



## Article

# Sweet Chestnut Wood Distillate's Role in Reducing *Helicoverpa armigera* Damage and Enhancing Chickpea Performance: Evidence from Field Trial

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**Abstract:** The moth *Helicoverpa armigera* (Lepidoptera: Noctuidae), better known as the pod borer, poses significant threats to chickpea (*Cicer arietinum* L.) production. Therefore, effective and sustainable crop management strategies are required to mitigate the impact of this cosmopolitan pest. The present study aimed at investigating the potential of wood distillate (WD), a liquid byproduct of the pyrolysis of waste lignocellulosic biomass, to both reduce *H. armigera* pest incidence and to enhance crop yields in field-grown chickpea. The application of WD as a foliar spray effectively reduced the number of damaged pods by 35% during the plant's reproductive stage compared with water-sprayed plants (~16 vs. 24 bored pods plant<sup>-1</sup>, respectively) and increased the number of healthy pods (~16 vs. 10 pods plant<sup>-1</sup>, respectively). Moreover, the lower pest incidence was accompanied by an improvement of both the seed yield and the quality at the plant's full maturity stage. Specifically, WD-treated plants increased both the number and weight of seeds by ~80% compared to water-sprayed plants (~23 vs. 13 and 5.5 vs. 3 plant<sup>-1</sup>, respectively) which further showed a remarkable improvement in their nutritional value, with the concentration of total polyphenols, flavonoids, starch, calcium, and magnesium increasing by 17%, 56%, 43%, 23%, and 15%, respectively. These results underscore the potential of WD to both improve chickpea performance and to reduce *H. armigera* damage to sustainably improve the productivity of this critical legume crop, aligning with the principles of the circular economy and offering an environmentally friendly alternative to synthetic pesticides and fertilizers in agriculture.

**Keywords:** legumes; insect pests; integrated pest management (IPM); pyrolysis liquids; seed quality



Academic Editors: Maja Čačija, Ivan Juran and Carmelo Peter Bonsignore

Received: 15 April 2025

Revised: 24 May 2025

Accepted: 28 May 2025

Published: 30 May 2025

**Citation:** Carril, P.; Colzi, I.; Fedeli, R.; Gonnelli, C.; Loppi, S. Sweet Chestnut Wood Distillate's Role in Reducing *Helicoverpa armigera* Damage and Enhancing Chickpea Performance: Evidence from Field Trial. *Horticulturae* **2025**, *11*, 613. <https://doi.org/10.3390/horticulturae11060613>

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## 1. Introduction

Chickpea (*Cicer arietinum* L.) plays a vital role in both sustainable agriculture and food security, owing to its capacity to fix atmospheric nitrogen, soil fertility enhancement, and nutritional endowments, including proteins and minerals for human consumption worldwide [1]. However, chickpea crops are susceptible to a wide range of biotic stresses, with insect pests being regarded as the most critical in terms of production losses [2]. Among these pests, the chickpea pod borer, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), is one of the most destructive [3]. In fact, depending on the insect density

and cultivar susceptibility, *H. armigera* can cause yield losses ranging from 30% to 90% in different legume crops, including soybean, common bean, lentil, and chickpea, with a single larva capable of feeding on up to 30–40 pods in the latter [4–8]. In Italy, outbreaks of *H. armigera* have been observed in various crops, including tomato in the Tuscany and Emilia Romagna regions [9–11], maize in the Sardinia region [12], and pepper in the Basilicata region [13]. Both its widespread distribution and broad feeding preferences have earned *H. armigera* the status of a quarantine pest by the European and Mediterranean Plant Protection Organization, underscoring the urgent need for both effective and sustainable management strategies to limit the impact of this cosmopolitan pest [14].

In this context, the utilization of synthetic pesticides, such as carbamates, organophosphates, or organochlorines, has contributed positively to controlling *H. armigera* [3,15,16]. However, the overuse of these products has hindered the progress of long-term integrated pest management (IPM) programs due to their detrimental effects on non-target organisms, their prolonged persistence in the soil, and the potential risk they pose to human health [17]. Contemporary IPM frameworks increasingly emphasize reduced-risk alternatives to reduce crop pest incidence, creating new opportunities for plant-derived products that can fulfill multiple IPM functions—simultaneously suppressing pests while enhancing plant resilience and productivity—thereby aligning with the core IPM principles of economic viability and ecological balance. In this scenario, liquids resulting from the pyrolysis of waste lignocellulosic biomass are gaining increasing recognition as innovative and eco-friendly biostimulants in agriculture to improve plant growth and health [18]. These products offer an environmentally sustainable solution to enhance crop health when compared to other conventional approaches, owing to their reliance on renewable sources for production and their minimal impact on non-target organisms [19–21]. In particular, wood distillate (WD), also known as pyroligneous acid, wood vinegar, or liquid smoke, is a liquid byproduct obtained from the pyrolysis of woody biomass, which has emerged as a promising biopesticide in agriculture. Although the precise mechanisms of action of WD remain to be fully understood, several researchers suggest that its beneficial effects are primarily linked to its rich composition of bioactive compounds—such as organic acids, phenolics, alcohols, sugars, and esters—as well as the resulting changes in soil enzyme activity and the composition of the soil microbiome [22–24].

