Evaluation of Wood Vinegar from the Pyrolysis of Wood Residues of *Gmelina arborea* and its Application as Herbicide for Weed Control

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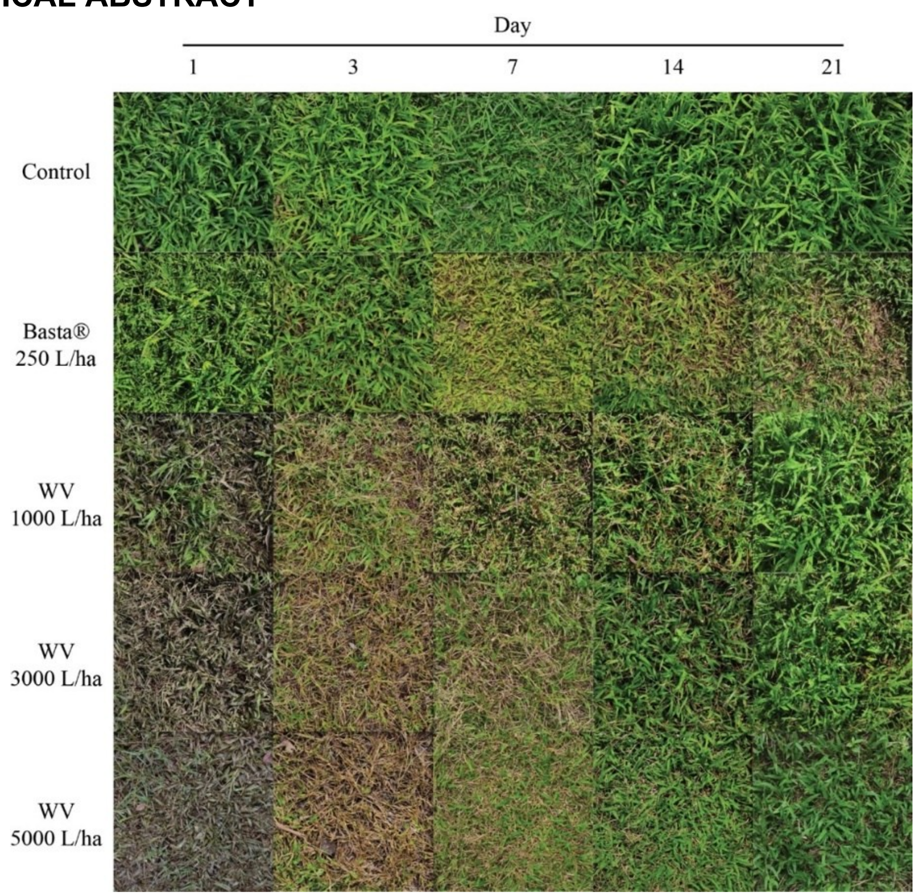
This article is dedicated to the memory of Jaime F. Quesada-Kimzey who died in March 2026.

GRAPHICAL ABSTRACT



Wood vinegar was used for weeds control under a tree plantation applied in doses of 1000, 3000 and 5000 L ha-1, with synthetic commercial herbicide as a control. Treatments with 3000 and 5000 L ha^{-1} doses caused rapid desiccation of grass and broadleaf weeds, achieving 85-88% visual injury during first seven days

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Wood vinegar (WV) produced *via* biomass pyrolysis, presents an organic alternative for weed control. This study aimed to: (i) determine the physical properties and elemental composition analysis of WV, and (ii) evaluate the efficacy of WV from wood residues of *Gmelina arborea* produced with slow pyrolysis to control weeds under a *Cupressus lusitanica* Christmas tree plantation. WV was dissolved in water at 75% and applied in doses of 1000, 3000 and 5000 L ha^{-1}, with the synthetic herbicide Basta® (glufosinate-ammonium) as a control. The efficacy of WV on weeds was visually evaluated from 0 (not injury) to 100 (plant death). Treatments with 3000 and 5000 L ha^{-1} doses caused rapid desiccation of grass and broadleaf weeds, achieving 85 to 88% visual injury. Biomass reduction of 40% can be obtained when WV is applied at high doses (3000 and 5000 L ha^{-1}) on mature grass-dominated weeds, showing effects comparable to synthetic herbicide. While WV effectively reduced weed biomass, it was insufficient to completely remove mature weeds.

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Keywords: Grass control; Organic herbicide; Grass weeds; Wood vinegar doses; Bioherbicides; Acid-pyrolysis

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INTRODUCTION

Herbicides rank as the third most toxic group of pesticides, after insecticides and fungicides (Mahmood *et al*. 2016). The most widely used herbicides in the world are the broad-spectrum and non-selective chemicals glyphosate, glufosinate-ammonium and paraquat (Maliang *et al*. 2022). Glyphosate inhibits enzymes essential for aromatic amino acid biosynthesis, ultimately causing plant death through starvation (Agostini *et al*. 2020). It is commonly applied to eliminate vegetation after harvest or before crop establishment (Ramírez-Muñoz 2021). Similarly, glufosinate is used for post-emergence and pre-plant burndown (Dayan *et al*. 2019). Its rapid phytotoxicity results from the accumulation of reactive oxygen species, which trigger lipid membrane peroxidation (Takano *et al*. 2019, 2020). Paraquat exhibit very fast uptake, producing reactive oxygen species that cause desiccation of plant tissues (Hawkes 2015). Paraquat has been banned in several countries due to health risks (Bang *et al*. 2017; Camargo *et al*. 2020; Albrecht *et al*. 2022).

