Improving Weed Control through the Synergy of Waste Wood-based Panels Pyrolysis Liquid and Rice Husks: A Sustainable Strategy

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Synergistic effects of herbicidal rice husks and pyrolysis liquid from waste wood-based panels were studied relative to the germination of three common weed species in a tea plantation. The pyrolysis liquid consisted of various organic acids, phenols, alcohols, ketones, and nitrogen compounds, with organic acids accounting for up to 46.8% of the content. Three seeds of smooth crabgrass (*Digitaria ischaemum*), annual fleabane (*Erigeron annuus*), and hedge-parsley (*Torilis scabra* (Thunb.) DC) were treated with 2000 and 4000 L/ha of pyrolysis liquid, as well as 50, 100, and 200 m^3/ha of pyrolysis liquid as a cover material. The pre-emergence herbicide tests demonstrated that the combination of rice husks and pyrolysis liquid effectively inhibited seed germination and aboveground biomass of the weeds. The weed control effect increased with the increase in the amount applied. The combination of rice husks (200 m^3/ha) and pyrolysis liquid (4000 L/ha) exhibited the highest weed control efficacy, reducing seed germination and aboveground biomass by 69.1%, 79.5%, and 97.6% for smooth crabgrass, annual fleabane, and hedge-parsley, respectively. Discarded furniture materials and rice husks can both be used as sustainable materials for weed control, offering a fresh approach to the efficient utilization of waste materials.

DOI: 10.15376/biores.19.4.7606-7618

Keywords: Synergistic herbicide; Rice husks; Pyrolysis liquid; Pre-germination herbicides

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INTRODUCTION

China's recent rapid socio-economic development has significantly increased living standards, prompting shifts in lifestyles and consumption patterns (Xiong *et al.* 2017; Wang *et al.* 2020; Wang *et al.* 2021). The shortened lifespan of furniture products has led to a surge in discarded items, with wood-based panel furniture as a major contributor. Reports indicate that approximately 85 million m^3 of various wood products, primarily furniture, are discarded annually in China, constituting a substantial portion of urban waste (Yang and Zhu 2021). These discarded items are managed by landfilling or incineration, contributing to environmental pollution. The combustion of wood-based panels, containing adhesives and surface decoration layers, releases harmful nitrogen-containing gases, such as NO, NO_2, HNCO, and HCN, thereby affecting air quality (Chen *et al.* 2011; Liu *et al.* 2019, 2021c).

In response to the environmental challenges posed by discarded furniture, various studies have explored repurposing these materials. Methods such as using discarded furniture panels for new manufacturing or producing organic fertilizer have been investigated (Jale *et al.* 2007; Foong *et al.* 2021; Liu *et al.* 2021a). However, these methods have limitations in scalability and environmental impact, indicating a need for alternative solutions.

Pyrolysis has emerged as a promising approach to managing wood-based waste. This thermal degradation process occurs in the absence or partial presence of oxygen, producing tar, solid char, gas, and pyrolysis liquid (Girods *et al.* 2009; Lam *et al.* 2018). Pyrolysis liquid contains over 200 compounds, including organic acids, alkanes, alcohols, and esters (Liu *et al.* 2023a,b). The operational parameters of pyrolysis, such as temperature and speed, influence the production yield, with low-temperature slow pyrolysis favoring char production and fast pyrolysis favoring liquid products (Jaworski and Kajda-Szcześniak 2019).

Pyrolysis liquid from wood materials has shown potential in various applications due to its rich composition. It possesses antioxidant, antimicrobial, and termite-resistant properties, making it useful as an additive in animal feeds, deodorants, and anti-inflammatory agents (Lee *et al.* 2010; Benzon and Sang-Chul 2016; Chen *et al.* 2020). Additionally, lower doses of pyrolysis liquid can serve as a foliar or soil fertilizer, while higher concentrations may exhibit phytotoxicity, potentially acting as an herbicide. Previous research has indicated the efficacy of pyrolysis liquid in controlling specific weeds (Chu *et al.* 2022; Lu *et al.* 2020). However, the impact on a broader range of weed species remains largely unexplored.

Current weed management heavily relies on synthetic herbicides, which exert significant selection pressure on weeds, leading to widespread herbicide resistance (Duke *et al.* 2019). The slow pace of discovering new herbicide modes of action has necessitated the exploration of non-selective herbicides, such as glyphosate, glufosinate, paraquat, and diquat. Nonetheless, resistance issues and the prohibition of synthetic herbicides in certain regions, such as tea plantations, vegetable farms, and herbal crops in China, highlight the need for alternative weed control practices (Liu *et al.* 2021b; Heap 2024). One such practice includes using rice husk to suppress weed growth (Yao and Zhang 2023).

