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Evaluation of Pelargonic Acid as a Sustainable Defoliant in Cotton (*Gossypium hirsutum* L.) Production

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Abstract

Cotton production faces sustainability challenges due to the lack of effective sustainable defoliants for mechanical harvesting, which constrains the expansion of organic cotton (currently 0.5% of global production). In this framework, this study evaluated pelargonic acid, a rapidly biodegradable compound, as a sustainable defoliant alternative, comparing it with the synthetic pyraflufen-ethyl and a water placebo. A two-year field trial (2023–2024) in Sicily, southern Italy, tested three application rates per treatment in a randomized complete block design. Parameters assessed included defoliation efficacy, root diameter, boll number per plant, average boll weight, raw yield, lint yield, and seed yield. Results indicated significant "Year × Treatment" interaction effects on all parameters. Pelargonic acid applied at 16 L ha^{-1} achieved the highest boll number per plant in 2024, significantly exceeding pyraflufen-ethyl at its label-recommended rate, with treatments at 12 L ha^{-1} also producing larger root diameters than the synthetic defoliant. Pelargonic acid at 18 L ha^{-1} in 2023 achieved complete defoliation, matching the efficacy of pyraflufen-ethyl, while the lowest pelargonic rate (12 L ha^{-1}) produced >90% leaf drop across both years. These findings position pelargonic acid as a rapidly degradable alternative to synthetic defoliants, directly addressing a key bottleneck in sustainable cotton production.

Keywords: cotton; defoliation; pelargonic acid; sustainable cultivation; pre-harvest management

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Received: 21 August 2025
Revised: 10 October 2025
Accepted: 12 October 2025
Published: 14 October 2025

Citation: Vitale, G.S.; Lombardo, S.; Pandino, G.; Guarnaccia, P. Evaluation of Pelargonic Acid as a Sustainable Defoliant in Cotton (*Gossypium hirsutum* L.) Production. *Agriculture* **2025**, *15*, 2134. https://doi.org/10.3390/agriculture15202134

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1. Introduction

Cotton (*Gossypium* spp.) is a globally important industrial crop, serving as the primary source of natural fiber for the textile industry [1]. According to FAO [2], annual cotton fiber production exceeds 24.8 million tons, cultivated across more than 80 countries, with China, India, Brazil and the United States being the top producers [3]. However, cotton cultivation faces significant challenges related to water consumption, pesticide use, and post-harvest management, necessitating the adoption of sustainable agronomic practices [4,5]. One critical step in sustainable cotton production is defoliation; a pre-harvest practice aimed at removing leaves to facilitate mechanical picking and reduce trash content in the harvested fiber [6]. The absence of effective organic defoliants remains a primary constraint in global organic cotton production, which constitutes merely 0.5% of total output [1]. While conventional cotton production relies on synthetic defoliants to enable efficient mechanical harvesting, organic systems must depend on manual boll picking—a labor-intensive practice that significantly limits scalability [7]. Traditionally, this operation is carried out through the application of chemical defoliants based on compounds such as Tribufos, Dimethipin, Pyraflufen-ethyl, and Ethephon, which are widely used [8–10]; some

of these active substances are authorized within the European Union (e.g., pyraflufen-ethyl, ethephon), whereas thidiazuron—widely employed in other parts of the world, including the United States—was not included in Annex I of Directive 91/414/EEC [11], and authorizations for products containing this substance were withdrawn by Commission Decision 2008/296/EC [12]. These substances promote leaf drop by accelerating cellular senescence [13,14]. However, the prolonged use of these products raises concerns regarding their environmental persistence, residual phytotoxicity, and potential health risks to humans [15,16].

In response to these issues, research is increasingly focusing on agronomic practices aimed at promoting the plant's natural senescence without resorting to chemical defoliants and without causing significant yield losses. One such approach is irrigation termination, which consists of stopping irrigation 4–5 weeks before the final harvest to stimulate natural defoliation [4,17–19].

In addition, efforts have been made to identify organic and environmentally friendly defoliants. For instance, the use of vinegar—specifically, applying 30% vinegar at a rate of 280 L ha^{-1} before cotton harvest—has shown some promise as an organic alternative to synthetic defoliants. However, its efficacy is lower, and it requires higher application volumes compared to conventional defoliants [20]. Moreover, cotton pickers and strippers often face difficulties due to incomplete defoliation, which can result in reduced lint recovery efficiency [21]. Other authors have reported the use of sodium chloride (NaCl) [7] or acetic acid [22]; however, no studies have yet been conducted regarding their application on cotton. Currently, there is no universally accepted sustainable defoliant for cotton capable of delivering results comparable to synthetic products. For this reason, researchers have turned their attention to pelargonic acid, an organic compound widely used as a defoliant in other crops, such as onion [23] and curly willow, where defoliation is necessary for the commercial quality of the product [22].

Pelargonic acid ($CH_3(CH_2)_7$ COOH) is a saturated fatty acid composed of nine carbon atoms [24]. It was first isolated from the leaves of *Pelargonium roseum* Willd and can also be found in various vegetables and fruits (such as grape, orange, apple, and potato), as well as in milk, cheese, and beef [25,26]. This compound functions as a contact, non-selective, non-residual foliar bioherbicide that disrupts plant cells and rapidly desiccates green tissues, with degradation in the soil occurring in less than two days [27].