Compared to conventional pesticides, biopesticides have reduced risks to human health and the ecosystem, as they are derived from natural sources such as plants, bacteria, or other organisms [25]. The application of WD has shown both insecticidal and repellent properties against different insects, including members of the Noctuidae family. For example, the application of both sugarcane- and tobacco-derived WD significantly inhibited the growth of feeding larvae from the genus *Spodoptera*, including *S. frugiperda* (JE Smith) and *S. litura* (Fabricius) [26,27]. Moreover, the application of 2% WD (Biopirrol 7M<sup>®</sup>) reduced *S. frugiperda* caterpillar hatching and larval mortality without negative effects on its natural enemy *Eriopsis connexa* (Germar) [28]. Insect mortality was also successfully reduced for neonates of black cutworm *Agrotis ipsilon* (Hufnagel) when exposed to WD-treated cabbage leaf disks [29].

Beyond its well-documented role as a biopesticide, WD has been widely utilized in horticulture and legume cultivation to enhance plant growth, boost fruit yield, and improve the nutritional quality of edible plant tissues [24,30–33]. However, despite these known benefits, no studies have yet explored the dual functionality of WD—its simultaneous biopesticidal/biorepellent (pest damage reduction) and biostimulatory (growth-promoting) effects—on chickpea plants under *Helicoverpa armigera* infestation. Investigating this dual mechanism could provide critical insights into the integrated use of WD in sustainable pest management and crop production. Given the increasing demand for eco-friendly

agricultural inputs, such research would not only advance our understanding of plant–pest interactions but also support the development of WD-based strategies to enhance both the yield and nutritional value of chickpea, a vital legume crop. Beyond its biopesticidal effects, WD is also widely used to promote plant growth, to increase fruit production, and to enhance the nutritional value of edible plant parts in both horticultural and leguminous crops [24,30–33]. However, no reports exist on the dual (pest damage reduction and biostimulatory) action of WD on chickpea plants infected by *H. armigera*. Therefore, to provide new insights into the use of WD in the interaction of chickpea plants with pests and in its production and quality, the aims of this study were as follows: (1) to assess the effectiveness of WD in managing a naturally occurring *H. armigera* outbreak in a chickpea crop field, and (2) to investigate whether WD could increase both seed yield and seed nutritional quality of *Cicer arietinum*.

## 2. Materials and Methods

### 2.1. Plant Material and Wood Distillate Characteristics

This study utilized seeds of *Cicer arietinum* L. (cv. Cece Piccolo Aretino) provided by Del Colle Srl. (Bientina, Italy). This variety was selected for its distinctive agronomic and culinary characteristics, such as superior seed integrity due to a thin yet firm seed coat, enhanced pigmentation compared to standard commercial varieties, and excellent cooking properties characterized by rapid hydration while maintaining structural integrity, making it particularly suitable for whole-seed consumption applications. Wood distillate (WD), derived from the pyrolysis of sweet chestnut (*Castanea sativa* Mill.) biomass, was supplied by BioEsperia<sup>®</sup> Srl (Arezzo, Italy). To produce the WD, the sweet chestnut biomass underwent pyrolysis using a thermal gradient from 750 to 900 °C, after which it was left to settle for a minimum of three months. The WD analysis conducted by the producer revealed the following characteristics: pH 3.5–4.5, acetic acid 2–2.3% (v/v), density 1.05 kg L<sup>-1</sup>, and polyphenol content 22–25 g L<sup>-1</sup>. The mineral content of WD, as reported in [32], was as follows: Fe 3.2 mg L<sup>-1</sup>, Na 4.9 mg L<sup>-1</sup>, K 32.9 mg L<sup>-1</sup>, Ca 944.2 mg L<sup>-1</sup>, Zn 3.6 mg L<sup>-1</sup>, and Mg 16 mg L<sup>-1</sup>.

### 2.2. Study Site and Experimental Setup

The experiment was carried out in a chickpea crop field at Meristema S.r.l. (Buti, Tuscany, Italy) following organic farming principles, where no synthetic fertilizers or pesticides were added and spontaneous weeds were not eliminated. The chickpea seeds were sown on 30 April 2024 in a soil characterized by 26% clay, 37% sand, and 3.3% organic matter. When plants reached the fifth node stage (the phase where the plant progresses towards maturity and typically exhibits the formation of five nodes along the main stem), six experimental plots (1.5 m × 6 m) were delimited, each containing 30 plants. The plots were separated by a row of untreated plants (1 m wide), and within each plot, border plants (i.e., those neighboring the raw untreated plants, 10 plants per plot) from all measurements were excluded to account for potential neighboring effects in the analyses. Following a randomized complete block design (two plots per block—one WD-treated, one control), half of the plots were foliar sprayed weekly and fertigated every two weeks with WD. The other half was treated in the same way but using tap water only (control). Before application, the WD was diluted in tap water at 0.2% (v/v) for foliar treatments and at 0.3% (v/v) for fertigation, according to the producer's instructions. The volume of treatment applied varied according to the plant growth stage (~100 mL/plant during the first three weeks, ~150 mL/plant during the fourth, fifth, and sixth week, and ~250 mL/plant during the last month). All applications were performed between 07:00 and 09:00 am under similar environmental conditions.

