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Multivariate Regression Analysis of Bio-Oil Yield Using Literature-Derived Biomass Data

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***Abstract* – The distribution of products formed during biomass pyrolysis depends strongly on the physical and chemical properties of the feedstock, yet quantitative comparisons across studies remain limited. This work compiles experimental and modelling data from literature to examine how five commonly reported biomass characteristics (moisture content, lignin content, ash content, higher heating value, and particle size) influence bio-oil yield. Pairwise trends highlight substantial variability in the explanatory strength of these parameters, with higher heating value showing the most consistent positive association with yield. A multivariate regression approach was then applied to assess the combined effects of all variables within a single analytical framework. The resulting model identifies higher heating value as the most informative predictor across the heterogeneous dataset, while the influence of other parameters is more dependent on interactions and covariation among biomass properties. Predicted yields for locally analysed biomass samples align with general tendencies reported in the literature, though these estimates remain provisional due to the limited size and heterogeneity of the compiled data. The study provides an integrative perspective on feedstock quality factors relevant to bio-oil production and underscores the need for experimental validation and expanded datasets to support more robust predictive modelling.**

***Keywords* – Biomass; bio-oil; experimental results; multiple linear model; pyrolysis; multivariate regression analysis; sustainable consumption and production.**

1. INTRODUCTION

Biomass pyrolysis is a thermochemical conversion carried out in an oxygen-limited environment [1] that breaks organic matter into three main products: a liquid fraction (bio-oil), a solid carbonaceous by-product (biochar), which is widely utilized as a soil amendment, sorbent material, and long-term carbon storage medium, and a combustible gas mixture (syngas) [2]. This route is valued both to produce renewable fuels and as a practical method for sequestering carbon [3], [4].

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1.1. Biomass Pyrolysis Products

Bio-oil is the condensable liquid formed when biomass thermally decomposes. It can retain a large portion of the feedstock's chemical energy (commonly up to around 70–80 % in favourable cases [5]) and is chemically complex: a mixture of oxygenated species such as organic acids, alcohols, ketones and phenolic compounds. That complexity makes bio-oil useful as a feedstock for chemicals and as a potential fuel, but it also explains its practical problems: acidity, storage instability, and corrosiveness, which complicate handling and downstream use [6], [7]. Consequently, much research focuses on stabilization and upgrading routes before bio-oil can be used reliably at scale [8]–[10].

Biochar is the solid, carbon-rich product left after pyrolysis. Beyond serving as a sorbent for pollutants, biochar is widely studied for its agricultural benefits, which include improving soil structure, water retention, and nutrient availability, as well as its role in long-term carbon storage [11]. Its dual function as a soil amendment and a relatively stable carbon sink is a key reason biochar attracts attention beyond the energy sector.

Syngas is the non-condensable gaseous stream composed primarily of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4) [12]. It can be burned for heat and power or, after specific treatment, converted into synthetic fuels and chemicals [13]. The quantity and quality of syngas depend strongly on operating parameters, including temperature, heating rate, and residence time, which shift the balance between liquids, solids, and gases and alter the hydrogen-to-carbon monoxide (H_2-to-CO) ratio that downstream processes require [14]. Optimizing these conditions is therefore critical when syngas is the target product.

1.2. Bio-Oil Importance

Bio-oil stands out as the most commercially valuable product of biomass pyrolysis due to its high yield, energy content, and versatile applications. The energy content of bio-oil varies, with higher heating values (HHV) ranging from 16 to 24 MJ/kg, depending on feedstock and process conditions [15], [16]. This energy density is approximately 40–50 % of that of conventional diesel fuel, which has a HHV of around 42–46 MJ/kg; in comparison, modern biodiesel HHV is around 10 % lower than regular diesel [17]. The bio-oil market is experiencing significant growth, with projections indicating an increase from 5.8 billion EUR in 2024 (assuming that 1 USD is equal to 0.85 EUR) to ~ 200 billion EUR by 2033, reflecting a compound annual growth rate of about 7.3 % [18]. This expansion is driven by the increasing demand for renewable energy sources and the versatility of bio-oil as a feedstock for biofuels and chemicals. In summary, bio-oil's combination of high yield, substantial energy content, and broad applicability underscores its status as the most valued product of biomass pyrolysis.

