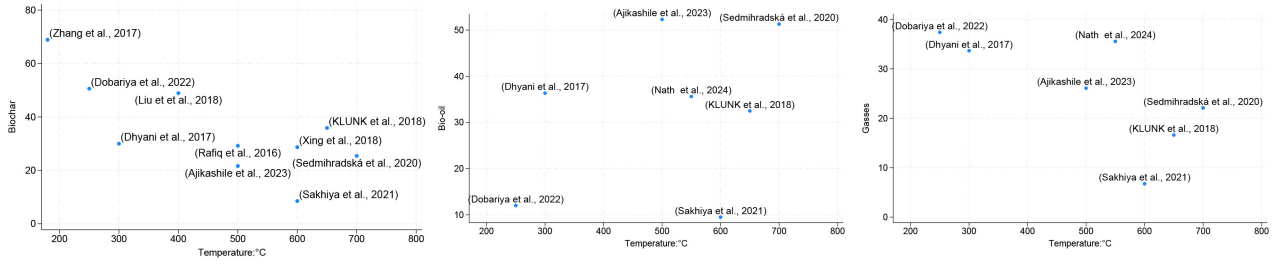
(a) (b) (c)

Figure 9. Relationship between heating rate and the yields of (a) Bio-char, (b) Bio-oil, and (c) Gases.



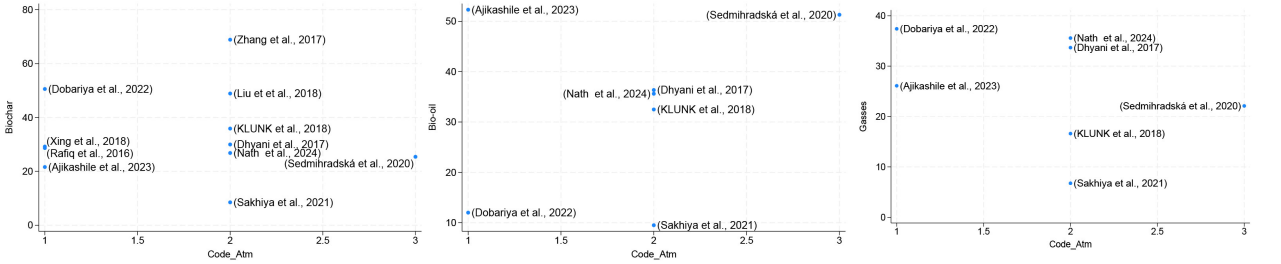
(a) (b) (c)

Figure 10. Relationship between retention and the yields of (a)Bio-char, (b) Bio-oil, and (c) Gases.



(a) (b) (c)

Figure 11. Relationship between temperature and the yields of (a) Bio-char, (b) Bio-oil, and (c) Gases.



(a) (b) (c)

Figure 12. Relationship between atmosphere and the yields of a) Bio-char, b) Bio-oil, and c) Gases.

3.5. Sensitivity Analyses with Trim-and-Fill

The nonparametric trim-and-fill sensitivity analysis presented in Table 3 indicated no evidence of publication bias. The key publication bias was caused by the small sample size. In future research, a relatively larger sample size of studies will

be included, covering various types of straw and various carbonization process conditions.

Table 3. Sensitivity analyses with trim-and-fill.

Items	Studies	Effect size	[95% conf.	interval]
Bio-char	Observed	32.543	23.724	41.363
	Observed + Imputed	32.543	23.724	41.363
Bio-oil	Observed	16.733	16.346	17.12
	Observed + Imputed	16.733	16.346	17.12
Gases	Observed	15.264	14.766	15.763
	Observed + Imputed	15.264	14.766	15.763