The plants were grown for ten weeks until they were completely dry and nearly 90% of the pods were physiologically mature (golden yellow color).

### 2.3. An Evaluation of *H. armigera* Damage Across the Reproductive Stage

The effect of WD treatment on the number of healthy and *H. armigera*-damaged pods was investigated across three timepoints during the reproductive stage of chickpea. The first timepoint was 22 July, corresponding to the late pod filling stage (i.e., the pod cavities are filled with one or two fresh seeds), the second timepoint was 10 August, corresponding to the mid-maturity stage (i.e., when approximately 50% of the pods reach maturity and thus become dry, turning into a light yellow color), and the third timepoint was 2 September, corresponding to full maturity (i.e., when ~90% of pods reach maturity) stages, respectively. To evaluate the degree of *H. armigera* damage, the pods were counted and classified as healthy (the absence of a feeding hole and the presence of at least one seed) or bored (the presence of a feeding hole and the absence of seeds). Finally, at the full maturity stage, the pods were collected and the total number of seeds in each plant was counted, weighed, and their diameter, mean weight, and total weight measured.

### 2.4. Seed Nutritional Parameters

At the end of the experiment, all healthy seeds were collected and ground into flour using a professional mixer (IKA A10, IKA Labortechnik, Staufen, Germany). Seeds from each plant were pooled and treated as a single replicate, resulting in 20 replicates across the two treatments.

#### 2.4.1. Polyphenol Concentration

The method reported by [34] was used to determine the concentration of total polyphenols. One gram of the samples was homogenized in 4 mL of a 70% acetone/water solution. After that, 0.950 mL of deionized water, 0.750 mL of saturated  $\text{Na}_2\text{CO}_3$  solution, and 0.125 mL of the Folin–Denis reagent (Sigma-Aldrich, Saint Louis, MO, USA) were added to the extract (0.5 mL). After being centrifuged once again, the resultant solution was kept at 36 °C for 30 min. The samples were then read using a UV spectrophotometer (8453, Agilent, Santa Clara, CA, USA) at 750 nm. For the quantification, the absorbance of the samples was referred to using a calibration curve ( $5\text{--}20\ \mu\text{g mL}^{-1}$ ) of gallic acid (Sigma-Aldrich, USA) as the standard.

#### 2.4.2. Flavonoid Concentration

The method reported by [35] was used to determine flavonoids. After homogenizing the samples (about 1 g) in 2 mL of 80% ethanol/water, they were centrifuged at 15,000 rpm for 5 min. A total of 300  $\mu\text{L}$  of deionized water and 500  $\mu\text{L}$  of the supernatant were combined with 45  $\mu\text{L}$  of a 5%  $\text{NaNO}_2$  solution. A total of 300  $\mu\text{L}$  of a 1 M NaOH solution, 300  $\mu\text{L}$  of deionized water, and 45  $\mu\text{L}$  of a 10%  $\text{AlCl}_3$  solution were then added. After that, a UV-VIS spectrophotometer (8453, Agilent, Santa Clara, CA, USA) was used to read the samples at 510 nm.

#### 2.4.3. Starch Concentration

The method reported by [36] was used to determine the starch concentration. Fifty milligrams of the samples were emulsified in 2 mL of dimethyl sulfoxide. As a result, 0.5 mL of 8 M HCl was added, and the samples were then heated to 60 °C in an oven for 30 min. Seven mL of deionized water and 0.5 mL of 8 M NaOH were added after cooling. The samples were then centrifuged at 4000 rpm for 5 min, after which 0.5 mL of the supernatant was added to 2.5 mL of the Lugol solution (0.05 M HCl, 0.03%  $\text{I}_2$ , and

0.06% KI). Using a UV–VIS spectrophotometer (8453, Agilent, Santa Clara, CA, USA), the samples were read at 605 nm after 15 min.

#### 2.4.4. Element Concentration

The quantification of the mineral elements followed the method of [37]. Before the analysis, chickpea seeds were ground with a professional mixer (IKA A10, IKA Labortechnik, Staufen, Germany). Approximately 200 mg of ground material was dissolved in 3 mL of 67% nitric acid (HNO<sub>3</sub>), 0.5 mL of 30% hydrogen peroxide, and 0.2 mL of hydrofluoric acid (HF) using a Milestone Ethos 900 microwave digestion device (Ethos 900, Milestone Srl., Milan, Italy). Following digestion, the samples were filtered using filter disks (particle retention = 40 µm; VWR, Darmstadt, Germany), and 50 mL of ultrapure water was subsequently added. Inductively coupled plasma mass spectroscopy (ICP-MS, NexION 350 Perkin-Elmer Inc., Shelton, CT, USA) was utilized to quantify the concentrations of potassium (K), phosphorus (P), magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), zinc (Zn), sulfur (S), and copper (Cu). The analytical quality was verified using certified reference materials “GBW 07604-Poplar leaves” and “GBW 07603-Branches leaves”, with recovery rates in the range of 96–104%. Analytical precision was assessed using the coefficient of variation of five replicates, and this was consistently > 98%.