The use of pesticides has been increased in recent decades due to the increment of crops production; unfortunately, the risks associated with their use have outweighed their beneficial effects (Mahmood *et al*. 2016). Latin America has been no exception. This region is one of the world's main agricultural areas with a very intensive use of pesticides (Hilber *et al*. 2024). This situation is aggravated by the fact that research and legislative efforts on pesticide use and management in the different countries are not as exhaustive as their temperate counterparts (Daam *et al*. 2019). Extensive research has been conducted on the problems associated with synthetic herbicides. Among these issues are: weed resistance, exposure of workers and health issues (Hsiao *et al*. 2021; González-Moscoso *et al.* 2023; Flafel *et al*. 2024), residues on food (Soares *et al*. 2021) and animal feed (Heydebreck 2021), and the effects on the environment (Daam *et al*. 2019; Kanissery *et al*. 2019) biodiversity (Brühl and Zaller 2021; El Jaouhari *et al*. 2023), water (Syafrudin *et al*. 2021; Mugudamani *et al*. 2023) and soils (Rose *et al*. 2016; Dennis *et al*. 2018).

Costa Rica, a small country in Central America, despite being known worldwide for its environmental policies, is one of the largest consumers of pesticides (Ramírez-Muñoz *et al*. 2017). Costa Rica has had intensive use of the synthetic herbicides glyphosate and paraquat (Montero-Rojas 2018; Staudacher *et al*. 2020; Viales-López 2024), which are the second and third most imported pesticide by volume, respectively (Vargas-Castro 2021). Training of pesticide applicators on proper use practices and protection should be encouraged to reduce health and safety risks to workers and the environment (Hilber *et al*. 2024). However, training and awareness programs may not effectively translate into behavioral changes (Yuantari *et al*. 2015; Fuhrimann *et al.* 2020).

On the other hand, there is a growing need for sustainable weed management approaches that support economic profitability, reduces environmental impact and respond to social demands (Cordeau *et al.* 2016). In this context, bioherbicides, products of natural origin for weed control (Bailey 2015), align with circular economy principles, as they rely on renewable resources and can reduce dependence on synthetic agrochemicals, while they often are more environmentally benign (Hasan *et al.* 2021) and have the potential to cause rapid plant degradation (Cordeau *et al.* 2016). The use of WV is a potential solution to the pressure to adopt sustainable agricultural practices that minimize over-reliance on the use of chemicals (Ouattara *et al.* 2023). For example, in Costa Rica, D-limonene, as well as pine and rosemary extracts were found to be effective and even faster than a synthetic herbicide in post-emergence weed control (Aguirre *et al.* 2020a). Organic compounds used for weed control include flavonoids, terpenoids, alkaloids and quinones, and phenolic acids (Ramírez-Muñoz 2021).

Recently, wood vinegar (WV), produced by pyrolysis of biomass, has attracted interest for its use as a bioherbicide (Aguirre *et al.* 2020a). WV consists mostly of water (80 to 90%) and more than 200 organic compounds categorized as acids, alcohols, ketones, aldehydes, esters, furans and nitrogenates (Aguirre *et al.* 2020a,b). The herbicidal properties of WV are attributed to the large amount of acids, especially acetic acid, which usually occupies the largest proportion, and phenols (Liu *et al.* 2021a; Maliang *et al.* 2022). It has been shown that WV, at high concentrations and application doses, presents effective herbicidal effects for the management of weeds (Liu *et al*. 2021b; Chu *et al.* 2022). However, only a few studies as an herbicide in natural conditions have been conducted (Aguirre *et al.* 2020). In China, WV from elm (*Ulmus* spp.) and apple (*Malus* × *domestica* Borkh) tree branches pruning waste has been demonstrated to control weed species under field conditions, similar to a non-selective herbicide, by causing fast desiccation on plants due to high content of acids (Liu *et al.* 2021a,b). Similarly, in Spain, Aguirre *et al.* (2020a) concluded that WV helps to control the development of annual plants by damaging the entire epidermis and its stomatal cells.

The presence of phenolic compounds in WV confers antifungal and pest control properties, increases the permeability of agrochemicals into leaf tissue, and enhances the effectiveness of chemical pesticides when used in combination. WV has been found to be effective against houseflies in some publications and is an alternative to agrochemicals and therefore, it can be used as a bioherbicide and potentially replace synthetic chemical herbicides (Ouattara *et al.* 2023). The phenols, organic acids, carbonyls, alcohols, and other organic acids present in pyroligneous acid influence its herbicidal activity (Liu *et al.* 2021a), and these are not present in synthetic components. Acetic acid, the main component of pyroligneous acid and a naturally occurring component of this product, has been used in agriculture for weed control.

