

## Article

# Temperature-Dependent Chemical Profiles of Pyroligneous Liquor Fractions from a Kiln-Furnace System

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## Abstract

Pyroligneous liquor (PL) is a by-product of charcoal production with potential applications in agriculture, forestry, and industry. This study evaluated the influence of carbonization temperature on the yield, chemical composition, and physicochemical properties of PL obtained from *Eucalyptus* spp. in a sustainable kiln-furnace system. PL fractions were collected at four temperature intervals: T1 (60–170 °C), T2 (171–270 °C), T3 (271–350 °C), and T4 (351–400 °C). The recovery of condensable gases did not affect the quality of the charcoal and minimized pollutant emissions. Gas chromatography–mass spectrometry (GC-MS) identified 78 organic compounds, mainly carboxylic acids, phenolic compounds, alcohols, carbohydrates, and aromatics. The highest PL yield was obtained in T3 (271–350 °C), accounting for 27% of the recovered liquor and showing high phenolic content, including syringol and catechol. In contrast, T1 (60–170 °C) showed the lowest yield and was dominated by carboxylic acids, particularly acetic acid. Carbonization temperature affected both PL composition and physicochemical properties, resulting in higher electrical conductivity and vegetable tar content at higher temperatures. Hierarchical cluster analysis revealed distinct compound groups according to their concentration patterns across the evaluated temperature intervals. These results reinforce the notion that the evolution of pyrolysis vapors is not a continuous or homogeneous process, but rather occurs through discrete and chemically distinct stages driven by the sequential decomposition of hemicellulose, cellulose, and lignin—a behavior that directly justifies the temperature-based fractionation approach adopted. It was found that temperature-controlled fractionation effectively yields pyrolysis liquid (PL) fractions with distinct chemical profiles, facilitating the selective recovery of value-added compounds for forest biomass biorefineries and specific end-use applications, in addition to offering environmental benefits.

**Keywords:** *Eucalyptus*; charcoal production; wood vinegar; thermochemistry; phenolics; biomass; pyrolysis



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## 1. Introduction

Pyroligneous liquor (PL) is a by-product of wood carbonization that is obtained through the condensation of gases released during the process of slow pyrolysis. The process of producing charcoal in a sustainable manner is widely employed and involves the thermal decomposition of wood, which is typically derived from plantation species such as *Eucalyptus* spp. during the process of carbonization, approximately 33% of the wood is converted into charcoal, whereas nearly 60% is recovered as valuable co-products, including PL, synthesis gas (syngas), and tar [1–3].

PL is the acronym for the aqueous fraction of bio-oil, a biphasic liquid formed by the condensation of volatile compounds generated during the process of pyrolysis. Subsequent to a settling period, the bio-oil undergoes a phase separation, resulting in the formation of two distinct phases. The first phase is a dense, oily fraction, which is commonly referred to as vegetable tar. The second phase is an aqueous fraction, which is also referred to as pyroligneous liquor. PL typically manifests a yellow to reddish-brown hue and is predominantly composed of water (80%–90%), along with a diverse array of organic compounds, including acetic acid, methanol, phenols, furans, and esters [4–6]. Due to its intricate chemical composition, PL has garnered significant interest for agricultural applications as a natural fertilizer and biopesticide. Additionally, it exhibits considerable promise for the synthesis of value-added chemicals and bioenergy [7,8].

The chemical composition of PL is found to be strongly influenced by the carbonization conditions, particularly the temperature at which it is collected. At moderate temperatures (80–120 °C), PL generally exhibits characteristics that are well-suited for agricultural applications, including relatively low concentrations of polycyclic aromatic hydrocarbons (PAHs). These toxic compounds tend to form at higher pyrolysis temperatures [9,10]. Furthermore, the thermochemical conditions applied during pyrolysis, along with the biomass characteristics, such as the contents of lignin, cellulose, and hemicellulose, directly affect the yield and chemical composition of PL [11–14].

Despite the fact that a considerable body of research has been dedicated to investigating the physicochemical properties and chemical composition of pyroligneous liquor, the majority of these studies have been conducted under controlled laboratory conditions using muffle furnaces or small-scale pyrolysis systems. Conversely, research assessing PL yield in industrial or semi-industrial charcoal production systems, such as kiln-furnace technologies, remains restricted. Furthermore, the majority of published studies treat pyroligneous liquor as a single product, neglecting to consider the collection of fractions across disparate carbonization temperature intervals. Consequently, there is still limited understanding of how the progressive thermal degradation of biomass affects the yield, physicochemical properties, and distribution of organic compounds throughout the carbonization process. Addressing these knowledge gaps is imperative for enhancing the selective recovery of high-value compounds and propelling the sustainable utilization of pyro-ligneous liquor within integrated forest biomass biorefineries.

Despite growing interest in pyroligneous liquor, two specific and complementary knowledge gaps remain: (i) a limited understanding of how the progressive thermal degradation of biomass constituents affects PL yield, physicochemical properties, and the distribution of organic compounds throughout an industrial-scale carbonization cycle; (ii) a lack of information on the effects of temperature-fractionated collection specifically under real, operational kiln-furnace conditions, as opposed to the controlled laboratory-scale pyrolysis systems addressed in most previous studies. Addressing these two complementary gaps is essential for improving the selective recovery of high-value compounds and advancing the integration of PL into sustainable forest biomass biorefineries.

## 2. Materials and Methods

### 2.1. Carbonization in a Kiln-Furnace System

Wood carbonization was carried out at the Sustainable Charcoal Production Unit of the Federal University of Minas Gerais (UFMG), located at the Institute of Agricultural Sciences (ICA), Montes Claros campus, Minas Gerais, Brazil (16°45'42" S, 43°50'51" W). According to the Köppen–Geiger climate classification [15], the region has an Aw climate (tropical savanna with a dry winter). Based on historical records from the Brazilian National Institute of Meteorology (INMET, 2003–2024), the site has a mean annual temperature of 23.1 °C, annual precipitation of 877 mm, and an altitude of 655.21 m.

The kiln–furnace system consists of four masonry kilns interconnected by ducts that convey non-condensable gases to a central furnace, where they are combusted. Its construction and operation follow a previously established methodology. Steel cylinders are installed to monitor temperature, while metal plates are used to support the structure and direct heat flow. During operation, butterfly valves regulate gas flow and air intake throughout the carbonization process, ensuring stable, controlled, and safe operation [16].

Condensable gases are recovered using a water-cooled condenser installed beneath the exhaust ducts. In this system, circulating water acts as the cooling medium, promoting heat exchange between the hot gases generated during carbonization and the cooled condenser surfaces. As the gas temperature decreases, condensable vapors liquefy, producing pyroligneous liquor (PL), whereas the remaining non-condensable gases are directed to the central furnace for combustion (Figure 1).