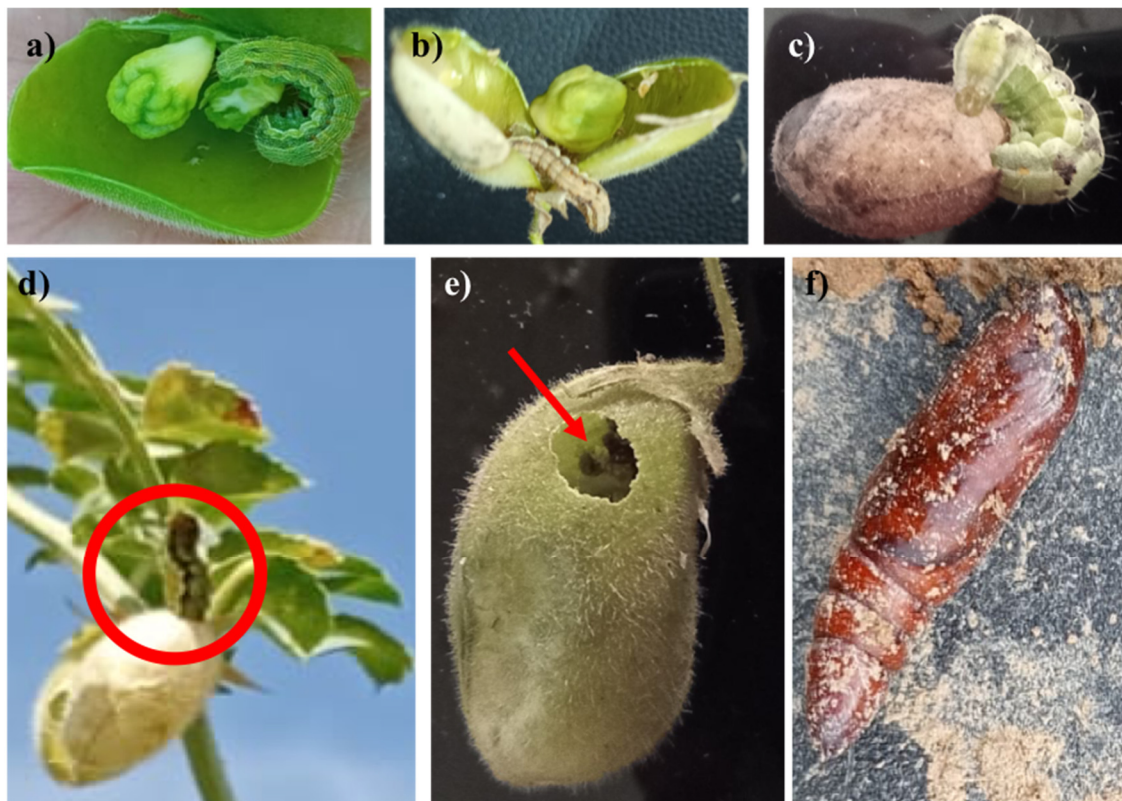
#### 2.5. Statistical Analyses

To check for significant differences in both yield and nutritional parameters between the control and WD-treated plots, a linear mixed-effect model (LMEM) was fitted for each measured variable and was run with the treatment as the fixed effect and the plot as the random effect. The results were presented as the mean ± standard error (SE). Analyses were performed using the SPSS software (IBM SPSS Statistics version 28, USA). For model validation, residuals were tested ( $p < 0.05$ ) for normality using a quantile–quantile (Q–Q) plot, which indicated that the residuals closely followed a straight line, suggesting that they were approximately normally distributed. Additionally, the Shapiro–Wilk test for normality was performed, which yielded a  $p$ -value of 0.43, further supporting the assumption of normality. To evaluate homoscedasticity, a scatterplot of the residuals against the fitted values was examined, and Levene’s test for homogeneity of variances was conducted, which returned a  $p$ -value of 0.55, confirming that the assumption of homoscedasticity was met. The significance of the models was checked with type II Anova (analysis of deviance) using the Wald chi-square test.

### 3. Results

#### 3.1. Observations of *H. armigera* Lifecycle in Chickpea Crops

Adult *H. armigera* moths were spotted for the first time during the last week of June, and the presence of eggs on chickpea leaves was noted nearly a week later. Larvae were spotted at their second (4–7 mm length, Figure 1a), fourth (12–20 mm length, Figure 1b), and sixth (25–30 mm length, Figure 1c,d) instar for the first time on 15 July, 1 August, and 8 August, respectively. Bored pods (Figure 1e) were observed for the first time on 20 July. The first pupae were spotted in the soil approximately in mid-August (Figure 1f) after fully grown larvae started crawling to the base of the plant and tunneled up to 10 cm into the soil.



**Figure 1.** *H. armigera* larva in its (a) second, (b) fourth and (c) sixth instar during the late filling, maturity, and harvesting reproductive stages; (d) fourth instar larva spotted in the field (e) typical *H. armigera* feeding hole in a fresh pod; and (f) *H. armigera* pupa recovered from the soil.