This study aims to investigate the combined herbicidal effect of rice husks and pyrolysis liquid from waste furniture panels on the seeds of three prevalent weeds: smooth crabgrass (*Digitaria ischaemum*), annual fleabane (*Erigeron annuus*), and hedge-parsley (*Torilis scabra* (Thunb.) DC). By exploring this combined approach, the study seeks to elucidate the potential synergistic impact and address the shortcomings of existing weed control methods. The novelty of this paper lies in its investigation of the synergistic herbicidal effects of rice husks and pyrolysis liquid, offering a potentially more sustainable and effective solution for weed management in tea plantations.

EXPERIMENTAL

Materials

Liquid from discarded furniture panels

The feedstock for pyrolysis was obtained from dismantling discarded panel furniture at a waste recycling station in Qixia District, Nanjing City, with a moisture content measured according to the GB/T 1931 (2009) standard ranging from 14 to 16%.

The panels were identified as particle board and plywood containing urea-formaldehyde adhesive. They were cut into approximately 5-cm-sized pieces before pyrolysis. The pyrolysis experiment was conducted in January 2020 in a laboratory reactor at Nanjing Forestry University (32.08°N, 118.81°E), Jiangsu Province, China, under anaerobic conditions. The complete procedure entailed heating the material in an electric furnace at 500 °C for 30 min. During pyrolysis, the resulting gases were collected in a glass condenser, while the liquid phase was stored in a glass jar. Following this, the light and heavy organic components were separated from the aqueous fraction through decantation, predominantly comprising pyrolysis liquid. The aqueous solution was stored in a sealed glass jar for approximately 1 year, resulting in three layers of products, including light oil at the top, brown pyrolysis liquid in the middle, and concentrated tar at the bottom.

Chemical Composition Analysis of Pyrolysis Liquid

The pyrolysis liquid's composition was analyzed using gas chromatography-mass spectrometry (GC–MS) equipment available at the Analytical and Testing Center of Nanjing Forestry University (EDA/PY-3030D, Shimadzu 2010, Shanghai, China). The pyrolysis sample was freeze-dried and then dissolved in methanol prior to GC–MS analysis. Separation was conducted using a 30 m Rrx®-5 ms GC column (Radnor, PA, USA), with helium serving as the carrier gas at a consistent volumetric flow rate of 1 mL/min. The GC was initially programmed to operate at a temperature of 50 °C for 1 min and then ramped up at a rate of 15 °C per min until reaching 450 °C, where it was held for 5 min. Electron ionization mass spectra were recorded within the range of 50 to 600 (m/z) at an electron energy of 70 eV in full-scan mode. The data were analyzed utilizing Bruker MS Workstation software (version 8.0, Bruker Daltonik, Bremen, Germany) and ACD/MS Fragmenter (Advanced Chemistry Development, Inc., Toronto, ON, Canada).

Water Content and pH Value of the Pyrolysis Liquid

The moisture content of the pyrolysis liquid arises from both free water in the raw material and water produced during pyrolysis. This factor greatly impacts the pH value and herbicidal efficacy of the pyrolysis liquid. The moisture content of the pyrolysis liquid was determined using a volumetric Karl Fischer titration instrument (MKS-520, Beijing DSA Instruments Co., Ltd., Beijing, China). Titration was conducted by reacting analytical-grade methanol with the Karl Fischer reagent. The pH value of the pyrolysis liquid was measured using a pH meter (MP551, Shanghai San-Xin Instrumentation, Shanghai, China).

Pre-emergence Herbicide Experiments

The experiment took place at Nanjing Forestry University from March to April 2021. It utilized a completely randomized split-plot design with four replications. The primary plot factor was the application volume of pyrolysis liquid, with two levels (2000 and 4000 L/ha), while rice husk coverage served as a sub-plot factor with three levels (50, 100, 200 m^3/ha). Seeds of three weed species (smooth crabgrass, annual fleabane, and hedge-parsley) were collected from a tea plantation in Jiangning District, Nanjing, in November 2019, with germination rates of > 98%. Each species had 25 seeds sown in square cups (10 cm × 10 cm) at a height of 15 cm, placed in a climate chamber at a controlled temperature of 25 ± 1 °C. The soil was obtained from a tea plantation in Jiangning District, Nanjing, and was characterized as a silty clay loam with 22% clay, 23% sand, and 50% silt. The pH value was 5.9, and the organic matter content was 5%. Before pre-emergence herbicide experiments, the soil obtained from the tea plantation underwent high-temperature sterilization, treated in an 80 °C oven for 48 h and then cooled before conducting the experiment. Germination of the weed seeds was observed weekly, and the count was recorded continuously for 6 weeks. Seeds that did not germinate were recorded as 0%, while the 25 seeds that all germinated were recorded as 100%. Aboveground biomass was harvested during week 6 after treatment, and fresh weight was determined immediately.