Although there is considerable data on the dosage of pelargonic acid as an herbicide [26,28,29], information on its use as a desiccant remains scarce. Greer et al. [22] reported that 1000 to 1500 mg·L^{-1} per plant of pelargonic acid is required to defoliate curly willow (*Salix matsudana* L.), where defoliation is necessary for commercial purposes. Other authors have observed that an application rate of 3400 g ha^{-1} of pelargonic acid caused up to 98% desiccation in white beans (*Phaseolus vulgaris* L.) [27]. However, no data are currently available regarding its use as a defoliant on cotton. For this reason, the study will be structured around two key objectives:

1. Evaluation of the defoliation efficacy of pelargonic acid at different concentrations, comparing its performance to that of pyraflufen-ethyl, a widely used defoliant in the cotton industry and authorized within the European Union [6,30], and to a placebo treatment (water).
2. Analysis of physiological and yield-related parameters in response to the defoliation treatments.

The results could open new perspectives for the adoption of a rapid-acting, biodegradable, low-toxicity organic defoliant, thereby contributing to the transition toward more sustainable cotton production in the Mediterranean basin.

2. Materials and Methods

2.1. Experimental Site and Weather Data

The experimental trial was conducted at the experimental farm of the Catania University, located in Primosole (Catania, Sicily, Italy) (37°24′ N, 15°03′ E; 10 m a.s.l.), during the 2023 and 2024 growing seasons. The chemical and physical characteristics of the soil, which is sub-alkaline clay, are presented in Table 1.

Table 1. Characteristics of the upper soil layer (0–50 cm) of the field site.

Soil Characteristics	Unit	Value	Method
Sand	%	16.6	[31]
Loam	%	27.8	[31]
Clay	%	55.6	[31]
N total	g kg^{-1}	1	Kjeldahl [32]
P	mg kg^{-1}	2.18	Ferrari [33]
K	mg kg^{-1}	203.3	Dirks and Scheffer [33]
Organic matter	%	1.1	Walkley and Black [33]
Electrical Conductivity	mS/m	15	[34]
Cation Exchange Capacity (CEC)	cmolc kg^{-1}	14.8	[35]
pH		7.6	In water solution
Bulk density	kg m^3	1200	[36]
Field capacity at −0.03 MPa	%	27	[37]
Wilting point at −1.5 MPa	%	11	[38]

The local climate is typically Mediterranean, with mild winters and hot, dry summers. Meteorological data on rainfall and air temperature were obtained from stations operated by the Sicilian Agrometeorological Information Service, located in proximity to the experimental site. The stations were equipped with MTX dataloggers (model WST1800) (Campogalliano, Italy) and a range of climatic sensors. Temperature data were recorded using an MTX TAM platinum PT100 heat-resistant sensor with a radiation shield (Campogalliano, Italy), while precipitation was measured using an MTX PPR tipping bucket rain gauge (Campogalliano, Italy). These instruments provided daily records of maximum and minimum air temperatures (°C) and total daily rainfall (mm). Reference evapotranspiration (ET_0), expressed as the monthly sum of daily values, was calculated according to the FAO Irrigation and Drainage Paper No. 56 [39]. The thermo-pluviometric data are shown in Figure 1.

A comparison of the two years showed that the summers were extremely hot, with temperature peaks exceeding 45 °C. Precipitation during the period from 1 April to 30 November decreased by approximately 21.8% in 2024 (147 mm) compared to 2023 (188 mm), with a particularly sharp decline observed in May and June.

2.2. Experimental Design and Treatment

The field experiments, repeated over two years (2023 and 2024), involved the comparison of three defoliants at different doses (Table 2):

- PELACID: Pure pelargonic acid (Beloukha®, Belchim, Saronno, Italy);
- PLACEBO: A water-based placebo solution;
- PYRAFETH: Pyraflufen-ethyl (Revolution®, Sipcam, Milan, Italy), a commonly used commercial defoliant in conventional cotton farming.

For each year, the experimental trials were arranged in a randomized complete block design with three replications. Each plot measured 16 m^2 (4 m × 4 m).

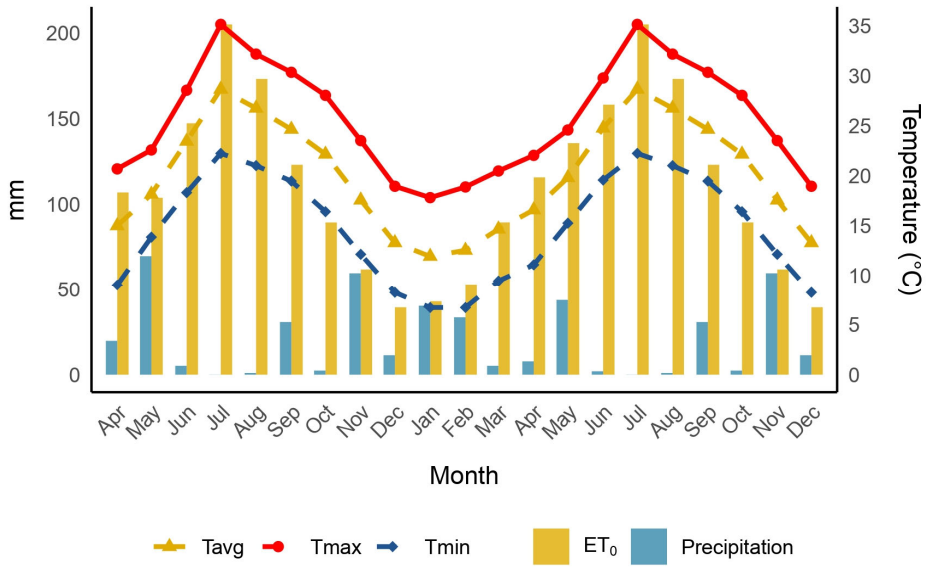


Figure 1. Temperature, precipitation and reference evapotranspiration trends at the experimental farm of the University of Catania (37°24′ N, 15°03′ E, 10 m a.s.l.) from April 2023 to December 2024. Tmax = month average of daily maximum temperature, Tavg = month average of daily mean temperature, Tmin = month average of daily minimum temperature, ET_0 = month sum of daily reference evapotranspiration [39], Precipitation = monthly rainfall.