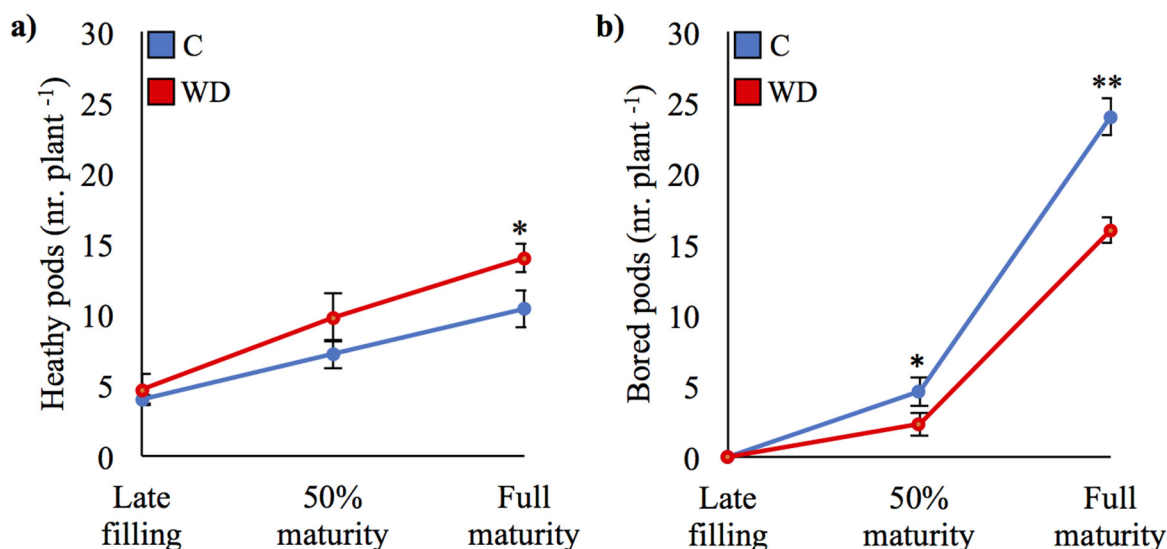
### 3.2. Reduced Damage in WD-Treated Plants

The observed effect of WD against *H. armigera* was repellent-like, as no dead larvae or moths were detected throughout the entire duration of the experiment.

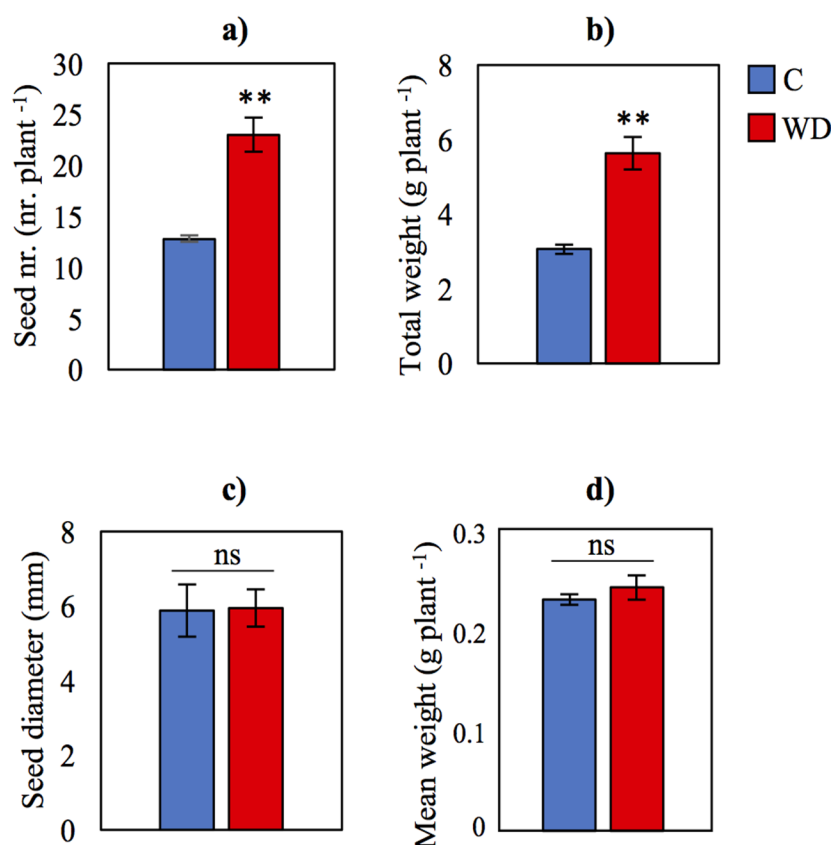
The effect of WD treatment on the number of healthy and *H. armigera*-damaged pods was investigated at the late filling, maturity, and harvesting stages of chickpea development. While differences in the number of healthy pods between treatments were not observed, neither at the late filling nor at the maturity stages, WD-treated plants showed an almost 40% increase in this parameter at the full maturity stage ( $14.5 \pm 1$  vs.  $10.4 \pm 0.4$  number of pods plant<sup>-1</sup>;  $p < 0.05$ , Figure 2a). Conversely, the number of bored pods decreased by 28% in WD-treated plants compared to control plants at the mid-maturity stage ( $3.3 \pm 0.8$  vs.  $4.6 \pm 0.9$  bored pods plant<sup>-1</sup>;  $p < 0.05$ ) and by almost 35% in the full maturity stage ( $16.2 \pm 0.9$  vs.  $24 \pm 1.3$ , bored pods plant<sup>-1</sup>;  $p < 0.01$ ) (Figure 2b).