Statistical Analysis

Analysis of variance (ANOVA) was conducted on the germination and growth data of the three weed species to evaluate the synergistic weed control effect of the pyrolysis liquid treatment and rice husk coverage. Statistical analysis was performed using SPSS software (IBM Corp., IBM SPSS Statistics for Windows, v. 25, Armonk, NY, USA), and the P-value was set at 0.05. Two-way ANOVA was applied with "pyrolysis liquid application volume" and "rice husk coverage" as independent factors and their interaction as "pyrolysis liquid application volume × rice husk coverage." Levene's test was used to assess the homogeneity of variance, while the Shapiro-Wilk test was used to verify the normality of the data distribution, both essential prerequisites for the two-way ANOVA. Fisher's protected least significant difference (LSD) test was subsequently utilized to distinguish treatment averages at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Pyrolysis Liquid Composition and Properties

Wood-based materials undergo pyrolysis, releasing gases, and the liquid collected through condensation is a brownish-yellow substance from the tar after filtering the surface. The GC-MS spectrum, illustrated in Fig. 1, provides the chemical formulas and chromatographic areas of the main compounds. The pyrolysis liquid extracted from the waste furniture particleboard contained a diverse array of organic compounds, encompassing acids, alcohols, aldehydes, carbohydrates, ketones, nitrides, and phenols (Heo *et al.* 2010; Aguirre *et al.* 2020a,b). Specifically, three organic acids were identified: acetic acid, propionic acid, and benzoic acid. Acetic acid constituted 46.8% of the chromatographic area, while propionic acid and benzoic acid accounted for 2.2% and 1.14%, respectively. Remarkably, the relative areas of the chromatographic peaks detected by GC-MS were not suitable for quantitatively determining the content of each compound in the pyrolysis liquid (Jale *et al.* 2007; Liu *et al.* 2021). Nevertheless, they expedited a quick estimation of the proportion of each compound in the pyrolysis liquid. Hence, additional research is warranted. Among the compounds identified, the acids, nitrides, phenols, and alcohol compounds contributed significant proportions. They contributed, respectively, chromatographic peak areas of 19.3%, 11.0%, and 11.1%. The remaining components included 6.36% carbohydrates, 1.69% lipid compounds, and 0.69% ketone compounds. Previous studies on the chemical composition of pyrolysis liquid from natural wood material have reported that organic acids constitute approximately 50%, similar to the acid proportions found in this study (Tiilikkala *et al.* 2010; Fagernas *et al.* 2012; Grewal *et al.* 2018). Additionally, natural wood pyrolysis liquid contains a substantial number of phenols and alcohol compounds, resulting from the pyrolysis of holocellulose and lignin in wood. Guaiacol and syringol in this study were degradation products of lignin composed of coniferyl and sinapyl propane monomers in wood (Liu *et al.* 2021; Yao and Zhang 2023). However, according to Heo *et al.* (2010), the composition of pyrolysis liquid produced from fresh wood materials may vary from that derived from contaminated wood materials, such as furniture waste, which could contain various additives (Heo *et al.* 2010). Therefore, in this study, nitrides were considered products of the thermal decomposition of the adhesives in the particleboard.