Table 2. Defoliation treatments used for the research.

Defoliation Treatment	Active Ingredient	Dose (L ha^{-1})
PELACID D1	Pure pelargonic acid 680 g L^{-1}	12
PELACID D2	Pure pelargonic acid 680 g L^{-1}	16 *
PELACID D3	Pure pelargonic acid 680 g L^{-1}	18
PLACEBO D1	Water	30 **
PLACEBO D2	Water	50
PLACEBO D3	Water	60
PYRAFETH D1	Pyraflufen-ethyl 10.6 g L^{-1}	1.5
PYRAFETH D2	Pyraflufen-ethyl 10.6 g L^{-1}	2
PYRAFETH D3	Pyraflufen-ethyl 10.6 g L^{-1}	2.5 ***

* Label-recommended dose for pre-harvest desiccation of soybean [*Glycine max* (L.) Merill]. ** Doses of PLACEBO treatments are expressed as volumes of carrier water. *** Label-recommended dose for pre-harvest desiccation of cotton.

Defoliants were applied when 80% of the cotton bolls were open (BBCH 88) using a handheld sprayer with the nozzle fully open. For both PELACID and PYRAFETH treatments, three carrier water volumes were used according to the treatment dose: 30 L ha^{-1} for D1, 50 L ha^{-1} for D2, and 60 L ha^{-1} for D3. To ensure proper experimental control, three PLACEBO (water-only) treatments were included, corresponding to these carrier volumes. Defoliant applications were carried out on 20 October 2023 (144 days after sowing, DAS) and 9 October 2024 (138 DAS). Manual harvesting was performed 21 days later, on 10 November 2023 and 30 October 2024, respectively.

2.3. Crop Management

The seedbed was prepared after the winter rains, in soil that had undergone a fallow period the previous year. The soil was plowed to a depth of 35 cm and tilled twice before sowing.

Armonia, a *Gossypium hirsutum* L. variety widely cultivated in the Mediterranean basin [40–42], was used as the target genotype. Sowing was carried out on 29 May 2023,

and 24 May 2024, during the first and second growing seasons, respectively. A plant density of 12 plants m^{-2} (0.08 m × 1.0 m) was adopted. Weed control in the inter-row areas was performed using a mower during the leaf development stage.

Fertilization was carried out using organic fertilizers. A basal fertilization was applied before sowing, consisting of 110 kg N ha^{-1}, 55 kg P_2O_5 ha^{-1}, and 55 kg K_2O ha^{-1}, supplied as an organic fertilizer (10 N, 5% P_2O_5, 5% K_2O; ORGA KEM®, Biolchim S.p.A., Medicina, Italy). Additionally, a liquid fertilizer containing 8.7% N (Tamarack, Growan Italia®, Faenza, Italy) was applied at a total rate of 40 kg N ha^{-1}, during the phenological stages corresponding to the appearance of the first true leaves (BBCH 11) and flowering (BBCH 51). No pest or disease control measures were applied during the trials, as no phytosanitary issues were observed.

Irrigation was scheduled when the cumulative daily crop evapotranspiration (ETm) exceeded 70% of the available soil water content at field capacity (123.2 mm).

Based on the hydrological constants for the experimental site shown in Table 1, crop water consumption was estimated for each phenological stage by multiplying ET_0 by the crop coefficients (Kc) defined in FAO Irrigation and Drainage Paper No. 56 [39]. Additionally, the soil depth explored by the roots was considered in the calculation of the available water volume (Table 3). The irrigation system consisted of a P5® dripline (Irritec S.p.A., Capo d'Orlando, Italy) equipped with emitters with a nominal flow rate of 2.1 L h^{-1} at a pressure of 100 kPa.

Table 3. Phenological phases and crop coefficients (Kc) values for cotton according to Allen et al. [39].

Phase	Description	Kc	Depth of Soil Explored by Roots (cm)
Initial	Germination: from dry seed (00) to emergence of hypocotyl with cotyledons (09)	0.4–0.5	30
Development	Leaf development: from cotyledons completely unfolded (10) to canopy closure (39)	0.7–0.8	50
Mid-season	Inflorescence emergence: from first detectable bud (51) to about 90% of capsules having reached their final size (79)	1.05–1.25	50
End-season	Senescence: from about 10% of discolored or abscessed leaves (91) to above-ground parts of dead plants	0.65–0.70	50

Harvesting was conducted manually to ensure accurate and reliable yield measurements, as opposed to mechanical harvesting. The procedure was carried out when most bolls had opened (BBCH 99), specifically on 10 November 2023, and 30 October 2024. Only capsules that were open at the time of harvesting were collected.

2.4. Economic Parameters

The economic assessment was based on four parameters. The Defoliant cost was calculated as the product of the unit cost of the defoliant and the application dose: PELACID costs approximately €20 L^{-1} (680 g L^{-1}) [43,44], whereas PYRAFETH (10.6 g L^{-1}) costs 37.5 € L^{-1} [45,46]. Gross revenue was obtained from lint yield multiplied by the lint market price (1.315 € kg^{-1}), derived from the average upland cotton price of 64.4 cents per pound for the 2023–2024 marketing year [47]. Net revenue was determined as the difference between gross revenue and the cost of the defoliant per hectare according to the applied dose. Finally, the Cost-Effectiveness Ratio (CER) was expressed as the ratio of net revenue to defoliant cost.