1.3. Biomass Quality Factors Influencing Pyrolysis Product Yield

Many factors shape the yield and quality of bio-oil, biochar, and syngas [19]. Feedstock type (e.g., lignocellulosic biomass, agricultural residues) plays a decisive role in the distribution of products when subjected to pyrolysis. The conditions of the process are equally important, as temperature, heating rate, and residence time determine the balance between the liquid, gas, and solid phases [20]. In addition, applying catalysts and additives, such as zeolites or metal oxides, can significantly enhance product selectivity and direct the process toward more desirable outputs.

Biomass can be grouped into three broad categories: plant-based, animal-based, and blended [21], [22]. Plant-based biomass is the most widely studied, as it is rich in organic matter and available in many different environments. The materials can take many forms, from leaves and seeds to bast fibres and wood residues [23]. Chemically, plant-derived biomass is composed primarily of cellulose, hemicellulose, and lignin, alongside extractives and smaller amounts of inorganic components, particularly alkali and alkaline earth metals. Because of this broad variation, plant biomass can include starch-rich and sugar-rich crops, oil-bearing seeds, and both microalgae and macroalgae, all of which offer different opportunities for conversion into renewable energy [24].

Animal-based biomass is generated within livestock farming and feedlot operations, where animals are bred, raised, and maintained to produce primary outputs such as meat, milk, and eggs [25]. Alongside these outputs, large quantities of manure and slurry are produced as secondary residues. Livestock manure is often applied to fields as fertilizer due to its high nitrogen, phosphorus, and potassium content [26]. However, heavy metals and antibiotic residues present an environmental concern. These contaminants enter largely because copper, zinc, and various antibiotics are routinely added to feed to support animal growth and prevent disease, and they later accumulate in animal feces. Despite these challenges, manure remains an essential feedstock for renewable energy, as it is widely used in anaerobic digestion to generate biogas or biomethane [27].

The third category of biomass is blended or non-lignocellulosic material, which primarily includes sewage sludge derived from municipal and industrial wastewater treatment. The composition of sludge is highly complex and variable, depending on its origin. Industrial sludge may arise from metallurgical plants, the textile and dyeing sector, pulp and paper mills, or chemical industries, and in each case, the mixture of organic matter, inorganic compounds, and contaminants differs substantially [28], [29]. Researchers have conducted numerous investigations into mixing sewage sludge with lignocellulosic residues such as rice straw or with microalgae, aiming to improve the efficiency of pyrolysis and produce higher-value energy products [30]. Because of its heterogeneous nature, sludge requires detailed characterization before conversion, and its behaviour under thermal or biological processes can vary greatly.

In all cases, whether dealing with plant-based residues, animal wastes, or sewage sludge, the physical and chemical properties of the biomass are of fundamental importance [31]. Moisture content [32], proportions of cellulose, hemicellulose, and lignin [33], ash content [34], caloricity [35], and the fraction (size of biomass particles before pyrolysis) [36] influence the logistics of handling, collecting, and transporting biomass, the pretreatment methods required, and the yields obtained in pyrolysis. At a more detailed level, modern techniques such as atomic force microscopy are used to study the microscopic morphology of biomass at the nanoscale [37]. At the same time, chemical analyses provide insights into the concentration and quality of organic matter. Together, these investigations show that biomass encompasses a broad and diverse set of materials, and that successful conversion into renewable energy – whether in gaseous, liquid, or solid form – depends on linking these inherent properties with the most suitable technological pathway.

1.4. Nature of the Study

The present study addresses the need for a clearer quantitative understanding of how fundamental biomass properties influence bio-oil yield during pyrolysis. Although numerous experimental studies report the effects of individual parameters, their results remain fragmented across different biomass types and operating conditions. To synthesize these dispersed findings, this work compiles literature data on moisture content, lignin content, ash content, higher heating value, and particle size, and evaluates their collective influence through a multivariate regression analysis (MRA). The objective is not to generalize universal predictive relationships, but to identify consistent trends across heterogeneous studies and to assess which biomass characteristics most strongly contribute to variations in bio-oil yield. By consolidating existing evidence into a single analytical scheme, the study provides an integrative perspective on feedstock quality factors while explicitly recognizing the limitations imposed by dataset heterogeneity and the need for further experimental validation.

2. METHODOLOGY

To investigate how selected biomass properties influence bio-oil yield, this study employed MRA as a quantitative evaluation method. Regression-based approaches are widely applied in biomass conversion research to identify statistically significant relationships between feedstock characteristics and pyrolysis outcomes [38]–[40]. In the present article, five parameters (moisture content, lignin content, ash content, higher heating value, and particle size) were selected based on their consistent representation in the literature and their known relevance to pyrolysis behaviour. The analysis focused on assessing the strength and direction of these relationships by compiling numerical data from published studies and evaluating the resulting dataset through a multivariate statistical framework.