4. Discussion and Conclusion

This research employs a meta-analysis method to systematically analyze the relevant studies published in English language from 2015 to 2026, focusing on the effects of crop straw types (rice, wheat, corn, sorghum, rapeseed, cotton, and soybean) and carbonization conditions (FC, volatile matter, temperature, heating rate, retention time, and atmosphere) on the yields of Bio-char, Bio-oil, and Gases. It is found that there is a significant statistical difference in their average yields for the selected types of straw. Their values can be partly explained by the components, such as FC, volatile matter, hemicellulose, cellulose, and lignin in the selected types of straw, as well as the carbonization conditions. Due to the impacts of the sampling size, the precise yields of Bio-char, Bio-oil, and Gases of the selected types of straw need further exploration or simulation by ASPEN. In terms of the influence of carbonization conditions on Bio-char, Bio-oil, and Gases, FC, volatile matter, temperature, heating rate, retention time, and atmosphere have different impacts on them. FC in the selected types of straw generally has a positive relationship with Bio-char and Bio-oil, but a negative relationship with Gases. Volatile matter in the selected types of straw generally has a positive relationship with the yield of bio-char, but a negative relationship with Bio-oil and Gases. Multiple components in crop straws, such as cellulose, lignin, and hemicellulose, can be used to generate Bio-char, Bio-oil, and Gases [14]. Several studies have paid attention to the relationship between components (FC and volatile matter) of crop straws and the product yields. FC and volatile matter are the key components in crop straws, with a total concentration over 68%. Volatile matter is positively related to Bio-char; however, as the pyrolysis temperature increases, the yield of bio-char and gases decreases while the yield of bio-oil increases. The relationship between volatile matter and Bio-char, Bio-oil, and Gases changes [30]. Heating rate typically has a positive relationship with Bio-oil and Gases while a negative relationship with Bio-char. A high heating rate contributed to more Bio-oil compared with a low heating rate [21]. A low heating rate favors bio-char formation as the main product [30]. Retention has a positive relationship with Gases and Bio-oil

while a negative relationship with Bio-char. Usually, retention has a diverse or opposite effect to heating rate; in this research, the relation between heating rate and Bio-char, Bio-oil, and Gases is not opposite to that between retention and them. The inconsistency might be caused by the small sample size or might be caused by the combined effect of the various carbonization conditions. Pyrolysis temperature has a positive relationship with Bio-oil while a negative relationship with Bio-char and Gases. This is not consistent with several existing studies that conclude that 300˚C - 700˚C is the recommended pyrolysis temperature range. Pyrolysis temperature and the type of substrates used, usually measured by FC and volatile matter, are the two main parameters that affect them [31]. Generally, higher pyrolysis temperatures increase the yield of carbon (Bio-char) [14]; however, after a certain pyrolysis temperature, Bio-char decreases whereas the yield of bio-oil increases. According to Li *et al.* [30], as pyrolysis temperature increases, the yield of bio-char decreases and the effects of pyrolysis temperature on bio-char yields are similar for different types of straw. Furthermore, Cheng *et al.* [32] argue that pyrolysis temperature has a more obvious effect compared with retention. An inert atmosphere has a positive relationship with bio-oil yields, while a negative relationship with bio-char and gas yields. Atmosphere is one of the key factors that affect the pyrolysis process and bio-char, bio-oil, and gas yields. However, the findings in existing studies are controversial. Some studies [33] conclude that CO_2 atmosphere significantly increases bio-oil yield while decreasing gas yield; other studies [34] report CO_2 atmosphere reduces bio-oil yield. In fact, the yields of Bio-char, Bio-oil, and Gases are the result of the combined effect of multiple factors. It needs an optimization program using ASPEN before carrying out the pyrolysis process of various types of straw [35], along with the traditional tile kiln and charcoal kiln. Maximum yields of bio-char, bio-oil, and gas can be achieved at suitable temperatures (300˚C to 700˚C), suitable retention times (0.1 - 2 h), and suitable heating rates (0.1˚C/s to 1˚C/s), with an inert atmosphere (N_2), which is proven by several studies [30] [36]. Thus, this research generates the hypothesis that it provides a practice guide for industry and research institutions to formulate targeted carbonization plans based on different types of straw, and enhance the efficiency of straw resource utilization, especially by making good use of the traditional tile kiln and charcoal kiln.

In all, it is found that there is a significant statistical difference in the average bio-char, bio-oil, and gas yields of the selected types of straw, such as crop straw, mainly including rice, wheat, corn, sorghum, rapeseed, cotton, and soybean straws. The carbonization conditions (FC, volatile matter, temperature, heating rate, retention time, and atmosphere) have different effects on the yields of bio-char, bio-oil, and gases. These yields are the result of the combined effect of multiple factors. Thus, optimal conditions—a suitable temperature (300˚C to 700˚C), a suitable retention time (0.1 - 2 h), a suitable heating rate (0.1˚C/s to 1˚C/s), and an inert atmosphere (N_2)—are recommended for straw carbonization.