2.5. Data Collection and Statistical Analysis

The effect of defoliation treatments under study was assessed by counting the number of leaves on 10 plants within a delimited area of 2.0 m^2 in each replicate, at two times: before treatment application and 21 days after application (i.e., at harvest), following the methodology of [48]. The defoliation rate was calculated as the percentage reduction in leaf number observed, considering only those that had abscised, at 21 days post-treatment.

At harvest, within the same 2.0 m^2 area of each replicate, the following parameters were measured: plant height (cm), number of open bolls per plant, and average boll weight (g) after oven drying. Additionally, root diameter (measured 1 cm below the crown) and raw cotton yield (kg ha^{-1}) were recorded as the total amount of opening capsules collected at the harvest.

Cotton lint was separated from the seeds using a laboratory ginning machine (Hebei Hanwu Cotton Machinery, China). Subsequently, both lint and seed yields (kg ha^{-1}) were determined for each replicate.

A two-way ANOVA was performed to assess the effects of treatments across the two growing seasons, with Year (Y) included as a random effect and Treatment (T) as a fixed effect. Tukey's HSD test was subsequently applied for mean separation. The Shapiro–Wilk test was used to verify the normality of residuals, while Bartlett's test was applied to assess homoscedasticity. All statistical analyses were conducted using R software (CRAN version 4.5.1).

3. Results

Analysis of variance (ANOVA) revealed that the factors Y, T, and their interaction (Y × T) had significant effects on all the parameters analyzed, as shown in Table 4.

Table 4. ANOVA for main effects and interactions on morphological and productive traits. The *p*-value is reported. ***, ** and * indicate significant at $p < 0.001$, $p < 0.01$ and $p < 0.05$, respectively. ns = not significant; df = degrees of freedom. Y = Year; T = Treatment.

Source of Variation	Parameters							
	df	Boll Number Plant^{-1}	Average Boll Weight (g)	Root Diameter (mm)	Raw Yield (kg ha^{-1})	Lint Yield (kg ha^{-1})	Seed Yield (kg ha^{-1})	Defoliation
Y	1	3.26×10^{-4} ***	0.19 ns	6.98×10^{-8} ***	5.14×10^{-5} ***	3.22×10^{-3} **	1.79×10^{-6} ***	4.33×10^{-7} ***
T	8	7.58×10^{-8} ***	2.95×10^{-8} ***	1.60×10^{-7} ***	1.09×10^{-10} ***	1.74×10^{-11} ***	1.02×10^{-10} ***	2×10^{-16} ***
Y × T	36	6.17×10^{-4} ***	1.19×10^{-2} *	1.33×10^{-3} **	4.51×10^{-4} ***	2.01×10^{-4} ***	7.85×10^{-4} ***	6.09×10^{-7} ***

3.1. Morphological and Productive Traits

Boll number per plant was influenced by the Y × T interaction. Plots under PELACID D2 in 2024 exhibited the highest boll number ($p < 0.001$), with a 73.2% increase compared to PLACEBO D1 in 2023 (7.29 bolls $plant^{-1}$ vs. 4.21 bolls $plant^{-1}$) and a 71.9% increase compared to PYRAFETH D3 in 2024 (7.29 bolls $plant^{-1}$ vs. 4.24 bolls $plant^{-1}$). PELACID D3 in 2023 also demonstrated good results (6.50 bolls $plant^{-1}$), representing a 10.8% reduction compared to PELACID D2 in 2024. In contrast, PELACID D1 in 2023 recorded only 5.08 bolls $plant^{-1}$ (Figure 2A).

The Y × T interaction also had a significant effect ($p < 0.05$) on average boll weight. PYRAFETH D1 in 2024 showed the highest value, equal to 8.45 g. PELACID D1 in 2024 recorded intermediate values, at 6.39 g. The lowest value was observed in 2023 under PELACID D3, with 3.74 g, corresponding to a 55.7% reduction (Figure 2B).

The Y × T interaction had a significant effect ($p < 0.01$) on root diameter, with the highest values observed in PELACID D1 in both 2023 (9.67 mm) and 2024 (9.87 mm), PELACID D2 in 2024 (9.65 mm), and PLACEBO D1 in 2024 (10.01 mm). The lowest value was recorded in PYRAFETH D2 in 2023, with 6.43 mm (Figure 3).