2.1. Data Collection

The authors searched for articles in the Scopus database, following the steps for creating a query using the previously used bibliometric analysis method [41], [42]. The queries comprised keywords related to identified biomass parameters and "pyrolysis" and "bio-oil". A total of 15 articles were randomly selected for data collection. The results in articles came from the experimental research (E) and modelling (M) of two types of reactors – fixed bed and fluidized bed. The types of pyrolysis were fast (F) and slow (S). Temperature remarks varied – most often 500 °C. The collected data is available in the tables below.

The authors compiled data on pre-pyrolysis biomass moisture content and bio-oil yield from a total of 7 articles (see Table 1). These articles explored different wood and non-wood biomass. Twenty variable and dependent values dataset was used for further MRA.

TABLE 1. DATA FOR DETERMINING THE CORRELATION BETWEEN MOISTURE CONTENT AND BIO-OIL YIELD

Biomass type	Type of research	Reactor/Modelling program	Pyrolysis type	Operating temperature, °C	Moisture content, wt%	Bio-oil yield, %	Source
Nazelnut shell	E	Fixed bed	S	700	6.00	30.50	[43]
					10.50	32.00	
Spruce wood	E	Fixed bed	S	700	6.50	31.50	
					11.50	35.50	
Wheat straw	E	Fixed bed	S	700	7.00	25.50	
					12.00	29.50	
Coconut residues	E	Fixed bed	F	700	10.60	22.00	[44]
					6.30	11.30	
					6.00	13.60	
					5.40	9.50	
Poultry manure	E	Fluidized bed	S	550	11.82	42.02	[45]
Corn stalks	E	Fluidized bed	S	550	7.95	43.12	
Wheat straw	E	Fluidized bed	S	550	10.63	41.73	
Pine sawdust	E	Fluidized bed	S	550	8.76	48.32	

Coffee husk pellet	M	OpenSMOKE++	S	550	7.20	67.00	[46]
Cogon grass	E	Screw reactor	S	500	5.28	52.72	[47]
Food waste	E	Fixed bed	F	500	7.14	36.70	[48]
Oil palm trunk	E	Fluidized bed	S	550	7.07	43.50	[49]
Oil palm fronds	E	Fluidized bed	S	550	6.48	44.50	
Rubberwood sawdust	E	Fluidized bed	S	550	7.13	54.50	

The authors took data on pre-pyrolysis biomass lignin content and bio-oil yield from 4 articles in total (see Table 2). These articles explored different wood and non-wood biomass. 11 variable and dependent values dataset was used for further MRA.

TABLE 2. DATA FOR DETERMINING THE CORRELATION BETWEEN LIGNIN CONTENT AND BIO-OIL YIELD

Biomass type	**Type of research**	**Reactor/Modelling program**	**Pyrolysis type**	**Operating temperature, °C**	**Lignin content, wt %**	**Bio-oil yield, %**	**Source**
Coconut residues	E	Fixed bed	F	700	40.50	22.00	[44]
					40.40	11.30	
					40.30	13.60	
					41.40	9.50	
Food waste	E	Fixed bed	F	500	15.04	36.70	[48]
Loblolly pine wood	E	Fluidized bed	F	500	27.10	45.70	[50]
					27.90	30.90	
					28.30	29.90	
Oil palm trunk	E	Fluidized bed	S	550	9.52	43.50	[49]
Oil palm fronds	E	Fluidized bed	S	550	13.15	44.50	
Rubberwood sawdust	E	Fluidized bed	S	550	17.44	54.50	

The authors took data on pre-pyrolysis biomass ash content and bio-oil yield from 5 articles in total (see Table 3). These articles explored different wood and non-wood biomass. 21 variable and dependent values dataset was used for further MRA.