In Costa Rica, pyrolysis of biomass has the potential to provide a solution to wood waste management (Aguirre *et al.* 2019b) while producing WV, as it is the major constituent of pyrolysis liquid (Jaworski *et al.* 2016). The second most planted tree in Costa Rica is *Gmelina arborea* Roxb. ex Sm (Instituto Nacional de Estadística y Censos 2022). The wood processing of this tree has been reported to be inefficient and producing great amount of residues (Espinoza-Durán and Moya 2013). For this reason, the yields and process of slow pyrolysis of *G. arborea* wood residues had been investigated. Recent research of *G. arborea* residues (Moya *et al.* 2024; Granados-Chacón *et al.* 2025) showed that yields of charcoal were 26 to 28%, WV from 28 to 30%, and non-condensable gases about 37%. However, these studies presented the importance and characteristics of solid products (charcoal) as energy and agriculture applications.

WV, produced by the slow pyrolysis of *G. arborea* wood residues, shows a high yield but no information has been presented about its potential as a natural alternative of weed control due to its herbicidal properties. So, further research is needed to elucidate its efficacy to control weeds. Then the objectives were established: (i) to determine the physical properties and chemical composition of WV, and (ii) to evaluate the efficacy of WV in three different doses from wood residues of *Gmelina arborea* produced with slow pyrolysis to control weeds under a *Cupressus lusitanica* Christmas tree plantation, evaluating visual injury and biomass reduction of weeds.

EXPERIMENTAL

Wood Vinegar Preparation

Wood vinegar (WV) was produced from the slow pyrolysis of wood residues of *Gmelina arborea* in a semi-industrial reactor prototype (Granados-Chacón *et al.* 2025). Wood board-ends were residues from the secondary wood processing with dimensions of 4 to 25 cm long and 12 to 32 mm thick and a moisture content of 16%. A cylindrical reactor of 58 cm diameter, 88 cm long, and 232 L capacity with a glass fiber insulating jacket was used. The pyrolysis process began at 25 °C and rate of temperature rise of 10 °C/min until reaching 450 °C. The process finished when the syngas flame was over, and then the reactor was kept closed until the temperature reached 25 °C, where the time varied from 5 to 6 hours. Detailed chemical composition of *Gmelina arborea* is reported elsewhere (Moya *et al*. 2024). The pyrolytic gases were cooled through a system of two coolers made of two helical coil heat exchangers. The first heat exchanger was cooled with air at room temperature and a second cooler with a closed water circuit moved by a pump, where wood vinegar was collected. Liquids were collected after each cooler. Non-condensable gases (syngas) continued its flow by pipe for the heating of the pyrolysis reactor (See Fig 2 in Granados-Chacón *et al.* 2025). This reactor presented a charcoal yield of 26 to 31% and a WV yield from 27 to 32%.

Wood Vinegar Physical Properties and Elemental Composition Analysis

The WV physical properties of pH, electric conductivity (EC), and density were determined by the Centro de Investigaciones Agronómicas (CIA) of the Universidad de Costa Rica (UCR). The concentration of elements (N, Cu, Fe, Zn, Mn, B, P, Ca, Mg, K and S) in pure WV was determined with an analysis of organic fertilizers. Nitrogen (N) was determined by MicroKjeldahl wet digestion with H_2SO_4 and colorimetric determination in the Flow Injection Analyzer (FIA) and P, Ca, Mg, K, S, Fe, Cu, Zn, Mn, B by digestion with HNO_3 and determination by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

Site and Soil Conditions

This experiment was conducted during the first months of the wet season (from May to June of 2024) in a *Cupressus lusitanica* Christmas tree plantation (9°50'29.2" N 83°47'05.2" W,

Fig. a) of approximately 1500 m^2 and 18 months old located in Paraíso, Cartago province, at 1130 masl. Grass was the dominant weed group.

Soil was characterized as clay loam with 32.3% clay, 36.3% sand, 31.3% silt, and 4.23% organic matter. Soil chemistry was characterized by 5.20 pH, acidity 1.12 cmol (+) L^{-1}, EC 0.20 mS cm^{-1}, Ca 10.95 cmol (+) L^{-1}, Mg 2.05 cmol (+) L^{-1}, K 0.53 cmol (+) L^{-1}, CEC 14.66 cmol (+) L^{-1}, acid saturation 7.77 %, P 44.7 mg L^{-1}, Zn 3.87 mg L^{-1}, Cu 22.7 mg L^{-1}, Fe 390 mg L^{-1}, Mn 26.0 mg L^{-1}, C 2.96%, N 0.34%, and a C:N ratio of 8.83.

Fig. 1. *Cupressus lusitanica* Christmas tree plantation before treatment (a) and plot treated with

wood vinegar (3000 L ha^{-1}, three days after treatment) (b).