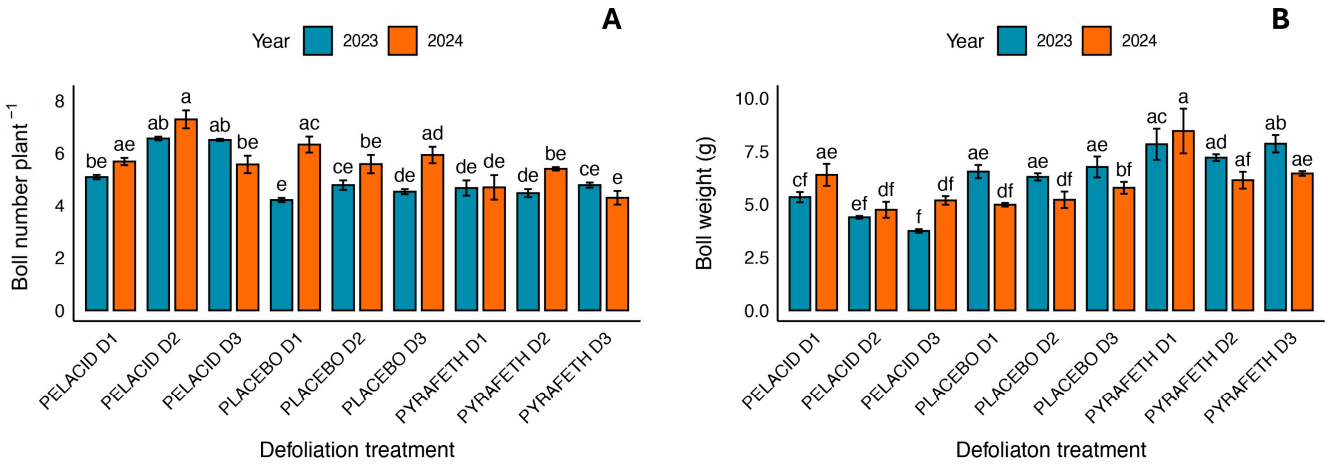


Figure 2. Effect of Y and T on boll number plant^{-1} (**A**) and average boll weight (**B**). For each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's HSD test. Error bars represent standard error. Treatment (PELACID D1 = Pure pelargonic acid at rate 12 L ha^{-1}; PELACID D2 = Pure pelargonic acid at rate 16 L ha^{-1}; PELACID D3 = Pure pelargonic acid at rate 18 L ha^{-1}; PLACEBO D1 = water at rate at 30 L ha^{-1}; PLACEBO D2 = water at rate at 50 L ha^{-1}; PLACEBO D3 = water at rate at 60 L ha^{-1}; PYRAFETH D1 = Pyraflufen-ethyl at rate 1.5 L ha^{-1}; PYRAFETH D2 = Pyraflufen-ethyl at rate 2 L ha^{-1}; PYRAFETH D3 = Pyraflufen-ethyl at rate 2.5 L ha^{-1}).

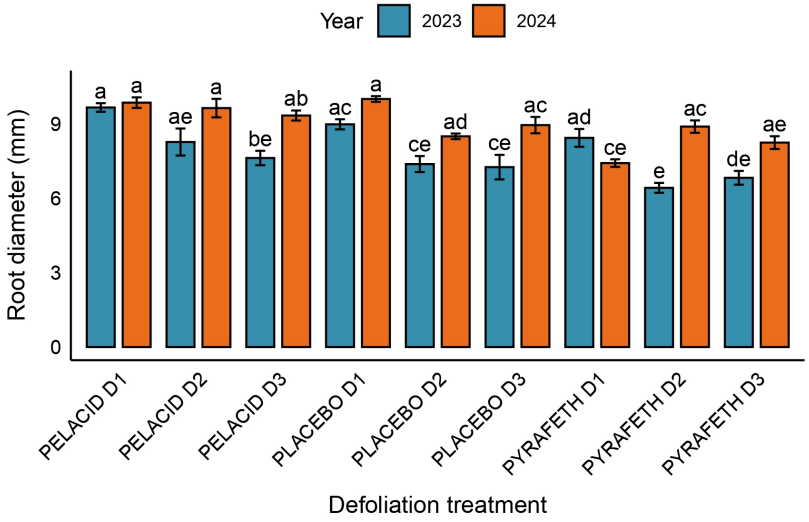


Figure 3. Effect of Y and T on root diameter. For each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's HSD test. Error bars represent standard error. Treatment (PELACID D1 = Pure pelargonic acid at rate 12 L ha^{-1}; PELACID D2 = Pure pelargonic acid at rate 16 L ha^{-1}; PELACID D3 = Pure pelargonic acid at rate 18 L ha^{-1}; PLACEBO D1 = water at rate at 30 L ha^{-1}; PLACEBO D2 = water at rate at 50 L ha^{-1}; PLACEBO D3 = water at rate at 60 L ha^{-1}; PYRAFETH D1 = Pyraflufen-ethyl at rate 1.5 L ha^{-1}; PYRAFETH D2 = Pyraflufen-ethyl at rate 2 L ha^{-1}; PYRAFETH D3 = Pyraflufen-ethyl at rate 2.5 L ha^{-1}).

The Y × T interaction had a significant effect ($p < 0.001$) on raw yield, lint yield, and seed yield.

As shown in Figure 4A, the highest raw yield was recorded in 2024 under PYRAFETH D2, at 2827 kg ha^{-1}, while PELACID D2 in 2024 achieved a raw yield of 2729 kg ha^{-1}, comparable to that observed in PYRAFETH D1 in 2023 and 2024.