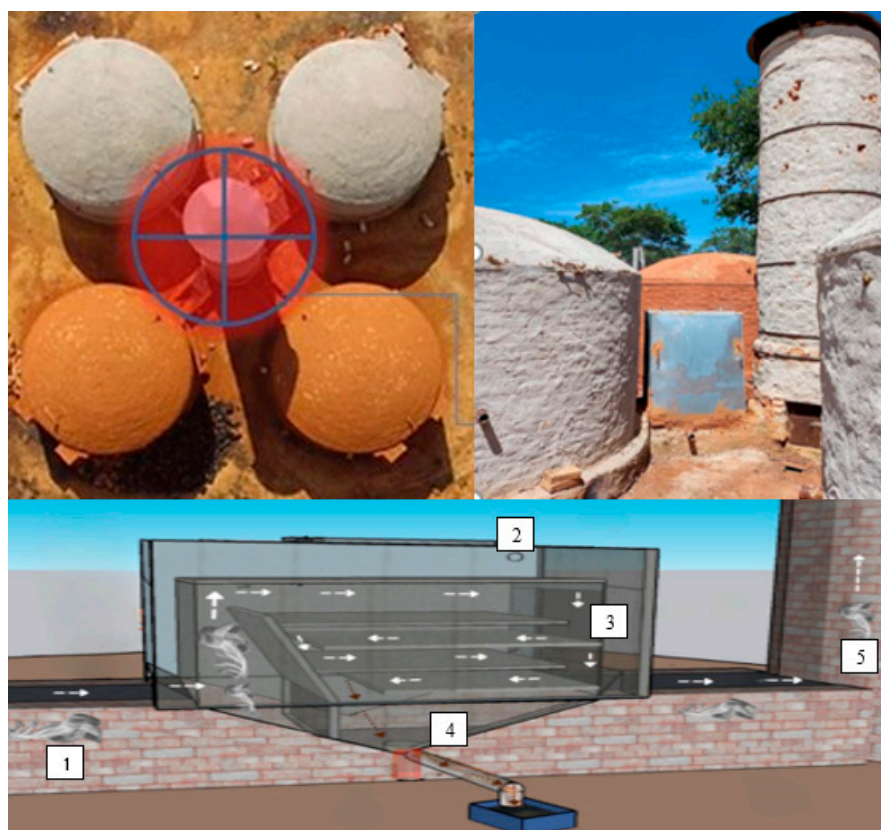


**Figure 1.** Carbonization plant of the kiln-furnace system with four furnaces interconnected in a central furnace. (1) Gas outlet from the furnaces during carbonization; (2) condenser and cooling of pyrolysis gases; (3) passage of gases through the condenser; (4) collection of pyroligneous liquor; (5) burning of non-condensed gases. Source: Adapted from the Sustainable Steelmaking Project, MMA, ICA—UFMG University, Brazil, 2019.

The carbonization cycle lasted 66 h. Throughout the process, temperatures were continuously monitored using a pyrometer, and aliquots of PL were collected at the condenser outlet. The collected liquor was subsequently separated into four fractions corresponding to the different thermal stages of the carbonization process, defined according to the temperature adopted in this study.

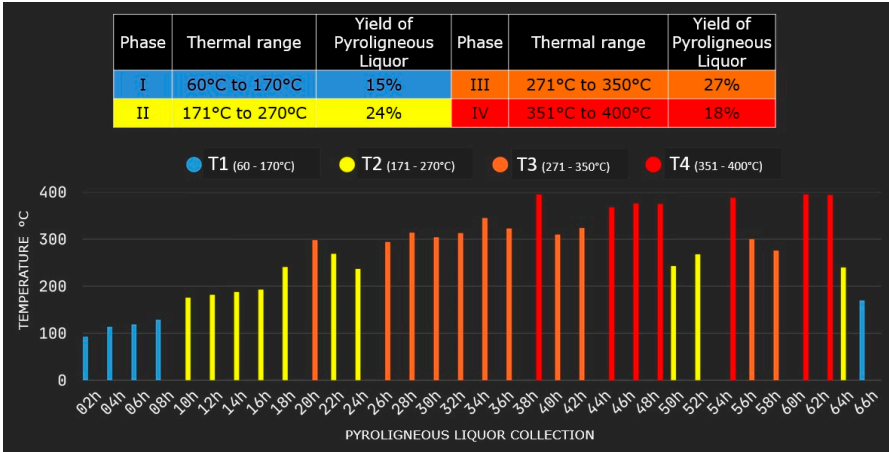
2.2. Experimental Sampling

The feedstock consisted of *Eucalyptus* spp. wood with an average density of 500 kg m<sup>-3</sup>. Logs ranging from 7 to 14 cm in diameter were carbonized in a kiln-furnace system during a single 66 h carbonization cycle. Each kiln was loaded with 9 m<sup>3</sup> of wood (4.5 t) at an initial moisture content of 12.6%. Throughout the process, the pyroligneous liquor (PL) produced in the condenser was continuously collected and fractionated according to the temperatures recorded by pyrometers installed in the system.

The carbonization process achieved a gravimetric charcoal yield of 30.3% and enabled the recovery of approximately 120 kg of condensable liquids (pyroligneous liquor and tar) from 4.467 kg of wood. Prior to the installation of the condenser, these condensable gases were lost as thermal energy during combustion in the furnace. Their recovery therefore represents an opportunity to increase the overall efficiency of the process by valorizing an additional carbonization co-product.

The condensable products consisted of approximately 84% pyroligneous liquor and 16% tar. Each thermal interval generated a distinct pyroligneous liquor fraction corresponding to a specific stage of the carbonization process (60–400 °C), allowing the evaluation of temperature-dependent changes in its chemical composition. The charcoal produced exhibited a bulk density of 161.9 kg m<sup>-3</sup>, 5.2% partially carbonized wood (atiço), and 0.7% fines. Its proximate analysis revealed 24.2% volatile matter, 75.2% fixed carbon, 0.65% ash content, and 5.5% moisture, indicating charcoal quality suitable for metallurgical applications.

Four temperature intervals were established based on the carbonization thermal profile: T1 (60–170 °C), T2 (171–270 °C), T3 (271–350 °C), and T4 (351–400 °C) (Figure 2). All PL produced within each temperature interval was collected and pooled to obtain a representative composite sample for the corresponding thermal stage, according to [16].



After collection, the samples were stored under ambient conditions and allowed to decant naturally for approximately one year to promote phase separation and stabilization. Subsequently, the aqueous fraction was separated and subjected to double filtration prior to physicochemical and chromatographic analyses, following the methodology described by [17].

### 2.3. Evaluation of the Organic Compound Composition of Pyroligneous Liquor

The chemical composition of the PL fractions was determined by gas chromatography–mass spectrometry (GC–MS). Analyses were performed using an Agilent Technologies GC 7890A gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) coupled to a mass spectrometer and equipped with an SLB-5MS capillary column (Supelco, Bellefonte, PA, USA; 30 m × 0.25 mm i.d. × 0.25 µm film thickness). Helium (99.999% purity) was used as the carrier gas at a constant flow rate of 1.0 mL min<sup>−1</sup>.

### 2.4. Physicochemical Characterization of Pyroligneous Liquor Fractions

Physicochemical analyses of the PL fractions were performed at the Federal University of Minas Gerais, Montes Claros campus. The pH was measured using a benchtop digital pH meter. Relative density (D) was determined gravimetrically using a glass pycnometer according to ASTM D1217 [18]. Electrical conductivity (EC) was measured with a conductivity meter following APHA Method 2510 [19], and the results were expressed as µS cm<sup>−1</sup>. Kinematic viscosity (V) was determined according to ASTM D1200 [20] and expressed in cSt (mm<sup>2</sup> s<sup>−1</sup>). Water content, soluble solids, and vegetable tar content were determined using a corrected Brix refractometer according to the methodology described by [21].

### 2.5. Data Processing and Analysis

The relationship between carbonization temperature and the chemical composition of pyroligneous liquor was evaluated using the compounds identified by GC–MS in the four temperature intervals: T1 (60–170 °C), T2 (171–270 °C), T3 (271–350 °C), and T4 (351–400 °C). Data processing and graphical analyses were performed using Microsoft Excel and RStudio v.4.2.2 [22].

Because the PL fractions represented composite samples obtained from a single carbonization cycle, the chemical composition data were interpreted descriptively, emphasizing the relative abundance and distribution of compounds among the evaluated temperature range.

To compare the chemical profiles among temperature intervals, only compounds detected in all four PL fractions were considered. A data matrix containing compounds unidentified, 21 compounds × 4 temperature range, expressed as relative percentage values, was standardized and subjected to hierarchical cluster analysis using Euclidean distance and the complete linkage method. This analysis enabled the classification of compounds according to similarities in class their concentration profiles across the different carbonization temperature ranges.

Following hierarchical clustering, the relative abundances of the compounds within each cluster were summarized using boxplots. Letter labels were assigned to identify the grouping of the average values among clusters and were used exclusively as a descriptive aid to facilitate data interpretation.

The physicochemical properties, including pH, relative density (D), electrical conductivity (EC), and kinematic viscosity (V), were determined in analytical triplicate. Mean values, standard deviations, and coefficients of variation were calculated. Water content, soluble solids, and vegetable tar content were also determined in analytical triplicate, and the corresponding mean values are presented.