### 3.3. Seed Yield and Nutritional Quality

The results from the measured seed biometric traits at the full maturity stage revealed that WD-treated plants increased both the total seed number per plant by over 80% ( $23.2 \pm 0.3$  vs.  $12.8 \pm 1.4$  plant<sup>-1</sup>;  $p < 0.01$ , Figure 3a) as well as the total seed weight by more than 85% ( $5.63 \pm 0.12$  vs.  $3.06 \pm 0.43$  g plant<sup>-1</sup>;  $p < 0.05$ , Figure 3b). On the other hand, significant differences were not observed, neither in seed diameter nor in the mean seed weight between both treatments ( $p > 0.05$  in both cases, Figure 3c,d).



**Figure 2.** (a) Number of healthy pods and (b) number of bored pods collected from C and WD-treated plants (mean  $\pm$  SE). \* = statistically significant difference at  $p < 0.05$ ; \*\* = statistically significant difference at  $p < 0.01$ . Abbreviations—C: control; WD: wood distillate.



**Figure 3.** Seed yield parameters (mean  $\pm$  SE) of C and WD-treated chickpea plants. (a) The seed number, (b) the total seed weight, (c) the seed diameter, and (d) the mean seed weight per plant. \*\* = statistically significant difference at  $p < 0.01$ . ns: not significant. Abbreviations—C: control; WD: wood distillate.

Furthermore, the application of WD increased the concentration of total polyphenols, flavonoids, and starch in the seed by 17% ( $p < 0.05$ ), 56% ( $p < 0.01$ ), and 43% ( $p < 0.01$ ), respectively, compared to the control plants (Table 1).

**Table 1.** Total polyphenols, flavonoids, and starch concentration (mean  $\pm$  SE) of chickpea seeds harvested from control and WD-treated plants. \* = statistically significant difference between treatments at  $p < 0.05$ ; \*\* = statistically significant difference at  $p < 0.01$ . Abbreviations—C: control; WD: wood distillate.

	Total Polyphenols (mg g <sup>-1</sup> )	Flavonoids (mg g <sup>-1</sup> )	Starch (mg g <sup>-1</sup> )
C	0.507 $\pm$ 0.005	0.191 $\pm$ 0.007	161 $\pm$ 7
WD	0.594 $\pm$ 0.007 *	0.298 $\pm$ 0.004 **	231 $\pm$ 4 **

Regarding the seed mineral concentration, the concentration of most analyzed elements, including Fe, Na, K, P, S, Zn, and Cu, was similar between the control and WD-treated plants ( $p > 0.05$ ) (Table 2). On the other hand, WD application led to a significant 20% and 10% increase in the concentrations of Ca (1527  $\pm$  34 mg kg<sup>-1</sup> vs. 1241  $\pm$  26 mg kg<sup>-1</sup>;  $p < 0.05$ ) and Mg (1589  $\pm$  11 mg kg<sup>-1</sup> vs. 1741  $\pm$  38 mg kg<sup>-1</sup>;  $p < 0.05$ ).

**Table 2.** Mineral concentration (mg kg<sup>-1</sup> dw; mean  $\pm$  SE) of seeds harvested from control and WD-treated chickpea plants. \* = statistically significant difference between treatments at  $p < 0.05$ . Abbreviations—C: control; WD: wood distillate.

	Ca	Mg	Fe	Na	K	P	S	Zn	Cu
C	1241 $\pm$ 26	1589 $\pm$ 11	76 $\pm$ 3	153 $\pm$ 16	10,226 $\pm$ 15	3660 $\pm$ 134	2064 $\pm$ 113	33 $\pm$ 1	9 $\pm$ 1
WD	1527 $\pm$ 34 *	1741 $\pm$ 38 *	79 $\pm$ 7	164 $\pm$ 33	10,791 $\pm$ 208	3834 $\pm$ 179	2107 $\pm$ 197	35 $\pm$ 3	10 $\pm$ 1

#### 4. Discussion

*Helicoverpa armigera* pests pose a significant threat to numerous crops worldwide, leading to reduced yields and substantial economic losses. The present study is the first to investigate a *H. armigera* outbreak in a leguminous crop in Italy and to explore the potential of WD as a means to control this pest.