Treatment and Experimental Test

Three different doses were applied using diluted wood vinegar at 75%: treatment applying doses of 1000 L ha^{-1} (WV 1000 L ha^{-1}), 3000 L ha^{-1} (WV 3000 L ha^{-1}), and 5000 L ha^{-1} (WV 5000 L ha^{-1}), according to previous results in other type of WV (Aguirre *et al.* 2020a, 2020b, Chu *et al.* 2022). These doses were selected considered economic aspects from high cost (WV 5000 L/ha) down to low cost (WY 1000 L/ha). After other two treatments for comparisons: one applying a commercial herbicide, specifically Basta® 14 SL of BASF (Bayer AG, Frankfurt, Germany) at 0.75% (0.375 kg ha^{-1}) at the level of 250 L ha^{-1} and a treatment without applications of WV or commercial herbicide (control). This commercial herbicide was selected due to its popularity, and it is considered moderately hazardous in Costa Rica. The applications of WV and commercial herbicide were using a manual sprayer equipped with a flat-fan nozzle on a sunny day during the first morning h. Personal protective equipment was used. Trees were covered with plastic sheeting to protect them from drift-related damage.

Before application, dominant weed species in the tree plantation were identified and classified as grass, broadleaf, and cyperaceous. Grass weed was the most dominant group. A completely randomized design was utilized for the experimental test with nine replications (0.5 × 0.5 m plots) established where grass covered > 90% of the area (

Fig. b). Grass coverage area (%) was determined by dividing the plot into 100 subplots (5 x 5 cm) and counting the subplots with grass as dominant weed group.

Evaluation of Treatment

Weed control was visually evaluated at 1, 3, 7, 14, and 21 days after doses application treatment (DAT). Visual injury was evaluated daily for 5 d on a scale of 0–100%, where 0 represents no injury, where all grass species maintained green color and 100 represents complete foliage desiccation, which the grasses were dead and their color brown. The values between these scales were designated by the loss of green color and the vigor of the plant, starting at scale 0 in Fig. 2 and reaching 100 when the plant presents the color shown in value 100 of the scale in Fig. 2. This method was proposed by Liu *et al.* (2022) for aboveground evaluation of biomass. A random sample of 162.2 cm^2 of aboveground biomass was harvested and fresh biomass immediately weighed, then oven-dried at 105 °C for 24 h and again weighed.

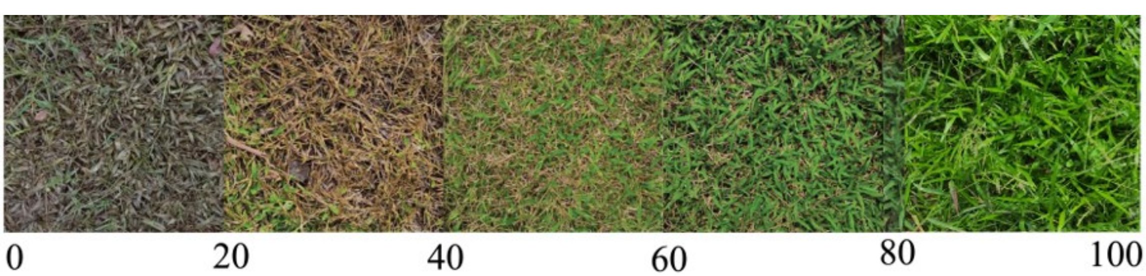

Fig. 2. Scales used in visual injury in grass for weed control with wood vinegar

Statistical Analysis

Homogeneity of equal variance was tested using Levene's test, and normality was tested using Shapiro-Wilk's test on the residuals of the one-way analysis of variance (ANOVA) model. To determine the effects of the application rates on the visual injury (%) and biomass reduction (kg ha^{-1}), one-way analysis of variance (ANOVA) with Tukey's

Honestly Significant Difference test was performed on parametric data, and Kruskal-Wallis's test and Wilcoxon signed-rank test were performed for non-parametric data. All the analyses were conducted using the statistical computing software R v.4.3.2 in the integrated development environment RStudio v.2023.16.0-421 (Viena, Austria).

RESULTS AND DISCUSSION

Wood Vinegar Physical Properties and Elemental Composition Analysis

WV was characterized with visually transparency, a yellowish-brown color, and a vinegar and smoky odor. The physical parameters presented the following values: pH 2.9, density 1.02 g mL^{-1} and EC 2.3 mS cm^{-1}. The elemental analysis showed the following values: N 0.02 % (w/w), Cu 7 mg kg^{-1}, Fe 1015 mg kg^{-1}, Zn 1053 mg kg^{-1}, Mn 3 mg kg^{-1}, B 4 mg kg^{-1}; while P, Ca, Mg, K and S were not detected by the analysis.

Visual Injury

The main grass species were *Paspalum conjugatum* P.J. Bergius, *Paspalum* sp. L., *Digitaria* sp. Haller and in lower proportion *Cynodon nlemfuensis* Vanderyst. Broadleaf weeds were identified as *Drymaria cordata* (L.) Willd. ex Schult., *Oxalis debilis* Kunth and *Ipomoea* sp. L.; and for the Cyperaceae family only *Cyperus* sp. L. was identified.