### 3. Results

#### 3.1. Organic Chemical Compounds Identified by GC-MS Analysis

A total of 78 compounds were identified by GC-MS based on their mass spectra and molecular structures (Table 1). The identified compounds included substances with different molecular complexities and concentrations, highlighting the diversity of organic constituents present in the pyrolygneous liquor (PL) obtained from the kiln-furnace carbonization system (Figure 3).

**Table 1.** Organic chemical composition and substances identified in the GC-MS analysis in the four temperature intervals evaluated.

| PL              | RT   | Peak | Organic Composition        | Molecule                                         | %    |
|-----------------|------|------|----------------------------|--------------------------------------------------|------|
| T1 (60–170 °C)  | 7.4  | 1    | Phenol                     | (C <sub>6</sub> H <sub>6</sub> O)                | 0.3  |
| T1 (60–170 °C)  | 7.5  | 2    | Lactic acid                | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 3.2  |
| T1 (60–170 °C)  | 8.1  | 3    | Acetic acid                | (C <sub>2</sub> H <sub>4</sub> O <sub>2</sub> )  | 12.0 |
| T1 (60–170 °C)  | 9.8  | 4    | 2-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 1.1  |
| T1 (60–170 °C)  | 10.4 | 5    | m-Cresol                   | (C <sub>7</sub> H <sub>8</sub> O)                | 0.2  |
| T1 (60–170 °C)  | 10.5 | 6    | 3-Hydroxypropanoic acid    | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 0.3  |
| T1 (60–170 °C)  | 10.8 | 8    | p-Cresol                   | (C <sub>8</sub> H <sub>10</sub> O <sub>2</sub> ) | 0.1  |
| T1 (60–170 °C)  | 13.8 | 10   | 4-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 4.4  |
| T1 (60–170 °C)  | 15.2 | 11   | Glycerin                   | (C <sub>3</sub> H <sub>8</sub> O <sub>3</sub> )  | 0.5  |
| T1 (60–170 °C)  | 16.5 | 12   | Catechol                   | (C <sub>6</sub> H <sub>6</sub> O <sub>2</sub> )  | 5.6  |
| T1 (60–170 °C)  | 16.9 | 13   | Methylbutanedioic acid     | (C <sub>5</sub> H <sub>8</sub> O <sub>4</sub> )  | 1.0  |
| T1 (60–170 °C)  | 17.2 | 14   | 5-Hydroxypentanoic acid    | (C <sub>5</sub> H <sub>10</sub> O <sub>3</sub> ) | 2.0  |
| T1 (60–170 °C)  | 19.0 | 16   | 4-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.2  |
| T1 (60–170 °C)  | 19.3 | 17   | 3-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.0  |
| T1 (60–170 °C)  | 19.4 | 18   | Syringol                   | (C <sub>8</sub> H <sub>10</sub> O <sub>3</sub> ) | 13.4 |
| T1 (60–170 °C)  | 19.8 | 19   | 2,4-Dihydroxybutanoic acid | (C <sub>4</sub> H <sub>8</sub> O <sub>4</sub> )  | 1.9  |
| T1 (60–170 °C)  | 21.3 | 20   | Guaiacol                   | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 0.5  |
| T1 (60–170 °C)  | 28.1 | 30   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 0.4  |
| T1 (60–170 °C)  | 28.4 | 31   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 12.3 |
| T2 (171–270 °C) | 7.4  | 1    | Phenol                     | (C <sub>6</sub> H <sub>6</sub> O)                | 0.4  |
| T2 (171–270 °C) | 7.5  | 2    | Lactic acid                | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 3.2  |
| T2 (171–270 °C) | 8.1  | 3    | Acetic acid                | (C <sub>2</sub> H <sub>4</sub> O <sub>2</sub> )  | 12.1 |
| T2 (171–270 °C) | 9.8  | 4    | 2-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 1.1  |
| T2 (171–270 °C) | 10.1 | 5    | Valeric acid               | (C <sub>5</sub> H <sub>10</sub> O <sub>2</sub> ) | 1.1  |
| T2 (171–270 °C) | 10.4 | 6    | m-Cresol                   | (C <sub>7</sub> H <sub>8</sub> O)                | 0.2  |
| T2 (171–270 °C) | 10.5 | 7    | 3-Hydroxypropanoic acid    | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 0.3  |
| T2 (171–270 °C) | 13.8 | 12   | 4-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 3.3  |
| T2 (171–270 °C) | 14.2 | 13   | Benzoic acid               | (C <sub>7</sub> H <sub>6</sub> O <sub>2</sub> )  | 0.2  |
| T2 (171–270 °C) | 15.2 | 16   | Glycerin                   | (C <sub>3</sub> H <sub>8</sub> O <sub>3</sub> )  | 0.3  |
| T2 (171–270 °C) | 16.5 | 19   | Catechol                   | (C <sub>6</sub> H <sub>6</sub> O <sub>2</sub> )  | 6.0  |
| T2 (171–270 °C) | 16.9 | 20   | Methylbutanedioic acid     | (C <sub>5</sub> H <sub>8</sub> O <sub>4</sub> )  | 0.8  |
| T2 (171–270 °C) | 17.2 | 22   | 5-Hydroxypentanoic acid    | (C <sub>5</sub> H <sub>10</sub> O <sub>3</sub> ) | 1.5  |
| T2 (171–270 °C) | 19.0 | 28   | 4-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.1  |
| T2 (171–270 °C) | 19.3 | 29   | 3-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.1  |
| T2 (171–270 °C) | 19.4 | 30   | Syringol                   | (C <sub>8</sub> H <sub>10</sub> O <sub>3</sub> ) | 12.4 |
| T2 (171–270 °C) | 19.6 | 31   | Glutaric acid              | (C <sub>5</sub> H <sub>8</sub> O <sub>4</sub> )  | 0.1  |
| T2 (171–270 °C) | 19.8 | 32   | 2,4-Dihydroxybutanoic acid | (C <sub>4</sub> H <sub>8</sub> O <sub>4</sub> )  | 2.3  |
| T2 (171–270 °C) | 21.3 | 36   | Guaiacol                   | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 0.6  |
| T2 (171–270 °C) | 27.8 | 54   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 0.3  |
| T2 (171–270 °C) | 28.1 | 56   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 0.3  |
| T2 (171–270 °C) | 28.4 | 57   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 10.3 |

Table 1. Cont.