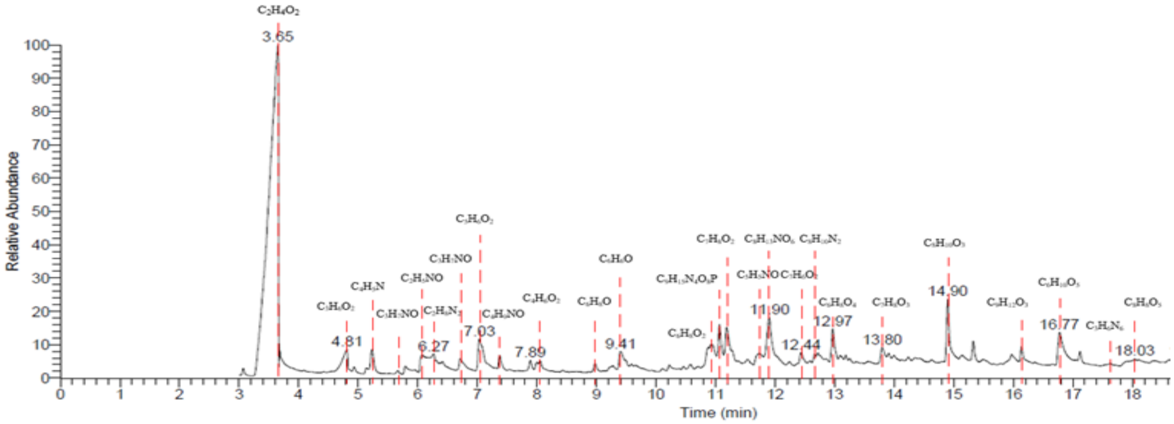

Fig. 1. Chromatogram of the pyrolysis liquid

Table 1. Chemical Formula and Chromatographic Areas of the Major Compounds Identified in the Pyrolysis Liquid

Group	Compound Name	Chemical Formula	Area (%)
Acids	Acetic acid	$C_2H_4O_2$	46.80
Acids	Propanoic acid	$C_3H_6O_2$	2.20
Acids	Benzoic acid	$C_7H_6O_2$	1.14
Phenols	Phenol	C_6H_6O	2.12
Phenols	Guaiacol	$C_7H_8O_2$	1.98
Phenols	Dihydroxy-3-methoxybenzeneMethoxybenzene-1,2-diol	$C_7H_8O_3$	3.47
Phenols	2, 6-dimethoxy-4-methylphenol	$C_9H_{12}O_3$	3.43
Ketone	3-methyl-2-cyclopenten-1-one	C_6H_8O	0.69
Alcohol	Cyclopropyl-carbinol	C_4H_8O	3.24
Alcohol	Syringol	$C_8H_{10}O_3$	4.38
Alcohol	Furfuralcohol	$C_5H_6O_2$	3.46
Ester	Gallate methyl ester	$C_8H_8O_5$	0.67
Ester	Butyrolactone	$C_4H_6O_2$	1.02
Carbohydrate	a´-D-Glucopyranose, 1,6-anhydro- C6H10O5 1.98	$C_6H_8O_4$	2.92
Carbohydrate	Carbohydrate 1,4:3,6-Dianhydro-`	$C_6H_{10}O_5$	3.44
Nitrides	Pyrrole	C_4H_5N	2.27
Nitrides	N,N-Dimethylformamide	C_3H_7NO	0.94
Nitrides	Acetamide	C_2H_5NO	3.11
Nitrides	Ethylenediamine	$C_2H_8N_2$	1.16
Nitrides	N-Methylacetamide	C_3H_7NO	1.22
Nitrides	N,N-Dimethylacetamide	C_4H_9NO	1.09

In this study, the results obtained from the volumetric Karl Fischer titrator test revealed that the pyrolysis liquid on average constituted 64.5% by weight (± 1.8 SE). Compared to previous studies (Heo *et al* 2010; Aguirre *et al.* 2020a,b), this study determined higher water content in the pyrolysis liquid. As an illustration, Bridgwater (2012) reported that the water content of pyrolysis liquid derived from straw was 53.5% by weight. Heo *et al.* (2010) found that the water content in pyrolysis liquid obtained from furniture waste ranged from 40% to 60% by weight (US EPA 2024). The variance in water content can be attributed to factors such as the type of raw material and the conditions of pyrolysis and temperature. Previous studies indicate that temperature is the primary factor influencing the water content of pyrolysis liquid (Wang *et al.* 2020). Additionally, the relatively higher water content observed in this study may be partly ascribed to the 1-year aging period.

The pH value of the pyrolysis liquid was 4.5, while in previous studies, the pH range for pyrolysis liquid using forest waste as raw material varied from 2.2 to 2.4, and for birch trees (*Betula pendula* Roth.) as raw material, it ranged from 1.8 to 2.9 (Bridgwater 2012; Fagernas *et al.* 2012). After aging pyrolysis liquid for 1 year, acidity remained almost unchanged, and the pH consistently remained below 3 (Aguirre *et al.* 2020). Compared to previous results, the higher pH of the pyrolysis liquid in this study may be due to the presence of 8 to 10% nitrogen-containing adhesives and decorative surface layers in the waste furniture particleboard. These materials likely led to the formation of a significant amount of amides and amines during pyrolysis.

Mechanism of Inhibiting Weed Growth

The detailed composition analysis of the pyrolysis liquid is crucial for understanding its potential mechanisms for inhibiting weed growth. Each component of the pyrolysis liquid could contribute differently to weed control:

Acids (Acetic, Propionic, and Benzoic Acids): Organic acids are known to lower the pH of the soil, creating an unfavorable environment for weed germination and growth. Acetic acid, in particular, is well-documented for its herbicidal properties, disrupting cell membrane integrity and causing desiccation in plant tissues (Evans *et al.* 2011).