However, this research has its limitations. Firstly, a limited number of studies

was chosen. Secondly, it does not investigate deep into the sources of heterogeneity. Particle size, drying degree, and carbonization equipment are also the affecting factors, which are not taken into consideration. Thirdly, the selected studies mainly are based on short-term indoor experiments, lacking long-term carbonization test data. Fourthly, this research may introduce language bias due to the exclusion of non-English literature, especially in a field where many straw pyrolysis studies may be published in Chinese, which had been confirmed in the studies using CiteSpace. The future study will address these limitations, expand the scope of the research, increase the geographical coverage, incorporate more relevant studies from developing countries, and further enhance the universality of the research conclusions. Additionally, it will take more factors into consideration. Furthermore, it will supplement long-term experimental data to explore the changes in the components of the straw during the long-term carbonization process and the dynamic changes in bio-char, bio-oil, and gas yields. Before carrying out the carbonization process of straw using traditional tile kiln and charcoal kiln, ASPEN simulations should be conducted to find suitable carbonization conditions. Alternatively, the meta-analysis should be conducted using the network visualizations or network meta-analysis reporting so as to improve transparency in pooled condition-ranking interpretation and deal with the meta-analysis with substantial heterogeneity [6] [7] [37] [38].

Highlights

- There is a significant statistical difference in the average bio-char, bio-oil, and gas yields of the selected types of straw.
- Carbonization conditions (types of straw, temperature, heating rate, retention, and atmosphere) have impacts on bio-char, bio-oil, and gas yields.
- Bio-char, bio-oil, and gas yields are the result of the combined effect of multiple factors, representing the overall outcome.
- Suitable temperature (300˚C to 700˚C), suitable retention (0.1 - 2 h) and suitable heating rate (0.1˚C/s to 1˚C/s) with an inert atmosphere (N_2) are recommended while carrying out the carbonization process of straw, which should be confirmed through ASPEN simulations.

Acknowledgements

The authors would like to acknowledge the previous researchers and the comments from the reviewers and editors. All data supporting this study are provided in full in the paper.

Author Contributions

Li Lianfa is responsible for the following: study conception and design, data collection, data analysis and interpretation of results, and manuscript preparation. Li Yaxin is responsible for the following: data collection, data analysis and interpretation of results, and proofreading. All authors have read and agreed to the pub-

lished version of the manuscript.

Conflicts of Interest

All authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this research, nor do they have competing interests.

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Supplementary Information

Table S1. Meta-regression analysis of key components of types of straw and Bio-char, Bio-oil, and Gases.

Effect size	_meta_es	Coefficient	Std. err.	*z*	*p* > *z*
Bio-char	FC	1.68	1.40	1.20	0.229
Bio-oil	FC	1.52	2.29	0.67	0.505
Gases	FC	−0.83	0.33	−0.97	0.332
Bio-char	Volatile matter	2.49	2.44	−0.34	0.735
Bio-oil	Volatile matter	−0.83	2.15	−0.39	0.699
Gases	Volatile matter	−0.63	2.29	−0.27	0.784

Table S2. Key components of types of straws [14].

Component	Cotton stalk	Rice straw	Wheat straw	Corn stover	Rape stalk
Cellulose/%	40.14 ± 0.87	41.75 ± 0.04	38.68 ± 0.01	35.96 ± 0.67	40.46 ± 0.45
Hemicellulose/%	1.73 ± 0.23	14.20 ± 0.23	17.90 ± 0.29	13.68 ± 0.35	13.40 ± 0.42
Lignin/%	27.45 ± 0.12	20.46 ± 0.60	22.47 ± 0.35	22.50 ± 0.06	18.54 ± 0.52
Volatile matter/%	82.38 ± 1.16	76.87 ± 1.39	80.70 ± 1.04	82.21 ± 1.15	86.09 ± 1.08
Ash/%	7.45 ± 0.21	13.07 ± 0.16	9.37 ± 0.32	8.86 ± 0.18	6.42 ± 0.19
Fixed carbon/%	10.17 ± 0.25	10.06 ± 0.18	9.93 ± 0.28	8.93 ± 0.17	7.49 ± 0.21

Table S3. Meta-regression analysis of heating rate and Bio-char, Bio-oil, and Gases.