| PL              | RT   | Peak | Organic Composition        | Molecule                                         | %    |
|-----------------|------|------|----------------------------|--------------------------------------------------|------|
| T3 (271–350 °C) | 7.4  | 1    | Phenol                     | (C <sub>6</sub> H <sub>6</sub> O)                | 0.7  |
| T3 (271–350 °C) | 7.5  | 2    | Lactic acid                | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 2.8  |
| T3 (271–350 °C) | 8.1  | 3    | Acetic acid                | (C <sub>2</sub> H <sub>4</sub> O <sub>2</sub> )  | 13.4 |
| T3 (271–350 °C) | 10.4 | 5    | m-Cresol                   | (C <sub>7</sub> H <sub>8</sub> O)                | 0.4  |
| T3 (271–350 °C) | 10.5 | 6    | 3-Hydroxypropanoic acid    | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 0.3  |
| T3 (271–350 °C) | 10.8 | 8    | p-Cresol                   | (C <sub>8</sub> H <sub>10</sub> O <sub>2</sub> ) | 0.2  |
| T3 (271–350 °C) | 13.8 | 10   | 4-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 2.7  |
| T3 (271–350 °C) | 15.2 | 12   | Glycerin                   | (C <sub>3</sub> H <sub>8</sub> O <sub>3</sub> )  | 0.3  |
| T3 (271–350 °C) | 16.5 | 13   | Catechol                   | (C <sub>6</sub> H <sub>6</sub> O <sub>2</sub> )  | 7.5  |
| T3 (271–350 °C) | 16.9 | 14   | Methylbutanedioic acid     | (C <sub>5</sub> H <sub>8</sub> O <sub>4</sub> )  | 1.3  |
| T3 (271–350 °C) | 17.2 | 15   | 5-Hydroxypentanoic acid    | (C <sub>5</sub> H <sub>10</sub> O <sub>3</sub> ) | 1.1  |
| T3 (271–350 °C) | 19.0 | 17   | 4-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.9  |
| T3 (271–350 °C) | 19.3 | 18   | 3-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.7  |
| T3 (271–350 °C) | 19.4 | 19   | Syringol                   | (C <sub>8</sub> H <sub>10</sub> O <sub>3</sub> ) | 10.4 |
| T3 (271–350 °C) | 19.8 | 20   | 2,4-Dihydroxybutanoic acid | (C <sub>4</sub> H <sub>8</sub> O <sub>4</sub> )  | 2.5  |
| T3 (271–350 °C) | 21.3 | 21   | Guaiacol                   | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 0.7  |
| T3 (271–350 °C) | 28.1 | 30   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 0.3  |
| T3 (271–350 °C) | 28.4 | 31   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 9.6  |
| T4 (351–400 °C) | 7.4  | 1    | Phenol                     | (C <sub>6</sub> H <sub>6</sub> O)                | 0.7  |
| T4 (351–400 °C) | 7.5  | 2    | Lactic acid                | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 2.0  |
| T4 (351–400 °C) | 8.1  | 3    | Acetic acid                | (C <sub>2</sub> H <sub>4</sub> O <sub>2</sub> )  | 7.7  |
| T4 (351–400 °C) | 9.8  | 4    | 2-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 0.7  |
| T4 (351–400 °C) | 10.4 | 5    | m-Cresol                   | (C <sub>7</sub> H <sub>8</sub> O)                | 0.3  |
| T4 (351–400 °C) | 10.5 | 6    | 3-Hydroxypropanoic acid    | (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )  | 0.2  |
| T4 (351–400 °C) | 13.8 | 9    | 4-Hydroxybutanoic acid     | (C <sub>4</sub> H <sub>8</sub> O <sub>3</sub> )  | 2.8  |
| T4 (351–400 °C) | 14.2 | 10   | Benzoic acid               | (C <sub>7</sub> H <sub>6</sub> O <sub>2</sub> )  | 0.3  |
| T4 (351–400 °C) | 15.2 | 11   | Glycerin                   | (C <sub>3</sub> H <sub>8</sub> O <sub>3</sub> )  | 0.3  |
| T4 (351–400 °C) | 16.5 | 12   | Catechol                   | (C <sub>6</sub> H <sub>6</sub> O <sub>2</sub> )  | 6.7  |
| T4 (351–400 °C) | 16.9 | 13   | Methylbutanedioic acid     | (C <sub>5</sub> H <sub>8</sub> O <sub>4</sub> )  | 1.8  |
| T4 (351–400 °C) | 17.2 | 14   | 5-Hydroxypentanoic acid    | (C <sub>5</sub> H <sub>10</sub> O <sub>3</sub> ) | 1.9  |
| T4 (351–400 °C) | 19.0 | 16   | 4-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 1.5  |
| T4 (351–400 °C) | 19.3 | 17   | 3-Methylcatechol           | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 0.9  |
| T4 (351–400 °C) | 19.4 | 18   | Syringol                   | (C <sub>8</sub> H <sub>10</sub> O <sub>3</sub> ) | 12.7 |
| T4 (351–400 °C) | 19.8 | 19   | 2,4-Dihydroxybutanoic acid | (C <sub>4</sub> H <sub>8</sub> O <sub>4</sub> )  | 2.7  |
| T4 (351–400 °C) | 21.3 | 20   | Guaiacol                   | (C <sub>7</sub> H <sub>8</sub> O <sub>2</sub> )  | 0.7  |
| T4 (351–400 °C) | 28.1 | 29   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 0.2  |
| T4 (351–400 °C) | 28.4 | 30   | Glucose isomer             | (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> ) | 6.3  |

LEGEND: Pyroligneous Liquor (PL), Retention Time (RT) minute, percentage (%) or relative area obtained by the Agilent Technologies gas chromatograph method (GC 7890A) equipped with a mass spectrum (MS) detector.

The compounds were classified into five functional chemical groups to facilitate the interpretation of the chemical composition of the PL fractions collected at different temperature intervals. The identified groups accounted for 62.9% of the total chromatographic area in T1 (60–170 °C), 61.2% in T2 (171–270 °C), 58.9% in T3 (271–350 °C), and 51.1% in T4 (351–400 °C). Thus, more than half of the compounds detected in each PL fraction were assigned to known functional chemical groups with defined molecular structures.

Furthermore the GC–MS analysis also detected several compounds that could not be identified by comparison with the NIST spectral library (Table 2).

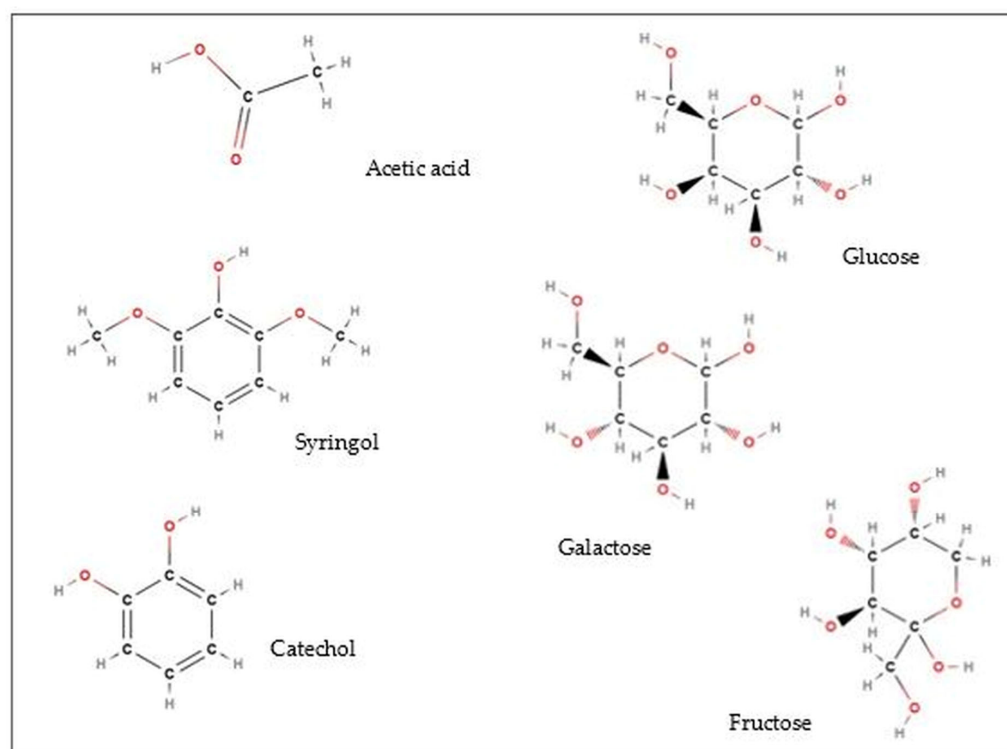


**Figure 3.** Structural formulas of organic compounds with the highest percentage in the treatments. Source: Prepared by the authors.

**Table 2.** Compounds not identified via GC-MS analysis.

| PL              | Compounds not Identified | %    |
|-----------------|--------------------------|------|
| T1 (60–170 °C)  | 5                        | 26.6 |
| T2 (171–270 °C) | 5                        | 28.9 |
| T3 (271–350 °C) | 7                        | 32.4 |
| T4 (351–400 °C) | 6                        | 39.6 |

LEGEND: Pyroligneous Liquor (PL), count of unidentified compounds.

The analytical method employed is primarily designed for the identification of low-molecular-weight organic compounds. Therefore, the occurrence of unidentified peaks may be associated with compounds not represented in the spectral database, as well as substances derived from the complex chemical matrix of *Eucalyptus* biomass. These unidentified constituents may include compounds formed during thermochemical conversion that require complementary analytical approaches for structural elucidation.