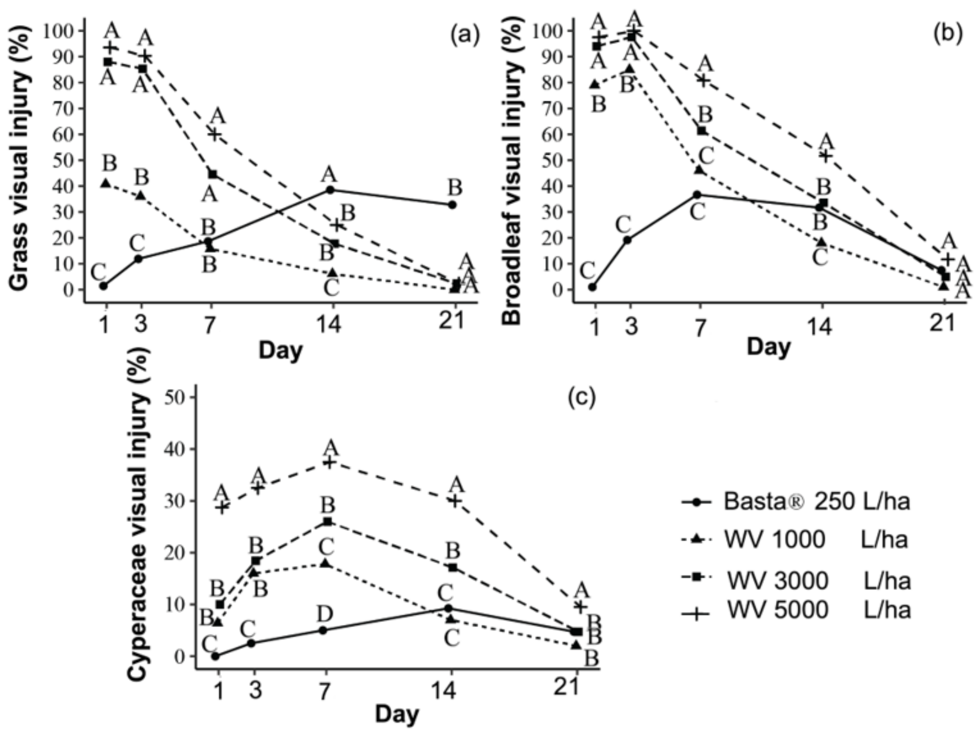

Fig. 3. Visual injury of weed groups: grass (a), broadleaf (b) and Cyperaceae (c); treated with synthetic herbicide Basta® and three wood vinegar (WV) application volumes over 21 days, in a *Cupressus lusitanica* Christmas tree plantation. Note: Different letters next to means represent statistical difference at 99% significance by Tukey test between different application for same day.

Grass and broadleaf weeds presented the highest visual injuries on day 1 and day 3 (Fig. a, b). WV 5000 and 3000 L ha^{-1} showed the highest grass control on the first 3 DAT, with 85 % and 89 % visual injury, respectively (Fig. 3a). However, the synthetic herbicide Basta® at 250 L ha^{-1} acted slowly and the effects were observable at 3 DAT and thereafter (

Fig.). The application of Basta® 250 L ha^{-1} showed an incrementing trend on plant injury until 14 DAT for grass and cyperaceous weeds (Fig. a,c) and kept stable until 21 DAT, for broadleaf weeds a considerable decrease was observed between 14 and 21 DAT (Fig. 3d). Cyperaceous weeds were the least visually injured plants, with a maximum visual injury of 50 % (Fig. c). Overall, plant desiccation followed a decreasing trend for wood vinegar treatments as the days passed, until almost reaching fully foliage recovery on day 21 (Fig. 4).