Effect size	_meta_es	Coefficient	Std. err.	*z*	*p* > *z*
Bio-char	Heating rate	−0.70	0.79	−0.89	0.374
Bio-oil	Heating rate	0.99	1.00	1	0.318
Gases	Heating rate	1.22	0.94	1.3	0.194

Table S4. Bio-char, Bio-oil, and Gases of various types of pyrolysis.

Types of pyrolysis	Heating rate ˚C/min	Retention	Bio-char	Bio-oil	Gases
slow	0.1 - 1.0	10 - 100 min	35	30%	35
fast	10 - 200	0.5 - 5.0 s	20	50%	30%
flash	>1000	<0.5 s	12%	75%	13%

Source: Elshareef *et al.* (2025) [22].

Table S5. Meta-regression analysis of retention and Bio-char, Bio-oil, and Gases.

Effect size	_meta_es	Coefficient	Std. err.	*z*	*p* > *z*
Bio-char	Retention	−0.09	0.11	−0.86	0.388
Bio-oil	Retention	0.15	0.16	0.94	0.347
Gases	Retention	0.09	0.11	0.81	0.42

Table S6. Meta-regression analysis of temperature and Bio-char, Bio-oil, and Gases.

Effect size	_meta_es	Coefficient	Std. err.	*z*	*p* > *z*
Bio-char	Temperature	−0.07	0.02	−3.14	0.001
Bio-oil	Temperature	0.03	0.04	0.82	0.414
Gases	Temperature	−0.05	0.02	−2.15	0.031

Table S7. Meta-regression analysis of inert atmosphere and Bio-char, Bio-oil, and Gases.

Effect size	_meta_es	Coefficient	Std. err.	*z*	*p* > *z*
Bio-char	code_atm	−0.88	8.19	−0.11	0.915
Bio-oil	code_atm	6.97	10.54	0.66	0.508
Gases	code_atm	−5.59	6.82	−0.82	0.413

Forest Plots of Studies on Bio-Oil

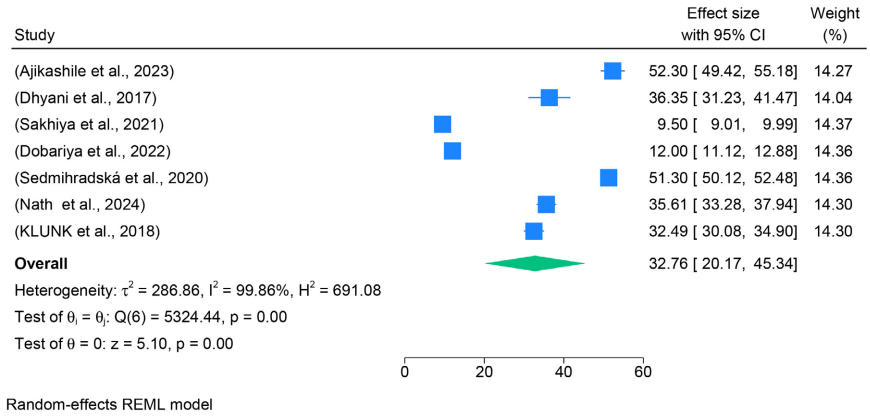


Figure S1. Overall analysis of studies on Bio-oil.

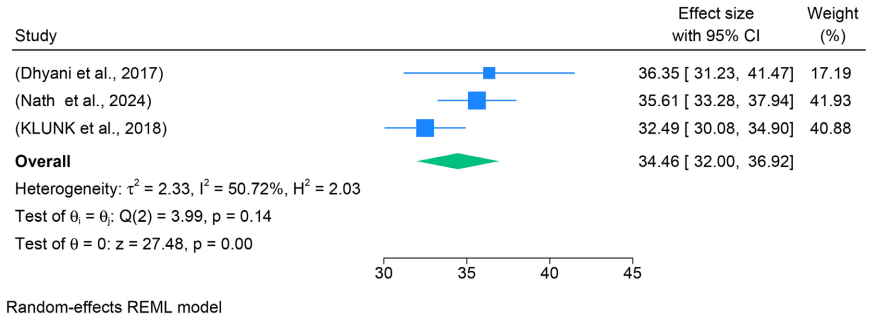


Figure S2. Sensitive analysis of studies on Bio-oil.