Differences in PL yield were observed among the evaluated temperature intervals. The highest yield was obtained for the PL fraction collected between 271 and 350 °C (T3), corresponding to 27% of the total recovered liquor, followed by the fraction collected between 171 and 270 °C (T2) with 24%, the fraction collected between 351 and 400 °C (T4) with 18%, and the fraction collected between 60 and 170 °C (T1) with 15%. The highest PL recovery occurred within the intermediate temperatures (271–350 °C), indicating that condensable product formation was maximized during this stage of carbonization.

### 3.2. Chemical Composition Analysis

The chemical composition of the pyroligneous liquor (PL) fractions varied according to the carbonization temperature interval, indicating that thermal conditions influenced the formation and distribution of organic compounds throughout the process. Differences were

observed in the relative abundance of the major functional chemical groups, particularly carboxylic acids, phenolic compounds, carbohydrates, and aromatic compounds.

At lower temperatures within T1 (60–170 °C), the PL fractions were characterized by a greater contribution of compounds associated with the initial degradation of hemicelluloses, especially carboxylic acids such as acetic acid. At intermediate temperatures within T2 (171–350 °C), the decomposition of hemicellulose and cellulose intensified, accompanied by the onset of lignin degradation and an increased occurrence of phenolic compounds, including syringol and catechol.

The fraction collected within T3 (271–350 °C) exhibited the highest yield and the greatest abundance of phenolic compounds, were characterized by a greater contribution of carboxylic acids, especially acetic acid, which is associated with the degradation of hemicelluloses during the initial stages of biomass thermoconversion. These fractions also showed lower concentrations of phenolic compounds derived from lignin decomposition.

At higher temperatures within T4 (351–400 °C), the chemical profile reflected the continued transformation of lignin-derived structures and the formation of secondary phenolic compounds. These compositional changes indicate that the chemical characteristics of PL evolve throughout the carbonization process and are closely associated with the temperature interval at which condensable products are recovered.

This pattern is consistent with the progressive degradation of lignin and the formation of secondary oxygenated compounds during intermediate stages of carbonization. The enrichment of phenolic constituents in this temperature interval suggests a greater recovery of lignin-derived compounds, which have been associated with antioxidant and bioactive properties in previous studies.

In contrast, the fraction collected at the highest temperatures within T4 (351–400 °C) presented a distinct chemical profile characterized by the persistence of phenolic compounds and a reduction in carbohydrate-derived compounds. This behavior reflects the continuation of lignin decomposition reactions and the increasing thermal transformation of intermediate products generated during earlier carbonization stages.

### 3.3. Hierarchical Clustering of Organic Compounds

Hierarchical cluster analysis grouped the identified compounds according to similarities in their relative abundance across the four PL fractions (Figure 4). Compounds exhibiting similar abundance profiles were clustered together in the hierarchical structure, allowing the identification of groups with related chemical behavior throughout the carbonization process and compounds not identified: Unidentified (U), Unidentified aromatic (UA), Unidentified carbohydrate (UC).

Cluster numbering follows the hierarchical branch-merging order ( $k = 4$ , Euclidean distance) and does not imply a hierarchy of importance or magnitude among the clusters. Colors are consistent with those used in Figure 5. Cluster 1 comprised compounds with relatively low concentrations and limited variation among temperature intervals. Cluster 2 included compounds with intermediate concentrations and moderate variation. Cluster 3 was composed of compounds with higher relative abundances and more pronounced changes across the evaluated temperature. Different letters indicate the grouping of the average relative abundances among clusters and are used solely for descriptive purposes to highlight the differences in magnitude between groups.

Changes in the solution occur due to oxygen removal and the relative increase in hydrogen and carbon. In Cluster 1-predominant T4 (351–400 °C), semiquinone stabilization and alkylation (replacing a hydrogen atom in hydrocarbons) occur, leading to the formation of charcoal. In Cluster 2-predominant T1 (60–170 °C) and T2 (171–270 °C), initial deoxy-

genation and a transition of solution compounds take place. In Cluster 3-predominant T3 (271–350 °C), lignin degradation and oxidative demethoxylation occur.

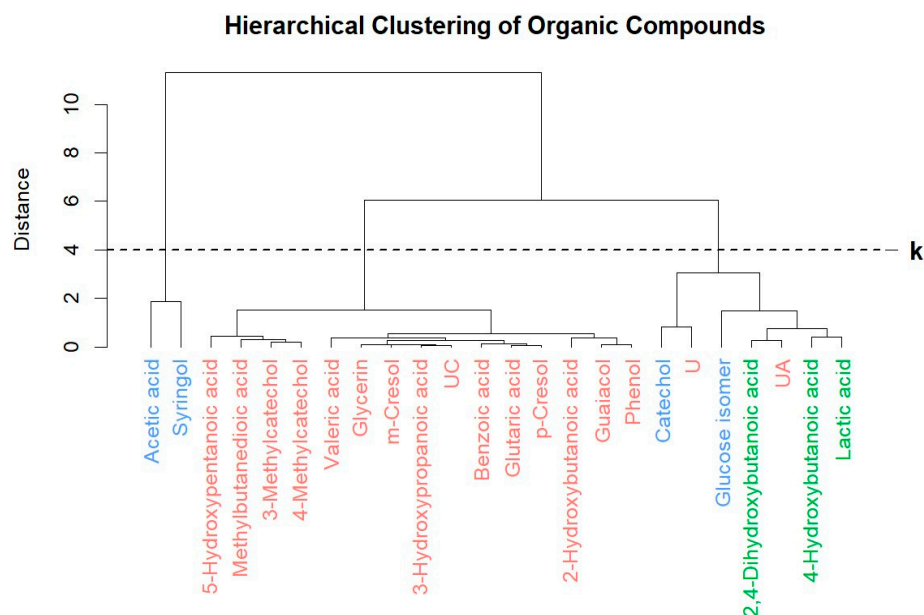


**Figure 4.** Dendrogram of organic chemical compounds present in pyroligneous liquors. Source: Prepared by the authors.

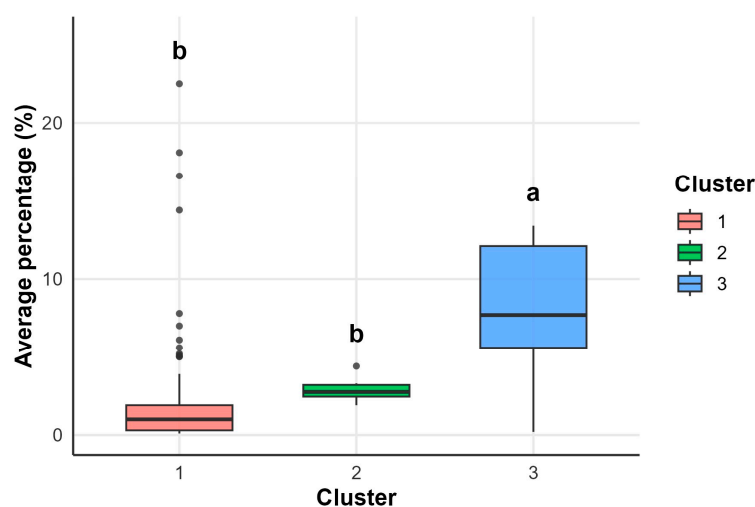


**Figure 5.** Distribution of the average concentration of organic chemical compounds by cluster. Source: Prepared by the authors.

The hierarchical clustering analysis demonstrated that compounds with similar concentration patterns can be grouped according to their behavior during thermochemical conversion. We found that contributes to understanding the distribution of organic compounds among PL fractions and supports the selective collection of pyroligneous liquor according to the desired chemical composition and potential end use.

### 3.4. Chemical Groups of Pyroligneous Liquor Fractions

The compounds identified by GC–MS were classified into five major functional chemical groups, namely carboxylic acids, phenolic compounds, alcohols, carbohydrates, and aromatic compounds. The percentages presented represent the cumulative relative abundance of the identified compounds assigned to each group. Unidentified compounds and compounds not assigned to these categories were not included in this classification.