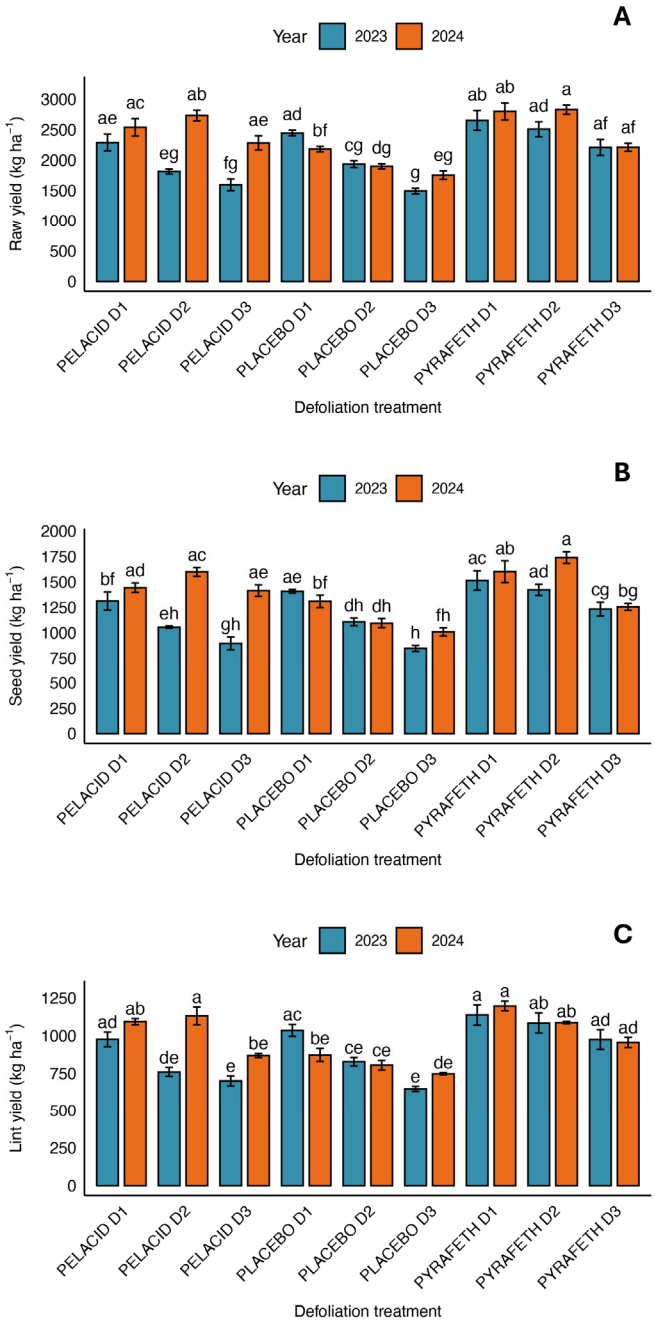


Figure 4. Effect of Y and T on raw yield (**A**), seed yield (**B**) and lint yield (**C**). For each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. Treatment (PELACID D1 = Pure pelargonic acid at rate 12 L ha^{-1}; PELACID D2 = Pure pelargonic acid at rate 16 L ha^{-1}; PELACID D3 = Pure pelargonic acid at rate 18 L ha^{-1}; PLACEBO D1 = water at rate at 30 L ha^{-1}; PLACEBO D2 = water at rate at 50 L ha^{-1}; PLACEBO D3 = water at rate at 60 L ha^{-1}; PYRAFETH D1 = Pyraflufen-ethyl at rate 1.5 L ha^{-1}; PYRAFETH D2 = Pyraflufen-ethyl at rate 2 L ha^{-1}; PYRAFETH D3 = Pyraflufen-ethyl at rate 2.5 L ha^{-1}).

The lowest value was observed in PLACEBO D3 in 2023, at 1490 kg ha^{-1}, corresponding to a 47.2% reduction.

Seed yield showed higher values in plots treated with PYRAFETH D2 in 2024, at 1740 kg ha^{-1} (Figure 4B), approximately 105% higher than PLACEBO D3 in 2023 (845 kg ha^{-1}).

PELACID D2 in 2024 reached 1597 kg ha^{-1}, comparable to the yield obtained with PYRAFETH D1 in 2023.

Regarding lint yield, the highest values were observed in PYRAFETH D1, with 1196 kg ha^{-1} in 2024 and 1136 kg ha^{-1} in 2023 (Figure 4C), as well as in PELACID D2 in 2024 (1131 kg ha^{-1}). The lowest yields occurred in 2023 for PELACID D3 (698 kg ha^{-1}) and PLACEBO D3 (646 kg ha^{-1}), representing reductions of 41.7% and 45.8%, respectively, when compared to the PYRAFETH D1 in 2024.

3.2. Defoliation Traits

The Y × T interaction had a significant effect ($p < 0.001$) on phylloptosis (Figure 5).

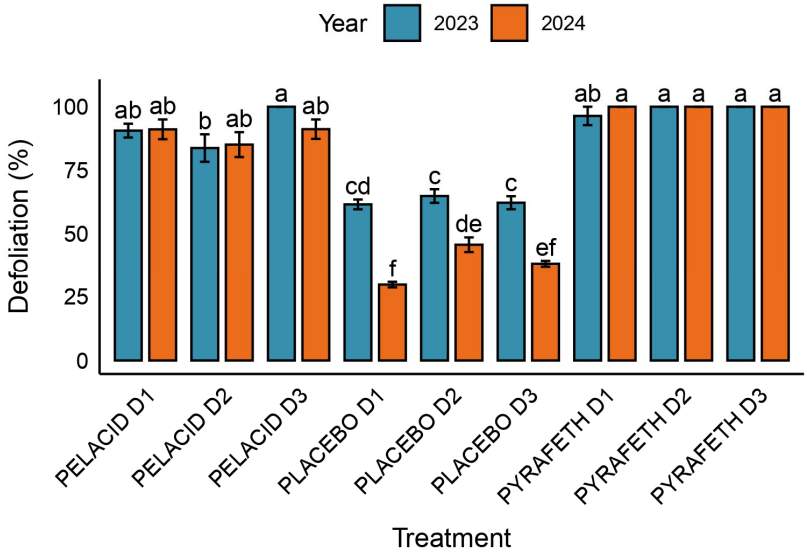


Figure 5. Effect of Y and T on defoliation. For each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. Treatment (PELACID D1 = Pure pelargonic acid at rate 12 L ha^{-1}; PELACID D2 = Pure pelargonic acid at rate 16 L ha^{-1}; PELACID D3 = Pure pelargonic acid at rate 18 L ha^{-1}; PLACEBO D1 = water at rate at 30 L ha^{-1}; PLACEBO D2 = water at rate at 50 L ha^{-1}; PLACEBO D3 = water at rate at 60 L ha^{-1}; PYRAFETH D1 = Pyraflufen-ethyl at rate 1.5 L ha^{-1}; PYRAFETH D2 = Pyraflufen-ethyl at rate 2 L ha^{-1}; PYRAFETH D3 = Pyraflufen-ethyl at rate 2.5 L ha^{-1}). Different letters indicate statistically significant differences between means at $p \leq 0.05$.