TABLE 3. DATA FOR DETERMINING THE CORRELATION BETWEEN ASH CONTENT AND BIO-OIL YIELD

Biomass type	**Type of research**	**Reactor/Modelling program**	**Pyrolysis type**	**Operating temperature, °C**	**Ash content, wt%**	**Bio-oil yield, %**	**Source**
Coconut residues	E	Fixed bed	F	700	1.90	22.00	[44]
					2.40	11.30	
					2.90	13.60	
					1.90	9.50	
Cogon grass	E	Screw reactor	S	500	10.35	52.72	[47]
Food waste	E	Fixed bed	F	500	2.55	36.70	[48]
Sweetgum	M	RA*	S	550	0.80	55.10	[51]
Beech bark	M	RA	S	550	7.40	29.20	
Acacia	M	RA	S	550	0.60	43.90	

Acacia bark	M	RA	S	550	3.30	33.80	
Corn stover	M	RA	S	550	8.10	27.70	
Red oak	M	RA	S	550	0.40	43.40	
Switchgrass	M	RA	S	550	1.40	51.40	
Sourwood	M	RA	S	550	0.50	58.00	
Yellow poplar	M	RA	S	550	0.60	52.30	
Red maple	M	RA	S	550	0.30	53.50	
Beech	M	RA	S	550	0.50	54.00	
Loblolly pine wood	M	RA	S	550	0.60	50.70	
Loblolly pine wood	E	Fluidized bed	F	500	0.50	45.70	[50]
					1.10	30.90	
					1.50	29.90	

* Regression analysis

The authors took data on pre-pyrolysis biomass HHV and bio-oil yield from 3 articles in total (see Table 4). These articles explored different wood and non-wood biomass. 10 variable and dependent values datasets were used for further MRA.

TABLE 4. DATA FOR DETERMINING THE CORRELATION BETWEEN HIGH HEATING VALUE AND BIO-OIL YIELD

Biomass type	Type of research	Reactor/Modelling program	Pyrolysis type	Operating temperature, °C	HHV, MJ/kg	Bio-oil yield, %	Source
Coconut residues	E	Fixed bed	F	700	17.70	22.00	[44]
					18.10	11.30	
					19.30	13.60	
					18.80	9.50	
Oil palm trunk	E	Fluidized bed	S	550	23.22	43.50	[49]
Oil palm fronds	E	Fluidized bed	S	550	22.52	44.50	
Rubberwood sawdust	E	Fluidized bed	S	550	23.77	54.50	
Groundnut shell	E	Fixed bed	S	450	19.90	31.00	[52]
Wheat straw	E	Fixed bed	S	450	19.77	30.00	
Chana straw	E	Fixed bed	S	450	18.60	26.00	

The authors collected data on pre-pyrolysis biomass particle size and bio-oil yield from a total of 5 articles (see Table 5). These articles explored different wood and non-wood biomass. 20 variable and dependent values dataset was used for further MRA.

TABLE 5. DATA FOR DETERMINING THE CORRELATION BETWEEN PARTICLE SIZE AND BIO-OIL YIELD

Biomass type	Type of research	Reactor/Modelling program	Pyrolysis type	Operating temperature, °C	Particle size, mm	Bio-oil yield, %	Source
Mallee	E	Fluidized bed	F	500	0.50	62.00	[53]
					1.00	52.00	
					1.50	49.00	
					2.70	48.00	
					3.80	47.00	
Not mentioned	E/M	Fluidized bed/Optimization via LightGBM	F	500	0.45	77.00	[54]
					0.47	74.00	
					2.50	72.00	
					0.30	62.12	
Pine sawdust	E	Fluidized bed	F	500	0.51	61.81	[55]
					0.80	50.47	
					1.50	49.82	
					2.68	49.22	
					3.68	45.98	
					4.38	45.52	
					5.18	48.56	
Energy cane	E	Fixed bed	F	550	1.40	48.00	[56]
					4.40	46.00	
Raw cattle manure	E	Fluidized bed	F	500	0.71	28.50	[57]
					1.70	23.52	

2.2. Data Analysis

In MRA, authors examine how a dependent (response) variable – bio-oil yield – is related to one or more independent (explanatory) variables – moisture content, lignin content, ash content, higher heating value (HHV), and particle size. This approach also allows predicting values of the dependent variable based on identified statistical relationships. For comparison, simple linear regression-based predictions for individual datasets can be expressed as

$$\hat{y} = b_0 + b_1 x, \quad (1)$$

where $\hat{y}$ is predicted value of y, b_0 is intercept (value of y when $x = 0$), b_1 is slope (how much y changes when x increases by 1 unit) and x is independent variable [58].

To evaluate the explanatory strength of such simple relationships, the coefficient of determination (R^2) can be calculated [59], where larger values indicate that a greater proportion of the variation in bio-oil yield is explained by the parameter under consideration [60].