The stages of the *H. armigera* lifecycle observed in this study were consistent with the previously documented behavior of this pest in chickpea, with the presence of eggs and larvae indicating population progression and with the first bored pods confirming the larvae's potential for yield loss and damage [38]. Across the plant's reproductive stages, the reduced number of bored pods suggests that WD could effectively mitigate larval damage through a potential deterrent-like action, causing the pest to avoid the treated plants, rather than causing direct mortality. Pyrolysis byproducts from hardwoods and other woody feedstocks (e.g., *Betula pendula*, *Eucalyptus urograndis*, *Acacia mearnsii*, and *Cocos nucifera*) wood contain several bioactive compounds—such as furfural, acetic acid, phenolic compounds (including syringol derivatives), and ether-soluble compounds (e.g., aldehydes, ketones, and lignin monomers)—that exhibit repellent effects against snails [39,40]. Similarly, wood vinegar produced from common conifers and deciduous species (e.g., *Cryptomeria japonica*, *Pseudotsuga menziesii*, *Quercus serrata*, and *Pinus densiflora*) has demonstrated termiticidal activity, primarily attributed to its acetic acid and phenolic constituents [41]. Additionally, lignin-derived polyphenols—such as phenol, cresol, guaiacol, and eugenol—found in wood vinegar from various feedstocks have been proposed to contribute to pest repellency [42,43]. The characteristic smoky odor of wood-derived (WD) products likely originates from methoxyphenols, furans, ketones, and other aromatic compounds generated during lignin and cellulose pyrolysis. These compounds may disrupt insect olfactory orientation, as observed with furfural in food substrates [44]. Although reduced larval damage and the absence of insect mortality suggest a repellent effect; the underlying behavioral mechanisms remain unclear and warrant further investigation. To substantiate the

potential of chestnut-derived WD as a biorepellent, future studies should include oviposition preference assays to assess whether WD deters egg-laying behavior, as well as larval feeding deterrence assays to determine if WD inhibits feeding via contact or ingestion. Additionally, chemical ecology approaches, such as analyzing WD-induced plant volatile organic compounds (VOCs), could elucidate pest avoidance mechanisms by comparing moth attraction to WD-treated versus untreated plants. Moreover, future studies should align WD applications with critical pest phenological windows (e.g., early egg deposition or first-instar larval emergence) to optimize the efficacy of this biostimulant. For instance, foliar sprays during egg-hatching—when neonates are most vulnerable—could exploit WD's oviposition-deterrent and antifeedant properties to refine IPM recommendations.

Compared to other products with biocidal action (e.g., synthetic insecticides), this repellency effect could contribute to the maintenance of more balanced ecosystem functioning and hence align well with the principles of IPM strategies [16,45]. In support of this statement, WD produced from different feedstocks (e.g., *Castanea* spp., *Populus* spp., and *Eucalyptus* spp.) and applied at similar concentrations has been shown to have minimal impact on non-target organisms, including lichens, mosses, aquatic ferns, threatened arable plants, and natural pest enemies [19–21,28,46]. However, further research in this field is needed to thoroughly evaluate the influence of WD application on other insects present in this type of agricultural system.

Notably, the reduced damage in WD-treated plants by *H. armigera* was accompanied by a biostimulatory effect on seed yield and quality. WD has been traditionally employed as biostimulant in agriculture, due to its remarkable effects in promoting plant growth and enhancing the nutritional value of edible plant parts in both horticultural and leguminous crops. By deterring *H. armigera* larvae, WD likely provided a favorable environment for chickpea plants to allocate resources towards growth and reproduction, as evidenced by the remarkable 80% increase in both the seed number and seed weight upon full plant maturity. Furthermore, the observed yield increases were accompanied by an improvement of the seeds' nutritional value, characterized by a substantial increase in the concentration of total polyphenols, flavonoids, and starch, respectively. Polyphenols, including flavonoids, are central players in the onset of defense responses against both abiotic and biotic stresses in plants, and play a significant role in human health, offering various benefits through their antioxidant and cell signaling properties [47,48]. Both the total polyphenol and flavonoid concentrations found across non-treated and WD-treated seeds was lower compared to those reported for other chickpea varieties, e.g., black, desi, and kabuli types, which are generally in the 0.7–2 mg g<sup>-1</sup> range in the case of polyphenols and in the 1–3 mg g<sup>-1</sup> range for flavonoids [49–53]. However, the extent of the WD-mediated increase in the concentration of these compounds is consistent with a recent study in chickpea seeds [36], suggesting that, in the presence of *H. armigera*, WD can increase the nutritional value of seeds in terms of polyphenol and flavonoid concentrations. Starch, on the other hand, acts as a major storage carbohydrate, providing plants with a readily available energy source for germination and growth [54]. Previously, Ref. [36] reported similar WD-mediated increases in both total polyphenol and starch concentrations in the absence of *H. armigera*, suggesting that WD, and not the pest, could be the main driver for the observed changes in these nutritional parameters. In this experiment, only the seeds from WD-treated plants reached similar starch concentrations to those generally reported, which range from 22 to 46% of the seed dry matter [55–57]. In this regard, the higher feeding activity of *H. armigera* larvae in control plants could have caused higher physical damage in both pods and seeds, disrupting starch biosynthesis and accumulation in the seed.