Plots treated with PYRAFETH D2 and D3 in both years, as well as PYRAFETH D1 in 2024 and PELACID D3 in 2023, reached 100% leaf drop. The lowest level of defoliation was recorded in PLACEBO D1 in 2024, with only 28.7% phylloptosis.

4. Discussion

The objective of this study was to achieve comparable defoliation efficacy and yield performance with more sustainable active principles, reducing reliance on conventional defoliants and thereby promoting more sustainable cotton production.

For this reason, we compared different application doses of a widely used synthetic defoliant—pyraflufen-ethyl—with increasing concentrations of pure pelargonic acid and a water-based placebo over two growing seasons. All analyzed parameters (boll number per plant, average boll weight, root diameter, raw yield, lint yield, seed yield, and phylloptosis) were significantly affected by the Y × T interaction.

From the results, it emerged that the highest boll numbers were recorded with PELACID D2, particularly in 2024. In contrast, PYRAFETH consistently underperformed, with the recommended dose (D3) yielding the lowest boll count in 2024. PYRAFETH, a

protoporphyrinogen oxidase (PPO) inhibitor—a key enzyme in chlorophyll biosynthesis—induces the accumulation of protoporphyrin IX and reactive oxygen species (ROS), leading to rapid cellular necrosis [49]. The excessive accumulation of ROS, such as H_2O_2, superoxide, singlet oxygen, and the hydroxyl radical causes cellular damage, which manifests itself through a marked increase in malondialdehyde, a reliable indicator of membrane integrity and oxidative injury under diverse stress conditions [50,51]. Although the plant attempts to respond by increasing the activity of certain antioxidant enzymes (such as superoxide dismutase and peroxidase), catalase activity decreases significantly, indicating that ROS scavenging capacity is weakened and homeostasis is disrupted [50]. This oxidative damage is directly related to the abscission rate [50,52].

This mechanism is exacerbated under high-temperature conditions, where it can cause severe tissue damage and significant yield reductions [53]. In 2024, prolonged water stress intensified this effect, further impairing developing cotton bolls and reducing their final number. Conversely, PELACID, which acts independently of PPO inhibition, exerts its defoliation effect by interacting with membrane phospholipids, causing cell lysis and loss of cellular compartmentalization, ultimately leading to rapid tissue desiccation [26]. This mode of action prevented the negative physiological impacts seen with PYRAFETH, allowing PELACID to maintain high boll numbers even under elevated temperatures.

Regarding boll weight, PYRAFETH D1 recorded the highest values in 2024, while higher doses (D2 and D3) reduced boll weight. This confirms reports by [53] that increased PYRAFETH dosage can trigger PPO-inhibition-related phytotoxicity, resulting in yield decline. Conversely, PELACID D3 in 2023 showed boll weight values below even the PLACEBO (across all dosages and in both years). This is explained by the elevated boll number induced by PELACID D3 that year, which reduced individual boll weight due to resource competition—consistent with the yield component compensation principle in *Gossypium hirsutum* [54–56].

Concerning root diameter, PELACID D1 in both years, as well as PELACID D2 in 2024, achieved the highest values—comparable to PLACEBO D1 in 2024. This indicated that even at increasing PELACID dosages, root morphology remains unaffected, preserving the plant's capacity to translocate water and nutrients to maturing bolls. As demonstrated in studies on herbaceous crops, a larger root diameter promotes (i) wider xylem vessels, enhancing the flow of water and nutrients (N, P, K) [57], and (ii) greater drought resistance—especially in semi-arid Mediterranean environments—while maintaining leaf photosynthetic efficiency [57–60]. Therefore, even following defoliation, a well-developed root system remains fundamental for the photosynthetic activity performed by the non-foliar photosynthetic organs, which in fact contribute to boll filling during the final stages of boll maturation [61,62].

PYRAFETH D2 exhibited a sharp reduction in root diameter in 2023, despite 21.8% higher rainfall compared to 2024. This suggested that pyraflufen-ethyl-induced phytotoxicity was dose-dependent and independent of hydric conditions. The effect was particularly pronounced at higher doses (D2 and D3), where PPO inhibition might have triggered ROS production, damaging root tissues [49,53].

Regarding raw yield, PYRAFETH D2-treated plots in 2024 showed the highest values compared to PLACEBO D3 in 2023, which recorded the lowest yield (with a 47.2% reduction). This substantial yield difference may result from incomplete defoliation in PLACEBO plots, which can prolong vegetative growth at the expense of reproductive development [63,64]. Interestingly, across both years, PYRAFETH D3 consistently showed significantly lower raw yields compared with lower-dose treatments (D1 and D2). This suggests that PYRAFETH applications exceeding 2 L ha^{-1} (10.6 g a.i. L^{-1}) cause substantial yield suppression, aligning with documented phytotoxicity thresholds in peanut (*Arachis*

hypogaea L.) [53,65]. Notable results emerged from PELACID formulations in 2024: both D2 and D1 yielded comparably to PYRAFETH D2, with only a 3.2% reduction in PELACID D2 and a 10.3% reduction in PELACID D1. In contrast, while PELACID D1 achieved optimal 2023 yields, higher doses (D2 and D3) caused significant yield declines. This phytotoxicity is attributed to high PELACID concentrations, which induce: (i) cellular membrane leakage via fatty acid intercalation, and (ii) light-dependent singlet oxygen peroxidation, with the consequent necrosis of plant tissues [44,66].

Concerning seed yield, PYRAFETH D2-treated plots in 2024 showed the highest values compared to PLACEBO D3 in 2023, which recorded the lowest yield (51.1% reduction). These results indicate that PYRAFETH D2 may represent the optimal dosage for maximizing seed yield, as it enhanced production without suppressing yield.