Phenols (Phenol, Guaiacol, Syringol): Phenolic compounds have antimicrobial and phytotoxic properties. They can interfere with cell wall synthesis, enzyme activity, and photosynthesis in plants (Li *et al.* 2015). Guaiacol and syringol, as lignin-derived phenols, might also contribute to allelopathic effects, inhibiting weed seed germination and seedling growth.

Alcohols (Cyclopropyl-carbinol, Furfuralcohol): These compounds can act as desiccants, leading to the dehydration of weed seeds and seedlings. Alcohols might also enhance the penetration of other active compounds into plant tissues.

Nitrides (Pyrrole, N,N-Dimethylformamide): These nitrogen-containing compounds may have herbicidal properties due to their role in disrupting protein synthesis and enzyme activity in plants.

The high water content of the pyrolysis liquid (64.5% by weight) may aid in the application and penetration of these compounds into the soil and plant tissues, enhancing their herbicidal effects. With a pH value of 4.5, which is higher than that of typical pyrolysis liquids derived from wood, the presence of alkaline nitride compounds might partially buffer the acidity. However, they still contribute to an overall acidic environment that inhibits weed growth.

Pre-emergence Herbicide Chamber Experiments

Tables 2, 3, and 4 present the weed control effect of rice husks and pyrolysis liquid on three species of weeds at different application volumes. The values represent the mean number of germinations of 25 seeds of each weed species in the pre-emergence herbicide chamber experiments. According to the table, rice husks and pyrolysis liquid have certain weed control effects on the germination of the three species of weeds considered in this work. Among the three species, hedge-parsley had the lowest number of germinated seeds, indicating that rice husk and pyrolysis liquid were the most effective for weed control. This effectiveness may be attributed to the larger size and length of hedge-parsley seeds, making them more susceptible to these treatments. In contrast, smooth crabgrass had the most germinated seeds, illustrating that rice husks and pyrolysis liquid had the poorest weed control.

Table 2. Weed Control Effect of Rice Husk and Pyrolysis Liquid on Smooth Crabgrass at Different Application Volumes

Smooth Crabgrass	Number of Germinated Seeds						Fresh Aboveground Biomass (g)
	1 WAT	2WAT	3WAT	4WAT	5WAT	6WAT	6WAT
Rice husks (m^3/ha)							
0	11.17^{a}	16.92^{a}	17.25^{a}	17.50^{a}	17.33^{a}	17.42^{a}	0.929^{a}
50	10.08^{a}	15.50^{a}	16.67^{a}	17.25^{a}	17.33^{a}	17.33^{a}	0.877^{a}
100	10.25^{a}	15.67^{a}	15.83^{a}	16.00^{a}	16.00^{a}	16.00^{a}	0.844^{a}
200	7.42^{b}	11.00^{b}	11.17^{b}	11.08^{b}	11.17^{b}	11.33^{b}	0.689^{b}
Pyrolysis liquid (L/ha)							
0	11.38^{a}	18.25^{a}	18.56^{a}	18.88^{a}	18.94^{a}	19.06^{a}	1.045^{a}
2000	10.06^{a}	14.19^{b}	14.88^{b}	14.75^{b}	14.66^{b}	14.88^{b}	0.812^{b}
4000	7.75^{b}	11.87^{c}	12.25^{c}	12.75^{b}	12.81^{b}	13.63^{c}	0.646^{c}
	P values						
Rice husks	0.002	0.410	<0.001	<0.001	<0.001	<0.001	0.002
Pyrolysis liquid	< 0.001	0.489	<0.001	<0.001	<0.001	<0.001	<0.001
Rice husks × Pyrolysis liquid	0.011	0.101	0.543	0.340	0.143	0.090	0.008

Values represent the mean number of germinations of 25 seeds in pre-emergence herbicide chamber experiments. Mean values of the “number of germinated seeds” followed by the same small superscript letters (a, b, c, d) within a group are not significantly different based on Fisher’s Protected LSD test at the 0.05 significance level.

P-value indicates the significance of the different influencing factors. A smaller P-value indicates stronger significance. P-values < 0.05 were significant, and Rice husks × Pyrolysis liquid values > 0.05 were not significant.

“Rice husks × Pyrolysis liquid” is the influence of the interaction between applying rice husks and applying the pyrolysis liquid.