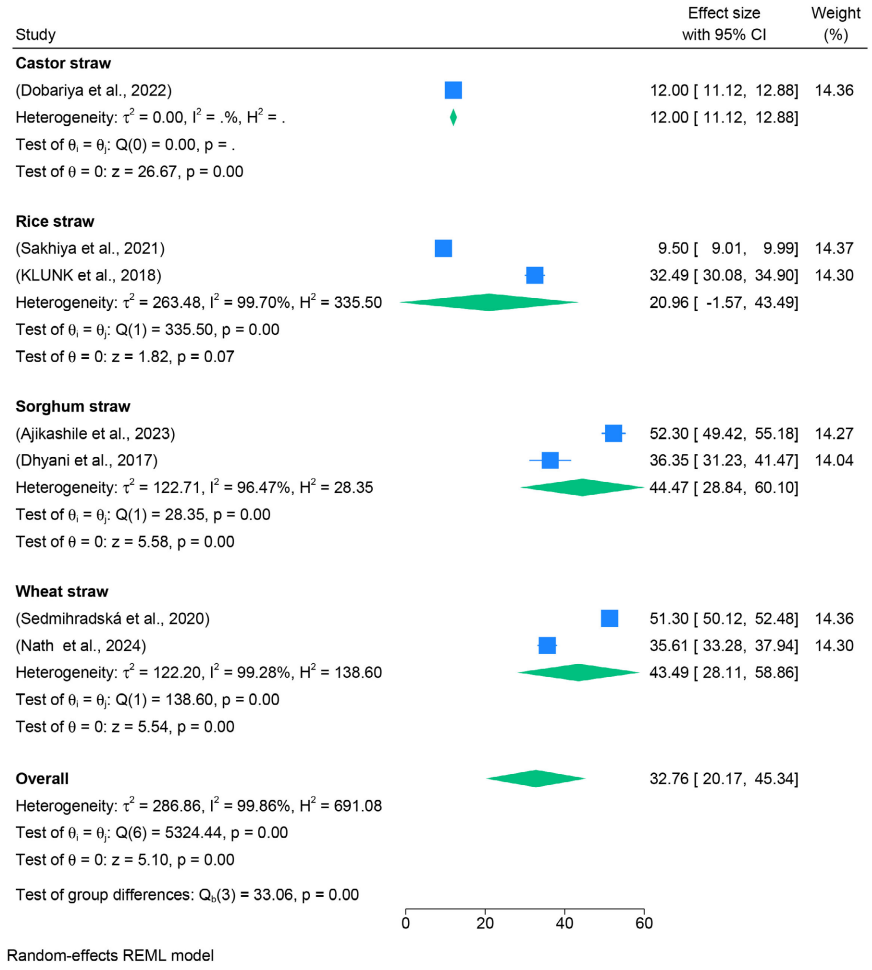


Figure S3. Sub-group analysis of studies on Bio-oil.

Forest Plots of Studies on Gases

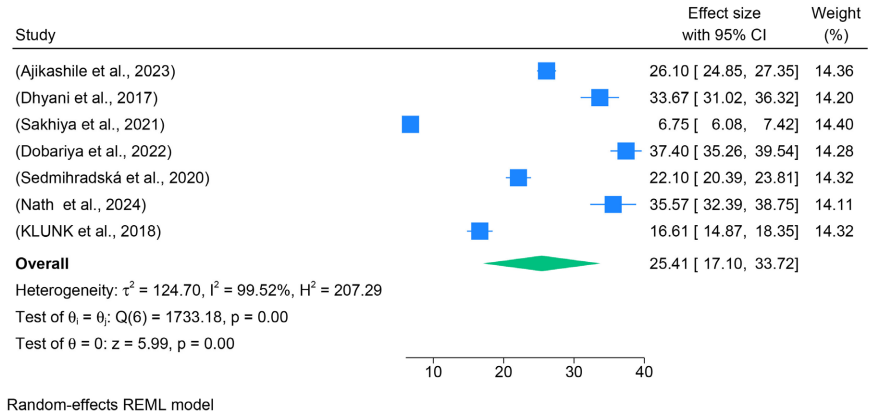


Figure S4. Overall analysis of studies on Gases.