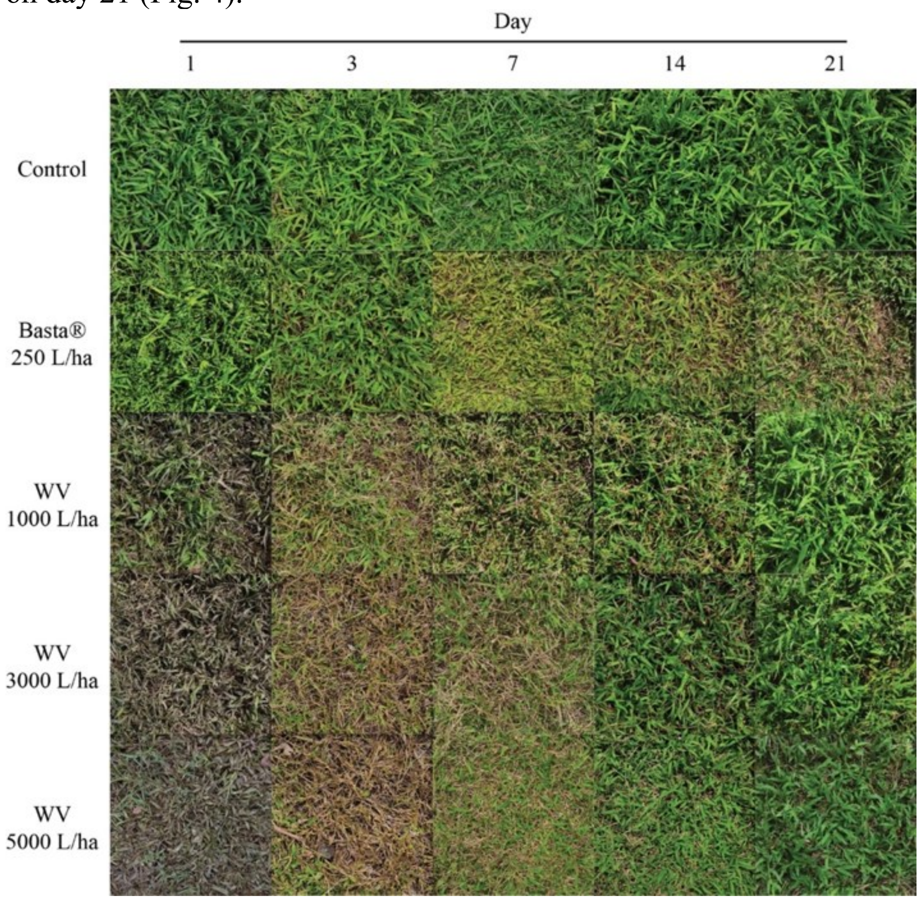

Fig. 4. Injury of weed caused after 1, 3, 7, 14 and 21 days after application of synthetic herbicide Basta® and three wood vinegar (WV) applications volumes in a *Cupressus lusitanica* Christmas tree plantation

Biomass

WV 3000 and 5000 L ha^{-1} and Basta® 250 L ha^{-1} showed no significant differences in aboveground biomass. In addition, they were significantly lower than the control and WV 1000 L ha^{-1} (Fig. 5). Basta® treatment reduced the fresh and dry aboveground biomass by 51.2 and 33 % respectively in relation to control treatment. Similarly, WV 3000 L ha^{-1} reduced aboveground biomass by 40.4 and 31.6% and WV 5000 L ha^{-1} by 37.4 and 33.4%, respectively. No biomass differences were found between the control treatment and WV

1000 L ha^{-1} (Fig. 5).

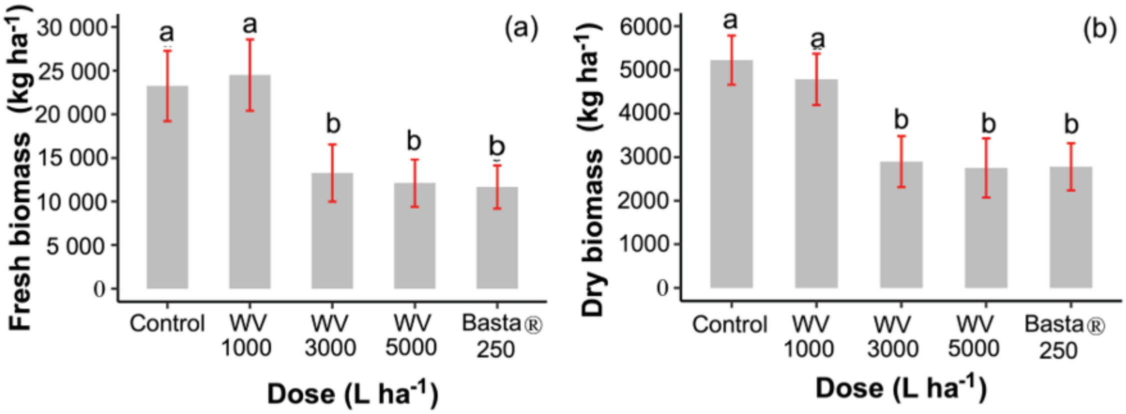

Fig. 5. Fresh (a) and dry (b) biomass of weeds 27 days after treatment with synthetic herbicide Basta® and three wood vinegar (WV) applications volumes in a *Cupressus lusitanica* Christmas tree plantation

Discussion

Wada (1997) presented several parameters to evaluate the WV quality. Seven parameters appear to be important when assessing the quality of WV. It should have a pH above 3, a specific gravity in the range of 1.010 to 1.050 g mL^{-1}, a color ranging from pale yellow to light brown and reddish, a distinct smoky odor, transparency with no suspended solids, ignition residue less than 0.2%, and dissolved tar content of less than 3%. Therefore, the five determined variables in WV of *G. arborea* met these criteria. In addition, different authors have reported pH values below 3 for WV from other species (Grewal *et al.* 2018; Luo *et al.* 2019).

Although the chemical composition of WV was not studied in the present study, the literature indicates that a large proportion of acid organic compounds is usually reported in WV, while acetic acids are generally considered its main active ingredient (Liu *et al.* 2021b; Chu *et al.* 2022). An important presence of phenolic compounds is reported (Liu *et al.* 2021a, Luo *et al.* 2019) and they can reach 30 to 60% of the total organic compounds in WV (Yang *et al.* 2016). Also, this phenolic composition has been associated with antioxidant and antibacterial activity of WV (Ma *et al.* 2011; Yang *et al.* 2016). Other components of WV, such as syringol, is a powerful antioxidant (Li *et al.* 2019; Ankona *et al.* 2023), which can comprise up to 30% of WV organic components (Grewal *et al.* 2018; Luo *et al.* 2019). So, considering those reports and that the WV obtained from *G. arborea* probably presents those characteristics, the effects that occurred in weed control in the *C. lusistanica* tree plantation are to be expected.