Under different applications, the rice husks and the pyrolysis liquid inhibited germination and growth of smooth crabgrass. With the increasing application of rice husks and pyrolysis liquid, the inhibition of smooth crabgrass germination increased, while the aboveground fresh weight gradually decreased. With the increasing concentration of the application of rice husks and pyrolysis liquid, the inhibition of smooth crabgrass germination increased, while the aboveground fresh weight gradually decreased. Some differences in the control effect of the combination of rice husks and pyrolysis liquid were observed in smooth crabgrass. The rice husk and pyrolysis liquid combination significantly inhibited the germination and aboveground fresh weight of annual fleabane.

Table 3. Weed Control Effect of Rice Husk and Pyrolysis Liquid on Annual Fleabane at Different Application Volumes

Annual Fleabane	Number of Germinated Seeds						Fresh Aboveground Biomass (g)
	1 WAT	2WAT	3WAT	4WAT	5WAT	6WAT	6WAT
Rice husks (m^3/ha)							
0	13.83^{a}	17.00^{a}	18.42^{a}	19.08^{a}	18.00^{a}	16.33^{a}	0.160^{a}
50	11.83^{a}	13.67^{b}	14.33^{b}	14.83^{b}	14.17^{b}	13.83^{b}	0.148^{ab}
100	8.17^{b}	11.42^{c}	11.50^{c}	12.92^{c}	11.42^{c}	11.33^{c}	0.134^{ab}
200	8.00^{b}	9.42^{c}	10.75^{c}	9.75^{d}	9.00^{d}	8.75^{d}	0.096^{b}
Pyrolysis liquid (L/ha)							
0	13.69^{a}	17.50^{a}	18.38^{a}	19.13^{a}	18.44^{a}	17.44^{a}	0.182^{a}
2000	10.25^{b}	12.38^{b}	13.31^{b}	13.25^{b}	12.63^{b}	12.13^{b}	0.119^{b}
4000	7.44^{c}	8.75^{c}	9.56^{c}	10.06^{c}	8.34^{c}	8.13^{c}	0.102^{b}
	P values						
Rice husks	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.058
Pyrolysis liquid	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
Rice husks × Pyrolysis liquid	0.006	0.041	0.272	0.007	0.008	0.190	0.615

Values represent the mean number of germinations of 25 seeds in pre-emergence herbicide chamber experiments. Mean values of the "number of germinated seeds" followed by the same small superscript letters (a, b, c, d) within a group are not significantly different based on Fisher's Protected LSD test at the 0.05 significance level.

P-value indicates the significance of the different influencing factors. A smaller P-value indicates stronger significance. P-values < 0.05 were significant, and Rice husks × Pyrolysis liquid values > 0.05 were not significant.

"Rice husks × Pyrolysis liquid" is the influence of the interaction between applying rice husks and applying the pyrolysis liquid.

Table 4. Weed Control Effect of Rice Husk and Pyrolysis Liquid on Hedge-parsley at Different Application Volumes

Hedge-parsley	Number of Germinated Seeds						Fresh Aboveground Biomass (g)
	1 WAT	2WAT	3WAT	4WAT	5WAT	6WAT	6WAT
Rice husks (m^3/ha)							
0	7.33^{a}	12.33^{a}	12.92^{a}	13.17^{a}	12.17^{a}	12.00^{a}	0.040^{a}
50	5.33^{b}	8.00^{b}	9.17^{b}	9.25^{b}	9.00^{b}	9.08^{b}	0.034^{ab}
100	4.50^{b}	7.33^{bc}	7.08^{c}	7.42^{c}	6.58^{c}	6.67^{c}	0.031^{ab}
200	4.25^{b}	5.67^{c}	5.92^{c}	5.33^{d}	5.00^{d}	4.83^{d}	0.011^{b}
Pyrolysis liquid (L/ha)							
0	10.38^{a}	16.44^{a}	16.50^{a}	16.88^{a}	16.00^{a}	15.88^{a}	0.065^{a}
2000	3.31^{b}	4.94^{b}	5.19^{b}	5.13^{b}	4.63^{b}	4.63^{b}	0.014^{b}
4000	2.38^{b}	3.63^{b}	4.63^{b}	4.38^{b}	3.94^{b}	3.94^{b}	0.008^{b}
	P values						
Rice husks	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.081
Pyrolysis liquid	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Rice husks × Pyrolysis liquid	0.036	0.043	0.037	0.021	0.100	0.124	0.068

Please refer to the notes below the previous table.