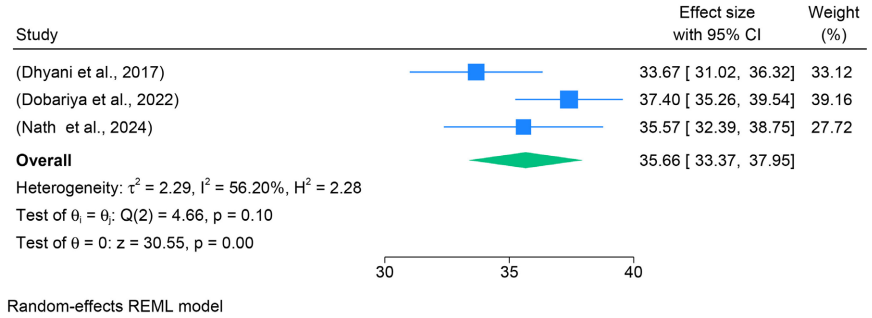


Figure S5. Sensitive analysis of studies on Gases.

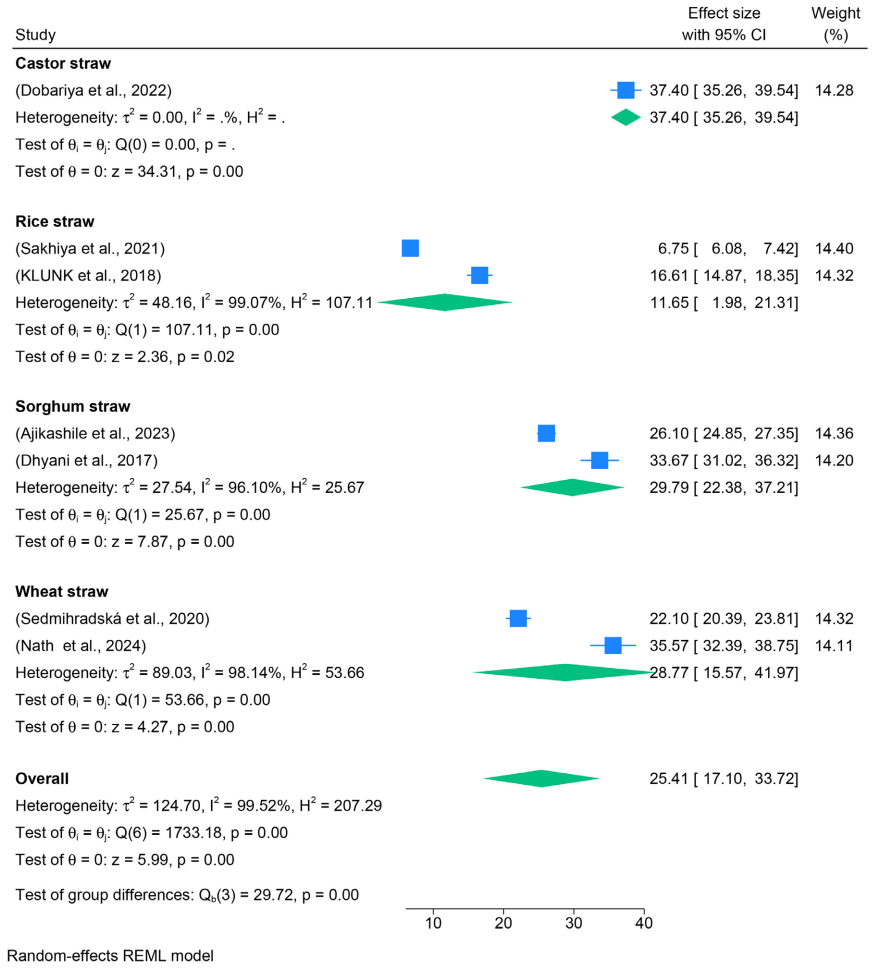


Figure S6. Sub-group analysis of studies on Gases.