For example, studies have found the presence of phenolic compounds in WV, which was also found in WV of *G. arborea*, had shown acute phytotoxicity in seed germination and seedlings growth (Guevara *et al.* 2019; Thomas *et al.* 2024), due to high concentration of acetic acid, which destroys the cell membranes of seeds and causes rapid desiccation of plant tissues (Mu *et al.* 2003). Thus, WV helps break down the natural barriers and defense mechanisms of growing weeds that make them susceptible to herbicide attacks (Radhakrishnan *et al.* 2018).

WV tested in this study showed control on different weed groups (grass, broadleaf and Cyperaceae, Fig. 4). Some effects associated probably to WV in weed control are: (i) phenols components in WV can reduce amylase activity in weeds, slowing the starch hydrolysis; therefore, delaying seed germination (Iacomino *et al.* 2024), (ii) the efficacy of wood vinegar increases with the increasing of phenols and acetic acids (Maliang *et al.* 2016), (iii) acidic conditions of WV (pH = 2.9) increase the phytotoxicity of organic acids and phenols (Domenghini 2020) and (iv) then these three effects can help produce injury in the different weed groups in this study.

Other research (Aguirre *et al.* 2020b; Maliang *et al.* 2022) established the importance of acetic acids and phenolic compounds mixed in WV for weed control, which can indicate its efficacy for weed control in *Cupressus lusitanica* Christmas tree plantation. Acetic acid is known to be an organic but costly alternative for herbicides. However, acetic acids and phenolic compounds in WV have shown a greater mixed effect compared to the effects of acetic acids alone (Maliang *et al.* 2022), suggesting a synergistic effect with other components of WV like phenols. According to Aguirre *et al.* (2020b) phenols can increase the phytotoxicity of WV by enabling acids to stick to the plant, explaining the synergistic effect of these compounds. However, the interactions and action mechanism of acids and phenols on plants are not fully understood and still need to be further investigated.

WV has been shown to be effective as a natural derived herbicide (Aguirre *et al.* 2020b; Liu *et al.* 2021a; Chu *et al.* 2022). The results of this study confirmed the effectiveness of WV from *Gmelina arborea* residues for weed control, especially grass and broadleaf (Fig. 4a-b). WV presented an immediate effect on grass weeds (Fig. 3), providing more than 88% of visual injury 1 DAT and 85% 3 DAT with the higher doses (3000 and 5000 L ha^{-1}), but low efficiency over time. Other studies confirmed this effect, reporting this pattern of great initial weed control but decreasing efficiency over time (Aguirre *et al.* 2020a; Liu *et al.* 2021). Similarly, Domenghini (2020) reported that horticulture grade vinegar (20 to 30% acetic acid, an important component of WV) show a fast initial control of weeds but is insufficient for a prolonged period of time; these results are similar to the findings for the WV of *G. arborea* wood. Another effect that affected the decreasing efficiency of WV control on weeds over time was the presence of rain. WV was applied in the rainy season in tree plantation. According to Aguirre *et al*. (2019b) the effectiveness of WV can be reduced by the dilution effect caused by rains. Therefore, it is recommended to apply wood vinegar during dry season, given the speed of action.

On the other hand, an inconvenient aspect was found in the use of WV for weed control; the weed *Cyperus* sp. was not effectively controlled with WV, showing a control of only 30% (WV 5000 L ha^{-1}) three weeks after treatment (Fig. c). Maliang *et al.* (2020) found that the herbicidal effects of pyroligneous acids (including wood-derived vinegar) on *Cyperus rotundus* increased with higher acid and tar content, reaching up to 80% of fresh weight control effect. The low content of acids identified in *G. arborea* wood vinegar may explain the low control of the cyperaceous weeds. However, the results of low herbicidal effects cannot be attributed solely to WV, since some *Cyperus* genera are known for being difficult to control and only a few herbicides (selective and systemic) are recommended for its effective control (Xu and Zhou 2017). Some *Cyperus* species have evolved resistance to selective herbicides such as acetolactate synthase (ALS) or photosynthesis II (PSII)-inhibiting herbicides (Chen *et al.* 2023), therefore, there is a need for alternative solutions. WV, despite not being able to provide effective control with a unique application, could be able to control cyperaceous weeds with repeating applications, as it is recommended for other non-selective and contact herbicides (Tehranchian *et al.* 2015).

Cyperus species grow close to the ground with boat-shaped tips and scaly rhizomes that, upon maturation, become fibrous and difficult to break, producing tubers and bulbs in chains. However, in other cases, they occur with weak, easily broken rhizomes bearing individual tubers and rarely form tuber chains (Bryson and Carter 2008). Due to apical dominance and bud dormancy, the tubers remain in the soil for long periods before sprouting. Control of this species would be facilitated if the tuber lifespan were short enough for all buds to sprout simultaneously, allowing for the removal of the resulting plants (Bahadur *et al.* 2015).