Regarding element concentration, seeds from WD-treated plants showed increased levels of Ca and Mg. Deficiencies in these elements are highly prevalent among human

populations, being correlated with type 2 diabetes and osteoporosis, respectively [58,59]. In a recent study, in the absence of the pest, Ref. [32] showed a similar WD-mediated increase in the concentration of these two minerals. However, in the present study, the extent of the increase was lower (75% vs. 23% increase for Ca; 33% vs. 10% increase for Mg), suggesting that the presence of *H. armigera* could have compromised the levels of these elements in the seeds. These observations highlight that WD application could critically contribute to alleviating the number of subjects affected by these deficiencies via food fortification approaches [60]. Considering that the recommended legume intake is approximately 1.5 cups (~200 g) per week [61,62], WD-fortified chickpea seeds harvested from the present field experiment could provide a higher amount of the required dietary Ca and Mg (~4% and ~13%) compared to control seeds. The concurrent improvement in plant nutritional quality, consistent with the reduced pest incidence, suggests a potential linkage between pest suppression and enhanced plant performance. However, further mechanistic studies are warranted to validate causality. Additionally, future studies should include comparisons with pest-free control plants to better isolate WD's protective versus growth-promoting effects.

Collectively, these results indicate that WD exhibited biostimulant properties, promoting plant growth and yield enhancement, and also reduced *H. armigera* damage, leading to an improvement in overall plant health. While the observed effects of WD are comparable to other known treatments (e.g., plant-derived compounds or the application of beneficial microorganisms), WD offers cost-effectiveness by utilizing locally sourced waste biomass, eliminating the need for additional cultivation or extraction processes [63–66]. Moreover, while the initial investment in wood distillate production equipment may be required, the long-term cost implications for farmers can be reduced due to the potential decrease in the need for synthetic fertilizers, pesticides, and other chemical inputs, leading to potential cost savings and improved profitability. This could significantly contribute to improved resource efficiency in agriculture, matching multiple Sustainable Development Goals (SDGs) outlined in Agenda 2030 [67], particularly those focused on achieving a balance between meeting current food demands and minimizing environmental impacts. In this regard, to fully assess the practical relevance of WD as a substitute for synthetic inputs, future work should prioritize collaboration with agricultural economists to conduct rigorous cost–benefit analyses accounting for region-specific factors (e.g., labor costs, subsidies, and yield stability). Additionally, comprehensive life cycle assessments (LCAs) are needed to quantify WD's environmental advantages, such as reduced fossil fuel dependence in fertilizer production and lower ecotoxicity, compared to conventional inputs. Such interdisciplinary studies would bridge the gap between agronomic efficacy and real-world adoption, providing policymakers and farmers with actionable data to evaluate WD's scalability and alignment with sustainable intensification goals, including SDGs 2, 12, and 15. Altogether, these promising results underline the need to conduct a thorough cost–benefit analysis and consider the specific agricultural context to determine the economic viability and potential returns of using WD in large-scale agricultural operations.

## 5. Conclusions

The results of this study demonstrated that the application of WD to chickpea crops affected by *H. armigera* not only reduced pest incidence but also improved seed yield and nutritional quality. Collectively, these findings have important implications for IPM strategies, as they highlight both the biorepellent and biostimulant potential of WD for sustainably improving seed quality and plant health. In addition to these benefits, it is also important to consider the following: (1) WD can be derived from locally sourced waste biomass through pyrolysis, reducing feedstock costs compared to synthesized agrochemicals. While

feedstock selection requires optimization—as wood composition affects WD efficacy—this approach can decrease the impact of waste on the environment, allow the replacement and reduction in the use of synthetic compounds in agriculture, and facilitate the transition to a sustainable circular economy; and (2) the distillation process during pyrolysis is relatively simple and requires less complex equipment compared to the extraction processes used for synthesizing plant extracts or oils. Hence, the use of WD could significantly contribute to achieving a balance between meeting current food demands and minimizing the use of synthetic fertilizers and pesticides in agriculture.

**Author Contributions:** Conceptualization, P.C., I.C. and S.L.; methodology, P.C., I.C., R.F. and S.L.; software, P.C.; validation, P.C., I.C. and S.L.; formal analysis, P.C. and R.F.; investigation, P.C., I.C. and R.F.; resources, S.L.; data curation, P.C. and R.F.; writing—original draft preparation, P.C.; writing—review and editing, P.C., I.C., R.F., C.G. and S.L.; visualization, P.C.; supervision, S.L.; project administration, S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the project CLASS (“Ceci, distillato di legno, biochar e intelligenza artificiale per un sistema agrifood smart e sostenibile”), Regione Toscana, project number B69J21027970008).

**Data Availability Statement:** All available data can be found in this manuscript.

**Acknowledgments:** The authors are grateful to Francesco Barbagli (BioDea © and BioEsperia Srl.) for providing the wood distillate and to Alessia Papi and Miriam Negussu for their help in the fieldwork. We also thank the project CLASS (project number B69J21027970008) for funding this research. The authors also acknowledge the support from NBFC to the University of Siena, funded by the Italian Ministry of University and Research, PNRR, Missione 4, Componente 2, “Dalla ricerca all’impresa”, Investimento 1.4, Project CN00000033.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

WD	Wood distillate
IPM	Integrated pest management

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