Among the identified constituents, acetic acid was the predominant carboxylic acid, whereas syringol and catechol were the main phenolic constituents. The proportion of carboxylic acids decreased from 25.9% in the fraction collected in T1 (60–170 °C) to 26.0% in T2 (171–270 °C), 24.1% in T3 (271–350 °C), and 20.1% in T4 (351–400 °C). In contrast, phenolic compounds increased from 22.3% in T1 (60–170 °C) to 23.5% in T3 (271–350 °C) and T4 (351–400 °C), with an intermediate value of 21.7% observed in T2 (171–270 °C).

Carbohydrates exhibited a progressive decrease with increasing temperature interval, ranging from 14.2% in T1 (60–170 °C) to 13.1% in T2 (171–270 °C), 11.0% in T3 (271–350 °C), and 8.1% in T4 (351–400 °C). Alcohols accounted for the smallest proportion among the identified functional chemical groups, varying from 0.5% in T1 (60–170 °C) to 0.3% in the remaining PL fractions.

Aromatic compounds showed relatively small variations among the thermal stage, corresponding to 10.7%, 9.8%, 8.6%, and 9.3% for T1 (60–170 °C), T2 (171–270 °C), T3 (271–350 °C), and T4 (351–400 °C), respectively. Overall, the relative abundance of the identified functional chemical groups changed throughout the carbonization process, resulting in distinct chemical profiles among the PL fractions collected at different temperatures.

### 3.5. Physicochemical Properties of Pyroligneous Liquor Fractions

All PL fractions exhibited acidic pH values ranging from 3.4 to 3.8, while relative density showed only minor variation among the evaluated temperature intervals, remaining close to that of water (Table 3). Electrical conductivity exhibited an increase with rising collection temperature, attaining its maximum value in the PL fraction collected between 351 and 400 °C (T4).

**Table 3.** Descriptive statistics of the physicochemical properties of pyroligneous liquors.

| Temperature Interval | Physicochemical Properties |            |          |         |
|----------------------|----------------------------|------------|----------|---------|
|                      | pH                         | EC (μS/cm) | D (g/mL) | V (cSt) |
| T1 (60–170 °C)       | 3.4                        | 4.9800     | 1.029    | 6.43    |
| T2 (171–270 °C)      | 3.5                        | 10.6500    | 1.038    | 7.01    |
| T3 (271–350 °C)      | 3.8                        | 10.1100    | 1.030    | 7.14    |
| T4 (351–400 °C)      | 3.6                        | 12.3000    | 1.020    | 7.21    |
| $\bar{x}$            | 3.6                        | 9.260      | 1.029    | 6.95    |
| s                    | 0.171                      | 3.174      | 0.007    | 0.36    |
| CV%                  | 4.78                       | 34.27      | 0.720    | 5.11    |

LEGEND: The parameters analyzed include pH, electrical conductivity (EC), relative density (D) and kinematic viscosity (V), mean ( $\bar{x}$ ), standard deviation (s) and coefficient of variation (CV%).

Kinematic viscosity exhibited minimal variation among the PL fractions and remained higher than that of pure water across the entire temperature range. The low viscosity values were consistent with the high water content of the samples.

The water, soluble solids, and vegetable tar contents are presented in (Table 4).

Conversely, an inverse relationship was observed between water content and temperature, with a decrease in water content observed at higher temperatures. In contrast, vegetable tar content exhibited an increase from lower to intermediate temperatures. The PL fraction collected between 271 and 350 °C (T3) exhibited the highest vegetable tar content. Soluble solids exhibited variability among the PL fractions, indicative of disparities in the concentration of dissolved constituents recovered during the carbonization process.

The physicochemical properties exhibited variability among the PL fractions, indicative of alterations in the composition of the condensable products recovered throughout the carbonization process. The findings substantiate the notion that the thermochemical conversion of biomass exerts a direct influence on the chemical composition and physicochemical

properties of the PL. The transition from carboxylic acid-rich fractions at lower temperatures to phenol-rich fractions at intermediate and higher temperatures underscores the importance of temperature-controlled collection systems for the development of integrated forest biomass biorefineries.

**Table 4.** Aspects of pyroligneous liquors verified on the brix scale and the difference in insoluble vegetable tar.

| Temperature Interval | Water | Soluble Solids | Tar  |
|----------------------|-------|----------------|------|
|                      |       | (%)            |      |
| T1 (60–170 °C)       | 95.7  | 4              | 0.30 |
| T2 (171–270 °C)      | 91.5  | 8              | 0.53 |
| T3 (271–350 °C)      | 87.1  | 12             | 0.93 |
| T4 (351–400 °C)      | 89.1  | 10             | 0.89 |

LEGEND: Percentage of water, soluble tar, and insoluble tar present in the pyroligneous liquor at different temperature ranges during complete carbonization.

A limitation of this study is that the PL fractions were obtained from a single carbonization cycle. Consequently, the results should be interpreted as a detailed characterization of temperature-dependent PL fractions under operational conditions representative of carbonization kilns. Future studies involving multiple carbonization cycles are recommended to assess process variability and confirm the reproducibility of the observed chemical and physicochemical trends.

Despite this limitation, this study provides one of the first detailed characterizations of temperature-fractionated pyroligneous acid obtained under actual kiln operating conditions, offering a valuable foundation for future research aimed at optimizing selective compound recovery and advancing applications in forest biomass biorefineries. It is worth noting that wood degradation and thermochemical conversion occur under varying temperature conditions, whereas PL properties depend specifically on the temperature at which the liquid is collected.

#### 4. Discussion

The present findings demonstrate that the chemical composition of pyroligneous liquor (PL) evolves systematically with carbonization temperature. This phenomenon reflects the sequential thermal degradation of the major lignocellulosic constituents of wood. The observed temperature-dependent behavior suggests that the generation of condensable vapors during the kiln-furnace carbonization cycle is not uniform. Rather, it occurs in discrete, chemically distinct waves that are associated with specific stages of biomass decomposition. Therefore, temperature-controlled fractionation is an effective strategy for selectively recovering PL fractions enriched in target compound classes, rather than a single, chemically averaged product. This distinction is of particular pertinence for forest biomass biorefineries, where process integration and coproduct valorization are pivotal strategies to enhance both the environmental sustainability and the economic viability of charcoal production.

According to [2], the thermal degradation of wood occurs through successive stages that transpire within designated temperature ranges and residence times. These stages culminate in the formation of solid, liquid, and gaseous byproducts. The recovery of PL is directly associated with the thermochemical decomposition of biomass constituents and the subsequent condensation of volatile compounds generated during carbonization [23,24].

Wood is a complex lignocellulosic material composed primarily of cellulose, hemicellulose, and lignin embedded in a structural matrix rich in carbon, hydrogen, and oxygen [25]. During carbonization, these constituents undergo progressive thermal degradation ac-

according to their intrinsic thermal stability. Hemicellulose decomposes at relatively low temperatures, followed by cellulose, whereas lignin degrades over a broader temperature range [26]. This sequential degradation explains the changes observed in the chemical composition of the PL fractions collected at different stages of the carbonization process.

The predominance of carboxylic acids in the fractions collected at lower temperatures is consistent with the degradation of hemicellulose and the formation of oxygenated compounds, particularly acetic acid. As carbonization progressed, the relative abundance of phenolic compounds increased, especially in the fractions collected between 271 and 400 °C. This trend reflects the increasing contribution of lignin-derived compounds to the condensable fraction. Similar changes in the distribution of phenolic and oxygenated compounds as a function of pyrolysis temperature have been reported by [27].

The occurrence of syringol, catechol, guaiacol, and related phenolic derivatives in the intermediate- and high-temperature fractions is particularly relevant because these compounds have been associated with antioxidant activity and other bioactive properties [12,26]. The enrichment of phenolic constituents in the fraction collected between 271 and 350 °C indicates that this temperature interval favors the recovery of higher-value lignin-derived compounds.