Thus, both the biological characteristics of the species and the production system make its management difficult. It is known that desiccation and extremely low temperatures can inhibit the tubers. This kind of a situation did not occur in the trial presented in this paper. Studies have shown that these weed species are managed by maintaining dormancy for 4 to 6 months (Bahadur *et al.* 2015), with their rhizomes remaining underground. Experience in managing these weeds in some regions has shown that the tuber population can be reduced by 80 to 95% using chemical control (Bryson and Carter 2008). Therefore, applying WV to this type of weed, which has a long lifespan and rhizome root systems above ground, makes treatment less efficient in the underground parts and more effective in leaves, allowing the grass to recover quickly (Bahadur *et al.* 2015). Thus, to manage these grasses, it is necessary to seek other types of control.

Weeds showed greater biomass reduction and signs of visual injury at higher application doses of WV (3000 and 5000 L ha^{-1}) at 27 DAT, reaching up to 40% mass reduction, with similar effect of the synthetic herbicide Basta® at a conventional dose (Fig. 5). These findings coincide with other studies that have reported greater weed control and biomass reduction with the increase of WV concentrations and application dosages (Chu *et al.* 2022; Xu and Zou 2017). However, no significant difference was found between the herbicidal effects of WV 3000 and 5000 L ha^{-1}. Hence, the recommended application level of *G. arborea* WV to inhibit weed growth is 3000 L ha^{-1}, since it can provide the same effect as the higher dose tested, but with lower investment of resources, time and effort. As observed in the present experiment, the efficacy of WV depends on the objective as WV is effective to limit biomass development, thus competition for resources with crops, but it is inadequate to completely remove the weed cover (Aguirre *et al.* 2020a).

One of the most important findings is the high initial efficacy of wood vinegar, followed by a progressive decrease in herbicidal activity over time (Hao *et al.* 2021). This reduction in efficacy can be attributed to several limitations: concentration or dose applied, species treated, the volatilization of active compounds, microbial degradation, environmental conditions (specifically, leaching by rain), the time of application, and the lack of systemic activity of WV, which acts primarily as a contact herbicide (Maliang *et al.* 2022).

The efficacy of WV of *G. arborea* is efficient at concentrations above 5000 L ha^{-1} for some species. However, the application occurred during the rainy season, where rainfall levels exceeded 30 mm day^{-1} and temperatures reached approximately 27 °C. Such conditions can allow for a leaching of WV components or degradation due to temperature. Environmental factors such as temperature and light conditions influence efficacy: WV is more effective at lower temperatures and in darkness, providing higher levels of weed suppression compared to higher temperatures or full daylight (Liu *et al*. 2021a-b; Chu *et al*. 2022). Overall, WV has some limitations compared to synthetic herbicides: it typically offers less persistent control than conventional herbicides such as glyphosate, often requiring repeated applications for consistent vegetation management (Chu *et al.* 2022). Thus, even at optimal doses, some weeds are only partially suppressed and may re-emerge more quickly than with synthetic products. This underscores the need for integrated management approaches and careful weed selection (Bonanomi *et al.* 2026).

To improve the efficacy, wood vinegar as a contact herbicide should have more effect on seedlings and annual weeds compared to perennials and more mature plants (Xu and Zhou 2017). Additionally, multiple applications in the same area could be performed; nevertheless, this approach may be costly (Aguirre *et al.* 2020b) and further investigation is needed in this regard. Also, further investigation is needed to evaluate the environmental effects of the application of WV as a natural alternative to synthetic herbicides.

CONCLUSIONS

Wood vinegar (WV) produced from the pyrolysis of *G. arborea* residues could be a potential solution for managing the waste generated during the processing of this species for weed control in agricultural applications. So, there is an opportunity to add value to a circular economy by converting forestry waste into a useful product and developing sustainable bioherbicides. WV exhibited adequate physical properties and can cause rapid wilting or discoloration of sensitive plants, acting similarly to a non-selective contact herbicide. High application doses of wood vinegar produced rapid weed control, with a desiccation effect observed within a few hours of application. Biomass reduction of up to 40% can be achieved when WV is applied at high doses to mature grass-dominated weeds, thereby reducing competition for resources with the main crop. Wood vinegar provided faster and more effective control, especially of grass and broadleaf weeds, but its efficacy decreased in Cyperaceae grass. When applied at a level of 100 L/ha, a single application of wood vinegar was able to provide effective control of this type of grass; however, sequential applications may be necessary to achieve adequate control, as the weeds recover after 21 days. Further investigation is needed into the frequency and timing of application to improve its effectiveness, as well as on its compatibility with other non-selective and contact herbicides.

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Conflict of Interest

Authors must make clear any personal interest or relationship that could potentially be affected by the publication of their manuscript.

Use of Generative AI

Any AI was used for this article.

Data Availability of Data and Materials

Data will be made available in https://doi.org/10.18845/RDA/QFLUUH

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