As the application of rice husk and pyrolysis liquid increased, the inhibition of germination and aboveground fresh weight of annual fleabane gradually increased. The control effect of the combination of rice husks and pyrolysis liquid on annual fleabane was also different. The rice husks and pyrolysis liquid had a significant inhibitory effect on the germination and above-ground fresh weight of hedge-parsley. As the amount of rice husk and pyrolysis liquid applied was increased, the aboveground fresh weight of hedge-parsley decreased gradually. The weed control effect of the combination of rice husks and pyrolysis liquid was different. In general, the weed control effect of the rice husks and pyrolysis liquid on the three weeds was significant (P-values < 0.005), and the weed control effect was gradually enhanced as the application amount increased. However, the interaction between the rice husks and pyrolysis liquid was not significant in controlling seed germination (P-values > 0.005). In addition, the weed control effect of the combination of rice husk and pyrolysis liquid on different weed species was different. These results provide a reference for selecting the appropriate treatment method and dosage.

In the control group, the average germination number of 25 smooth crabgrass, annual fleabane, and hedge-parsley were 24.2, 19.8, and 20.8, respectively. The control group was defined as 100% to calculate the relative germination rate, and the ratio between the seed germination rate of the other groups and the control group was the relative germination rate. The seed germination rate gradually decreased with the increase in the amount of rice husks applied. When the application amount was 200 m^3/ha, the relative germination rates of smooth crabgrass, annual fleabane, and hedge-parsley seeds were 57.7%, 74.7%, and 56.6%. These results indicate that the effect of 200 m^3/ha on the pre-bud weeding of the three weeds were 42.3%, 25.3%, and 43.4%, respectively. The effect of weeding was better when the amount of pyrolysis liquid applied was higher. When the application rate of pyrolysis liquid was 4,000 L/ha and the application rate of rice husks was 200 m^3/ha, the weed control effects compared to the three untreated weeds were 69.1%, 79.5%, and 97.6%, respectively. The effect of weeding was better when the amount of pyrolysis liquid applied was higher, regardless of the amount of rice husk applied. This result is similar to a previous study (Girods *et al.* 2009); the organic acids in the pyrolysis liquid inhibited seed germination. These results show that the combination of rice husks and pyrolysis solution was a good weed control method, and the germination of weed seeds was effectively inhibited when an appropriate amount of the combination was applied.

Fresh aboveground biomass is also a rapid and important indicator for evaluating the efficacy of herbicides. In Fig. 2, statisticians conducted data analysis and adjusted the function of rice husk (m^3/ha) × pyrolysis liquid (L/ha) levels using surface regression, considering only the final 6 WAT evaluations of biomass and analyzing the levels of rice husk (m^3/ha) and pyrolysis liquid (L/ha) as a function of germination evaluation dates. The biomass values of smooth crabgrass ranged from 0.514 to 1.432 g, while the biomass values of hedge-parsley ranged from 0.002 to 0.102 g. The impact surface of rice husk (m^3/ha) × pyrolysis liquid (L/ha) on the growth of three weed species exhibited regular changes. The functions obtained by fitting using the "Parabola2D" model were as follows,

$FAB = 1.13641 - 6.04288 \times 10^{-4}X - 1.33484 \times 10^{-4}Y - 2.90758 \times 10^{-6}X^2 + 8.38281 \times 10^{-9}Y^2$ for smooth crabgrass;

$FAB = 0.20746 - 2.00992 \times 10^{-4}X - 4.30937 \times 10^{-5}Y - 5.90152 \times 10^{-6}X^2 + 5.73437 \times 10^{-9}Y^2$ for annual fleabane;

$FAB = 0.07019 - 0.00107 \times 10^{-4}X + 4.55846 \times 10^{-6}Y + 3.65013 \times 10^{-6}X^2 - 7.49245 \times 10^{-10}Y^2$ for Hedge-parsley.

where X and Y represent the rice husk rate (m^3/ha) and pyrolysis liquid (L/ha), respectively. Through fitting the function, it can be observed that with an increase in the application of pyrolysis liquid and the coverage of rice husks, the quality of fresh aboveground biomass gradually decreased, indicating a synergistic weed control effect of the rice husk rate and pyrolysis liquid.