Hierarchical cluster analysis further demonstrated that compounds exhibiting similar concentration profiles could be grouped according to their distribution across the evaluated temperature intervals. The clustering of acetic acid, catechol, syringol, and glucose isomers suggests that these compounds are major contributors to the chemical profile of PL and represent key products formed during the thermochemical conversion of lignocellulosic biomass. Similar clustering patterns have been reported in studies investigating the evolution of pyrolysis products from lignocellulosic feedstocks [14].

The distribution of the major functional chemical groups also reflected the sequential degradation of wood constituents. Carboxylic acids predominated at lower temperatures, whereas phenolic compounds became increasingly abundant at intermediate and higher temperatures. This transition is consistent with the progressive decomposition of hemicellulose, cellulose, and lignin and highlights the potential of fractionated collection strategies to obtain PL enriched in specific classes of compounds.

The physicochemical properties of the PL fractions also reflected the influence of carbonization temperature on the composition of the condensable products. The acidic pH observed in all fractions is characteristic of pyroligneous liquor and is mainly attributed to the presence of carboxylic acids and other oxygenated compounds generated during biomass decomposition [14,23]. The persistence of acidic conditions throughout the evaluated temperature range indicates that these compounds remain important constituents of the condensed liquid phase during the entire carbonization process.

Electrical conductivity increased with collection temperature, reaching its highest value in the fraction collected between 351 and 400 °C. According to [28], increasing carbonization temperature affects not only product yield but also physicochemical properties. The increase in conductivity suggests a higher concentration of dissolved ionic species and inorganic constituents in the fractions collected at elevated temperatures. As reported by [29], the physicochemical behavior of acidic solutions is governed by dissociation processes, oxidation reactions, and interactions among dissolved compounds within the aqueous phase.

Relative density remained close to that of water in all PL fractions, confirming that water was the predominant constituent. According to [30], the low viscosity and high mobility of water strongly influence the physical behavior of aqueous pyrolysis products. Likewise, the relatively low kinematic viscosity observed in the PL fractions reflects their high water content, although dissolved organic compounds resulted in viscosity values slightly higher

than those of pure water. According to [31], molecular rearrangements occurring during carbonization directly influence the physicochemical properties of pyroligneous liquor through the continuous formation and cleavage of chemical bonds.

The inverse relationship between water content and vegetable tar content is consistent with the progression of carbonization reactions. The highest tar content was observed in the fraction collected between 271 and 350 °C, coinciding with the temperature range in which lignin degradation becomes more pronounced. Similar trends have been reported by APAN [32] and other authors [5,10,23]. According to [17], higher tar contents may also indicate a greater contribution of heavy aromatic compounds, including substances associated with polycyclic aromatic hydrocarbons (PAHs), which require careful monitoring because of their environmental and toxicological relevance. Likewise, ref. [33] emphasized the importance of controlling these aromatic compounds because some may exhibit carcinogenic, mutagenic, and genotoxic properties.

From the standpoint of biorefining, the results indicate that the chemical composition and physicochemical properties of pyroligneous liquor are significantly impacted by the temperature at which condensable products are recovered. As proposed by [34], selective condensation strategies have the potential to enhance the recovery of specific classes of compounds according to their formation temperatures. Consequently, fractionated collection during carbonization represents a promising approach for maximizing the recovery of value-added compounds and promoting the sustainable utilization of charcoal production coproducts.

This aligns with the temperature ranges and associated phenomena occurring across four phases during charcoal production [16]: Phase I (Endothermic)—Low Temperatures (60 °C to 170 °C): Drying, vaporization, and moisture loss; hemicellulose decomposition and initial formation of carboxylic acids, such as acetic acid. Phase II (Endothermic)—Intermediate Temperatures (171 °C to 270 °C): Torrefaction and gas release; hemicellulose degradation and lignin decomposition, leading to an increase in phenolic compounds like catechol. Phase III (Exothermic)—Specific Temperature Range (271 °C to 350 °C): Charcoal formation; cellulose degradation and a transition from carboxylic acids as the dominant compounds to a higher prevalence of phenolic compounds above 350 °C. This stage marks increased lignin degradation and oxidative demethoxylation, optimizing the composition of the pyroligneous liquor. Phase IV (Exothermic)—High Temperatures (351 °C to 400 °C): Carbon fixation, oxygen reduction, and increased carbon content; enhanced lignin degradation, favoring more complex phenolic compounds such as syringol and 4-methylcatechol.

It was discovered and demonstrate that the chemical composition of PL is strongly associated with the temperature range at which condensable gases are recovered. The progressive transition from acid-rich fractions—obtained at lower temperatures—to phenol-rich fractions—obtained at intermediate and higher temperatures—which indicates that severe decarbonylation and decarboxylation occur predominantly above 350 °C.

Collectively, these findings suggest that compounds with similar concentration patterns share common formation pathways during thermo-chemical conversion, supporting the selective collection of pyroligneous liquor according to the desired chemical composition and potential end use.

## 5. Conclusions

The chemical composition and physicochemical properties of pyroligneous liquor (PL) were strongly influenced by the temperature at which condensable products were recovered during charcoal production in a kiln-furnace system. A total of 78 organic compounds were identified, dominated by carboxylic acids at lower temperatures and by phenolic

compounds—particularly syringol and catechol—at intermediate and higher temperatures, consistent with progressive lignin degradation. The 271–350 °C fraction yielded both the highest PL amount and the greatest phenolic content. Physicochemical properties followed the same trend, with acidic pH across all fractions and electrical conductivity increasing with collection temperature.

These results confirm that temperature-controlled fractionation is an effective strategy for recovering PL fractions with distinct, targeted chemical profiles, supporting its use as a value-added biorefinery feedstock. Beyond chemical valorization, this strategy contributes to capturing condensable gases that would otherwise be released as non-condensable greenhouse gas emissions during charcoal production, adding an environmental dimension to the process. However, fractions of tar recovered retain a pollutant load that requires appropriate treatment.

Future studies should evaluate the biological activity, toxicological profile, and reproducibility of PL fractions across production cycles, and further characterize unidentified compounds. Overall, this study advances the understanding of temperature-dependent PL formation under operational kiln-furnace conditions and supports the integration of selective PL recovery into sustainable forest biomass biorefineries.

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**Conflicts of Interest:** All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References

1. Castro, A.F.N.M.; Castro, R.V.O.; Carneiro, A.D.C.O.; Lima, J.E.D.; Santos, R.C.D.; Pereira, B.L.C.; Alves, I.C.N. Análise Multivariada Para Seleção de Clones de Eucalipto Destinados à Produção de Carvão Vegetal. *Pesq. Agropec. Bras.* **2013**, *48*, 627–635. [\[CrossRef\]](#)
2. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of Process Parameters on Production of Biochar from Biomass Waste through Pyrolysis: A Review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [\[CrossRef\]](#)
3. Gonçalves, F.G.; Silva, A.G.; Ferraro, A.C.; Costa, N.N.M.; Souza, R.A.B.; Tosato, A.F. Captação de Líquido Pirolenhoso Da Carbonização Da Madeira de *Eucalyptus cloeziana* Em Forno Rabo Quente. *Agraria* **2010**, *5*, 232–237. [\[CrossRef\]](#)