A MRA was selected for this study because it enables the simultaneous evaluation of all five biomass parameters within a single statistical model. Unlike pairwise correlation analysis, which evaluates each parameter independently, MRA quantifies the partial effect of each variable while controlling for the influence of the others. This is essential when analysing literature-derived datasets in which biomass properties are often interrelated, leading to potential confounding and multicollinearity. By estimating the relative contribution of each predictor under these conditions, MRA provides a more meaningful assessment of which parameters exert the strongest influence on bio-oil yield. Furthermore, a unified multivariate model allows the identification of overlapping, suppressing, or reinforcing relationships among variables, offering insights that cannot be obtained from simple bivariate comparisons. This approach therefore supports a more robust interpretation of parameter importance within the constraints of a heterogeneous dataset.

3. RESULTS

The results are presented in Table 6. Three parameters – moisture content, ash content, and particle size – showed negligible correlation with bio-oil yield, whereas changes of lignin content and HHV variables were strongly correlated with the bio-oil yield.

TABLE 6. INDEPENDENT PARAMETERS CORRELATION WITH BIO-OIL YIELD

Determination coefficient	Moisture content	Lignin content	Ash content	HHV	Particle size
R^2	0.01	0.75	0.05	0.80	0.11

The equation

$$\text{Bio-oil yield} = 16.141 - 0.0247576 \times \text{Moisture content} - 0.668374 \times \text{Lignin content} - \\ - 0.0733111 \times \text{Ash conent} + 2.29048 \times \text{HHV} - 2.92075 \times \text{Particle size} \quad (2)$$

was obtained using *Statgraphics Centurion 19*. The program simultaneously analysed all five independent variables against bio-oil yield. Program automatically calculated the regression coefficients using the least-squares method to minimize the difference between observed and predicted values. The program provided R^2 and p-values to show how strongly each parameter influences the yield. This approach allowed the simultaneous assessment of interdependent effects and highlighted the parameters with the most pronounced influence on bio-oil yield.

Table 7 contains data on all independent parameters from the authors' experimental research of biomass samples. Wood sawdust is mentioned twice in Table 7(1) and (2) because they are two different samples from different types of trees. Using the Eq. (2), the bio-oil yield potential was calculated (see Fig. 1(b)).

TABLE 7. EXPERIMENTAL VALUES OF INDEPENDENT PARAMETERS FOR SELECTED BIOMASS SAMPLES

Biomass type	Label	Moisture content, wt%	Lignin content, wt%	Ash content, wt%	HHV, MJ/kg	Particle size, mm
Pine needles	B1	8.00	21.80	5.27	20.20	1.20
Wood sawdust (1)	B2	12.70	28.70	1.72	21.20	1.20
Brewer's spent grain	B3	3.10	34.40	3.85	21.20	1.30
Grains (damaged)	B4	13.60	22.50	2.21	18.50	2.00
Coffee grounds residue	B5	2.90	33.40	6.55	20.20	0.90
Sunflower husk	B6	12.50	32.50	3.08	20.10	1.20
Grass (from parks)	B7	13.10	31.70	9.75	19.30	1.20
Apple pomace	B8	15.00	23.30	2.06	18.90	3.40
Wood sawdust (2)	B9	24.00	27.40	0.19	20.70	4.50

Hemp	B10	14.10	22.30	11.27	18.60	4.00
Buckwheat husk	B11	9.80	38.50	2.15	19.70	1.50
Straw	B12	3.90	24.90	6.80	18.40	4.40
Canada Goldenrod	B13	15.40	24.60	6.80	19.70	5.50
Reeds	B14	5.10	28.50	6.74	18.80	4.80
Leaves (from parks)	B15	24.30	33.60	10.40	19.30	4.70

Lower moisture content generally corresponds to higher predicted yields. For example, P1 (8.00 %) and B3 (3.10 %) show high yields of 43.75 % and 37.72 %, respectively. In contrast, samples B9 and B15 with moisture contents over 24.00 % have lower yields of 31.44 % and 22.75 %, respectively. Higher ash content appears to negatively affect bio-oil yield. B5 and B10, which have ash contents of 6.55 % and 11.27 % and show moderate bio-oil yields 36.99 % and 31.03 %, respectively. In contrast, B2 with only 1.72 % ash shows a relatively high yield of 41.59 %. A higher lignin content tends to enhance bio-oil yield. B11 has a high lignin content (38.50 %) and a decent bio-oil yield (30.62 %). Similarly, B4 with 34.40 % lignin content achieves 37.72 % bio-oil yield. Higher HHV generally corresponds to higher predicted bio-oil yield. B2 and B3, both with 21.20 MJ/kg, have high bio-oil yields above 37.00 %. Smaller particle sizes seem to favour higher yields, possibly due to more efficient heat transfer during pyrolysis. B5 with the smallest size (0.9 mm) yields 36.99 % of bio-oil, while B15 with 4.7 mm yields only 22.75 % of bio-oil.