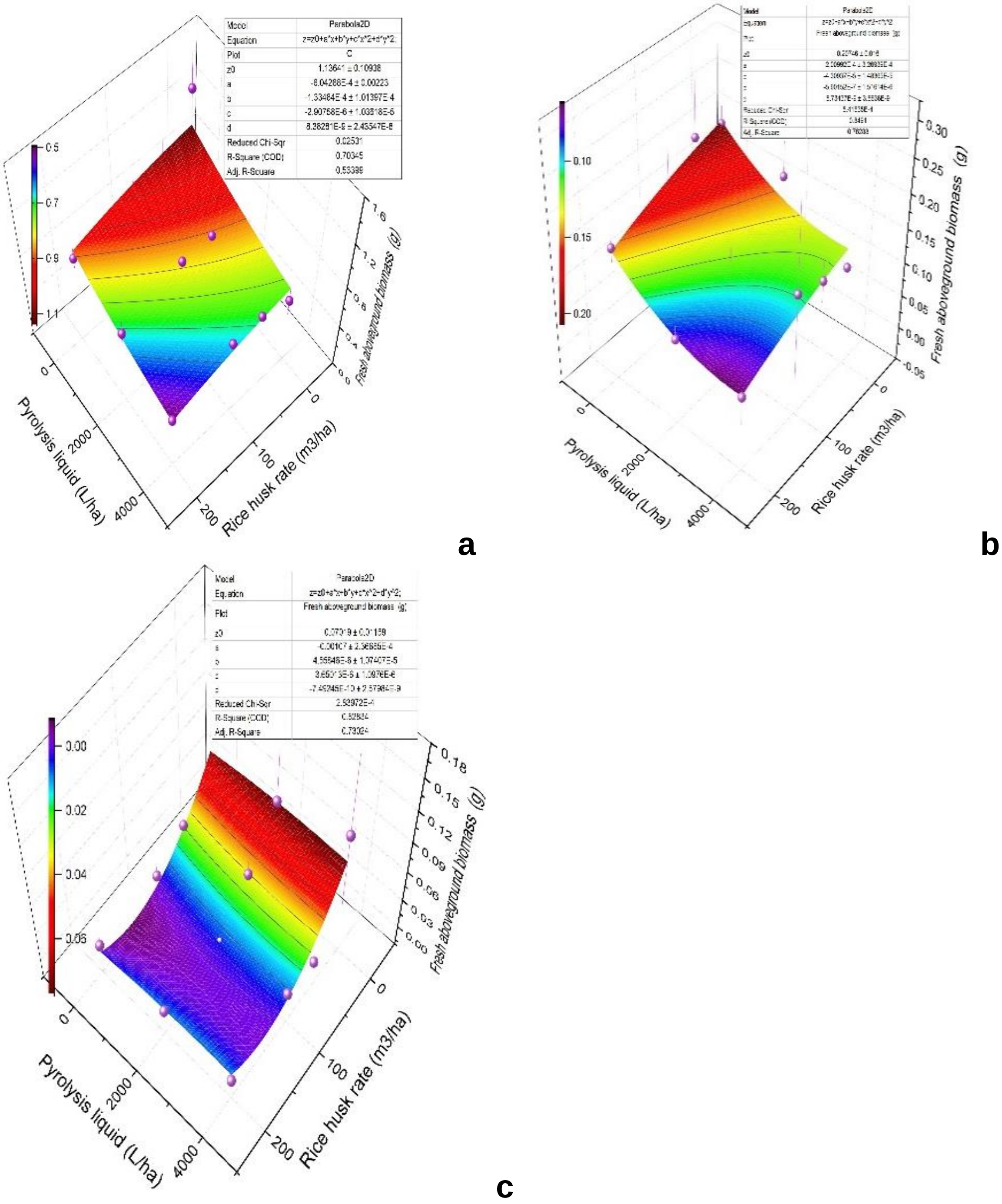

Fig. 2. Fresh aboveground biomass under different applications: a) smooth crabgrass; b) annual fleabane; c) hedge-parsley

CONCLUSIONS

1. The pyrolysis liquid exhibited inhibitory effects on the germination and aboveground biomass of smooth crabgrass, annual fleabane, and hedge-parsley weed species. The weed control effect of rice husks and pyrolysis liquid on weed species increased with higher application amounts, with the combination of 200 m^3/ha rice husks and 4000 L/ha pyrolysis liquid demonstrating the highest efficacy. The combination of rice husks and pyrolysis liquid showed significant control effects on seed germination and aboveground biomass of the weed species.
2. The combined use of rice husks and pyrolysis liquid in tea plantations proved to be an effective and environmentally friendly weed management approach, reducing seed germination and aboveground biomass of the weed species significantly.
3. The presence of various organic compounds in the pyrolysis liquid, including acids, phenols, alcohols, ketones, and nitrides, contributed to the herbicidal effects observed in the study.

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Article submitted: June 5, 2024; Peer review completed: July 31, 2024; Revised version received: August 7, 2024; Accepted: August 14, 2024; Published: August 27, 2024.
DOI: 10.15376/biores.19.4.7606-7618