4. Westerhof, R.J.M.; Brilman, D.W.F.; Garcia-Perez, M.; Wang, Z.; Oudenhoven, S.R.G.; Van Swaaij, W.P.M.; Kersten, S.R.A. Fractional Condensation of Biomass Pyrolysis Vapors. *Energy Fuels* **2011**, *25*, 1817–1829. [\[CrossRef\]](#)
5. Theappar, Y.; Chandumpai, A.; Farooongsarng, D. Physicochemistry and Utilization of Wood Vinegar from Carbonization of Tropical Biomass Waste. In *Tropical Forests—New Edition*; Sudarshana, P., Nageswara-Rao, M., Soneji, J.R., Eds.; InTechOpen: London, UK, 2018.
6. Ouattara, H.A.A.; Niamke, B.F.; Ahoke, M.E.M.F.; N’Guessan, J.L.L.; Yao, J.; Amusant, N.; Dumarcay, S. Physicochemical Characterization, Chemical Composition and Antioxidant Activities of Pyrolygneous Acids from Cocktails of Wood and Agricultural Residues from Ivory Coast. *J. Anal. Appl. Pyrolysis* **2024**, *181*, 106629. [\[CrossRef\]](#)
7. Campos, A.D. *Informação Técnica Sobre Extrato Pirolenhoso*; Technical Circular; Empresa Brasileira de Investigação Agropecuária—Embrapa: Brasília, Brazil, 2018; 9p.
8. Oramahi, H.A.; Maurisa, T.; Nurhaida, N.; Darwati, H.; Rifanjani, S. Optimization and Characterization of Liquid Smoke Produced by Terminalia Catappa Wood Pyrolysis and Its In Vitro Antifungal Activity. *Sci. Technol. Indones.* **2024**, *9*, 207–214. [\[CrossRef\]](#)
9. Campos, A.D. *Processo de Coleta e Produção do Extrato Pirolenhoso para Uso Agrícola*; Technical Circular; Empresa Brasileira de Investigação Agropecuária—Embrapa: Brasília, Brazil, 2018.
10. Almeida, R.S.R.; Taccini, M.M.; Moura, L.F.d.; Ceribelli, U.L.; Brito, J.O. Pyrolygneous Liquor Produced at Different Heating Rates in Pyrolysis of *Eucalyptus* Wood. *MCD A* **2018**, *2*, 1–5. [\[CrossRef\]](#)
11. Pimenta, A.; Fasciotti, M.; Monteiro, T.; Lima, K. Chemical Composition of Pyrolygneous Acid Obtained from *Eucalyptus* GG100 Clone. *Molecules* **2018**, *23*, 426. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Liu, Z.; Niu, W.; Chu, H.; Zhou, T.; Niu, Z. Effect of the Carbonization Temperature on the Properties of Biochar Produced from the Pyrolysis of Crop Residues. *BioResources* **2018**, *13*, 3429–3446. [\[CrossRef\]](#)
13. Liu, M.; Yao, J.; Zhang, C.; Hao, R.; Zhang, Z.; Cao, W. Quantitative Analysis of Multi-Components by Single-Marker: An Effective Method for the Chemical Characterization of Wood Vinegar. *Ind. Crops Prod.* **2022**, *182*, 114862. [\[CrossRef\]](#)
14. Ornaghi, H.L.; Monticeli, F.M.; Neves, R.M.; Agnol, L.D.; Bianchi, O. Influence of Different Cellulose/Hemicellulose/Lignin Ratios on the Thermal Degradation Behavior: Prediction and Optimization. *Biomass Conv. Bioref.* **2023**, *13*, 7775–7782. [\[CrossRef\]](#)
15. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; De Moraes Gonçalves, J.L.; Sparovek, G. Köppen’s Climate Classification Map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Ministério do Meio Ambiente. *Produção Sustentável de Carvão Vegetal: Manual de Operação de Sistema Fornos-Fornalha*; Ministério do Meio Ambiente—MMA: Brasília, Brazil, 2019. Available online: <https://www.undp.org/pt/brazil/publications/sistema-fornos-fornalha-manual-de-operacao> (accessed on 7 July 2026).
17. Pimenta, A.S.; Gama, G.S.P.; Feijó, F.M.C.; Braga, R.M.; De Azevedo, T.K.B.; De Melo, R.R.; De Oliveira Miranda, N.; De Andrade, G.S. Wood Vinegar from Slow Pyrolysis of *Eucalyptus* Wood: Assessment of Removing Contaminants by Sequential Vacuum Distillation. *Forests* **2023**, *14*, 2414. [\[CrossRef\]](#)
18. ASTM D1217-20; Standard Test Method for Density and Relative Density (Specific Gravity) of Liquids by Bingham Pycnometer. ASTM International: West Conshohocken, PA, USA, 2020.
19. APHA. *2510 Standard Methods for the Examination of Water and Wastewater*; Método 2510B; American Public Health Association: Washington, DC, USA, 2017.
20. ASTM D1200-10; Standard Test Method for Viscosity of Paints, Varnishes, and Lacquers by Ford Viscosity Cup. ASTM International: West Conshohocken, PA, USA, 2010.
21. Oasmaa, A.; Kuoppala, E. Solvent Fractionation Method with Brix for Rapid Characterization of Wood Fast Pyrolysis Liquids. *Energy Fuels* **2008**, *22*, 4245–4248. [\[CrossRef\]](#)
22. Komel, J.; R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2023. Available online: <https://www.scirp.org/reference/referencespapers?referenceid=3582659> (accessed on 17 June 2026).
23. Lin, X.; Dong, M.; Nie, W.; Rao, G.; Lu, J. Conversion Mechanism of Organic Components during the *Eucalyptus* Biomass Pyrolysis Process Based on the Multispectral Association Method. *Energy Fuels* **2024**, *38*, 7929–7940. [\[CrossRef\]](#)
24. Chen, D.; Gao, A.; Cen, K.; Zhang, J.; Cao, X.; Ma, Z. Investigation of Biomass Torrefaction Based on Three Major Components: Hemicellulose, Cellulose, and Lignin. *Energy Convers. Manag.* **2018**, *169*, 228–237. [\[CrossRef\]](#)
25. Evans, R.J.; Milne, T.A. Molecular Characterization of the Pyrolysis of Biomass. *Energy Fuels* **1987**, *1*, 123–137. [\[CrossRef\]](#)
26. Liu, X.; Cui, R.; Shi, J.; Jiang, Q.; Gao, J.; Wang, Z.; Li, X. Separation and microencapsulation of antibacterial compounds from wood vinegar. *Process Biochemistry* **2021**, *110*, 275–281. [\[CrossRef\]](#)
27. Medeiros, L.C.D.D.; Pimenta, A.S.; Braga, R.M.; Carnaval, T.K.D.A.; Medeiros Neto, P.N.; Melo, D.M.D.A. Effect of Pyrolysis Heating Rate on the Chemical Composition of Wood Vinegar from *Eucalyptus urograndis* and *Mimosa tenuiflora*. *Rev. Árvore* **2019**, *43*, e430408. [\[CrossRef\]](#)

28. Silva, A.D.P.; Andrade, A.M.D.; Dias Júnior, A.F. Investigando o Uso de Resíduos Do Processamento Da Madeira de Eucalipto Para a Produção de Combustíveis Sólidos Compactados. *Matéria* **2020**, *25*, e-12797. [[CrossRef](#)]
29. Andrade, J.C.D. Química Analítica Básica: Soluções Tampão Ácido-Base—Conceitos, Teoria e Prática. *Rev. Chemkeys* **2020**, *2*, e20001. [[CrossRef](#)]
30. Liu, Z.; Zhao, L.; Yao, Z.; Jia, J.; Wang, Z.; Liu, Z. Behaviors and Interactions during Hydrothermal Carbonization of Protein, Cellulose and Lignin. *Chem. Eng. J.* **2023**, *476*, 146373. [[CrossRef](#)]
31. Lima, S.G.D.; Santos, L.D.S.; Monteiro, L.P.C. Simulação da Pirólise de Resíduos Para a Produção de Combustível Limpo/Pyrolysis Simulation of Residues for the Clean Fuel Production. *Braz. J. Dev.* **2021**, *7*, 78706–78719. [[CrossRef](#)]
32. APAN Associação de Produtores de Agricultura Natural. *Produção e Padronização de Extratos Pirolenhosos Da APAN*; APAN: Brasília, Brazil, 2003.
33. Mogashane, T.M.; Mokoena, L.; Tshilongo, J. A Review on Recent Developments in the Extraction and Identification of Polycyclic Aromatic Hydrocarbons from Environmental Samples. *Water* **2024**, *16*, 2520. [[CrossRef](#)]
34. Guo, G.; Wang, Q.; Huang, Q.; Fu, Q.; Liu, Y.; Wang, J.; Hu, S.; Mašek, O.; Wang, L.; Zhang, J. Effect of Pyrolysis Temperature on the Characterisation of Dissolved Organic Matter from Pyrolygneous Acid. *Molecules* **2021**, *26*, 3416. [[CrossRef](#)] [[PubMed](#)]

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