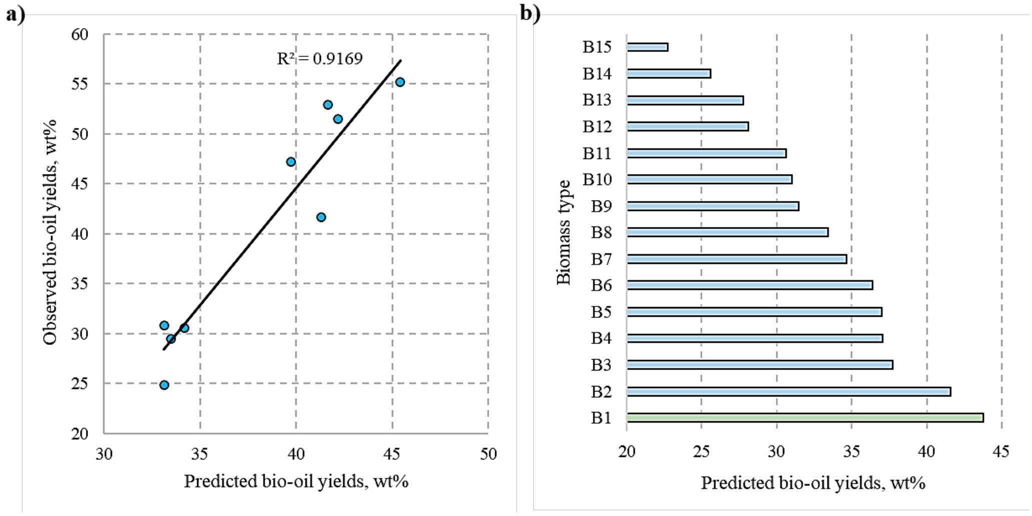

Fig. 1. Predicted bio-oil yield from biomass samples: (a) relationship between predicted and observed bio-oil yields with the fitted regression line; (b) predicted bio-oil yields for the 15 biomass samples. The colours distinguish biomass types based on predicted performance: green bar represent sample with comparatively higher predicted bio-oil yields.

The strong agreement between predicted and observed bio-oil yields is reflected in the coefficient of determination of the MRA model (R^2 = 0.92), which indicates good model fit and demonstrates that the selected parameters collectively explain most of the variation in the compiled dataset (see Fig. 1(a)).

4. Conclusion

The analysis of pairwise correlations demonstrates that not all biomass properties exert a meaningful influence on bio-oil yield. Among the examined parameters, higher heating value and lignin content show the strongest simple associations with yield, whereas moisture content, ash content, and particle size exhibit negligible correlations within the compiled dataset. These initial relationships provide a useful indication of general trends but do not account for interdependence among variables.

The MRA results clarify the apparent inconsistency between lignin's positive simple correlation and its negative partial effect. This inversion arises from multicollinearity: lignin content covers with other compositional characteristics, particularly higher heating value, and the partial coefficient reflects lignin's isolated contribution when these related properties are held constant. Such behaviour is chemically plausible, as lignin-rich fractions may promote the formation of heavier phenolic structures and char under certain pyrolysis conditions, thereby reducing the yield of condensable liquids.

Higher heating value emerges as the most consistent predictor across the evaluated models and may serve as an integrative screening parameter for estimating the potential bio-oil output of different feedstocks. Its strong performance likely reflects its role as a proxy for energy-dense organic fractions that favour volatilization and liquid formation.

Although the multivariate model achieves a high in-sample fit ($R^2 = 0.92$), this result should be interpreted cautiously. The dataset is limited in size, aggregated from heterogeneous studies, and subject to multicollinearity, all of which constrain the robustness and generalizability of the findings. Strengthening the statistical evidence will require reporting adjusted R^2, standard errors, p-values, confidence intervals, multicollinearity diagnostics, and residual analyses. Moreover, cross-validation or testing against independent experimental data is essential before drawing firm predictive conclusions.

Application of the MRA model to the locally measured biomass samples yields predicted bio-oil outputs in the range of 22.50 % to 44.00 %, identifying pine needles (B1) and wood sawdust (B2) as the highest-yielding candidates within this subset. These predictions are consistent with the general tendencies observed in the literature but should be validated experimentally to confirm their reliability under controlled pyrolysis conditions.

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