Notable results emerged from PELACID D2 in 2024, yielded comparably to PYRAFETH D2, with only an 8.0% reduction. In 2023, however, PELACID treatments demonstrated clear dose-dependent yield reductions, with yields decreasing by 19.8% from D1 to D2 (1312 to 1054 kg ha^{-1}) and by 31.3% from D1 to D3 (1312 to 895 kg ha^{-1}). This could be attributed to (i) progressive phytotoxicity due to increasing concentrations of PELACID [28,44,66], along with (ii) the milder climate observed in 2023, which was characterized by higher rainfall (188 mm during the 2023 growing season compared to 147 mm in 2024). The greater soil water availability likely prolonged vegetative growth, diverting assimilates away from reproductive development [67,68].

The significant reduction in seed yield observed in both years with the high dosage of PYRAFETH D3 may be attributed to its adverse effect on the critical process of residual photosynthesis in non-leaf tissues. Following defoliation, photosynthetic activity relies heavily on remaining green structures, primarily bracts and boll walls, which contain functional chloroplasts capable of substantial CO_2 assimilation—reaching 60–72% and 20–26% of leaf rates, respectively [61,62]. Defoliation shifts the source–sink balance by removing the dominant source, forcing greater reliance on any remaining photosynthetic tissues and on remobilization of stored carbohydrates, and often reducing carbon allocation to sinks [69]. Under defoliation stress, the contribution of these non-foliar sources, which normally provide over 24% of the plant's photoassimilates [61], becomes vital for yield formation. It is plausible that the high concentration of PYRAFETH D3 caused phytotoxic damage to these tissues, impairing this essential compensatory mechanism. This hypothesis is supported by shading studies showing that disrupting photosynthesis in bolls alone can reduce seed weight by 10–30% [62]. Therefore, the decrease in yield is likely a direct consequence of the failure to compromise carbon fixation, as the severity of the defoliant not only removed the leaves but also potentially damaged the tissues responsible for sustaining head development after defoliation.

Regarding lint yield, PELACID D2 in 2024 recorded the highest values, comparable to those observed with PYRAFETH D1 in both 2023 and 2024. In contrast, PELACID D3 in 2023 showed the lowest values, similar to those recorded with PLACEBO D3 in 2023.

These outcomes can be attributed to two main factors: first, the more favorable climate conditions in 2023, particularly in terms of rainfall, which may have promoted vegetative growth at the expense of lint yield [67,68]; and secondly, the high dosage applied in D3 (18 L ha^{-1} of pure pelargonic acid at 680 g L^{-1}), inducing cellular damage that directly compromised lint production, consistent with established herbicide mode-of-action research [28,44,66].

The parameter phylloptosis showed that PELACID D3 in 2023 achieved 100% fallen leaves, matching the performance of PYRAFETH D1 in 2024, as well as PYRAFETH D2 and D3 in both 2023 and 2024. This result demonstrated that PELACID at D3, corresponding to 18 L ha^{-1} of pure pelargonic acid (680 g L^{-1}), can achieve defoliation levels equivalent

to those of synthetic chemical defoliants, without compromising efficacy. This is because PELACID penetrates the leaf cuticular wax layer and integrates into plant cell membranes, causing leakage of intracellular solutes and triggering light-induced peroxidative reactions that lead to tissue necrosis [28,66]. This phytotoxic effect becomes visible within a few hours after application and affects only the treated areas, as the product acts strictly by contact and is not translocated within the plant [61,70,71]. Moreover, PELACID has a soil half-life (DT_{50}) of less than 1 day, resulting in a minimal risk of residues [61]. But even at dosages higher than those commonly applied-typically about 16 L ha^{-1} of a commercial formulation, equivalent to 10,880 g a.i. ha^{-1} for weed control [44], degradation in soil is very rapid, as reported in EU registration studies (DT_{50} of 17–38 h at a dose level of 20 mg/kg) [61,70]. These characteristics make it a promising candidate for sustainable cotton pre-harvest management.

Interestingly, even lower doses such as PELACID D1 proved highly effective, achieving 90.6% defoliation in 2023 and 91.1% in 2024, with results not far from those obtained with conventional chemical treatments. Such high efficacy at a low application rate—12 L ha^{-1}—could represent an optimal economic compromise. As reported in [44], the cost of PELACID is approximately €20 per liter, which translates to €300 ha^{-1} at the standard 16 L ha^{-1} dose. Reducing the dose and implementing complementary strategies such as irrigation termination (e.g., as described in [4])—which require no additional input costs—could both lower the adoption cost of PELACID and promote more sustainable agronomic practices.

Limitations and Future Research Directions

Beyond the clear agronomic efficacy of PELACID, two key limitations must be acknowledged.

The first concerns its economic feasibility: its high cost per hectare, driven by the large application volumes required compared with synthetic defoliants. Nevertheless, a cost–benefit analysis that considers both input costs and economic returns from yield provides important insights. The economic analysis revealed a substantial difference in application costs. While the synthetic defoliant PYRAFETH ranged from €56.25 ha^{-1} (D1) to €93.75 ha^{-1} (D3), PELACID treatments were considerably higher, costing €240 ha^{-1} at 12 L ha^{-1}, €320 ha^{-1} at 16 L ha^{-1}, and €360 ha^{-1} at 18 L ha^{-1}.

As shown in Table 5, at the lowest dose (PELACID D1, 12 L ha^{-1}), the treatment achieved net revenues comparable to those of PYRAFETH in both years. However, the CER (representing the economic return per euro invested in the defoliant) was consistently lower for PELACID because of the larger product volumes required.

Table 5. Cost–benefit comparison of T by Y.

Year	Treatment *	Dose (L ha^{-1})	Defoliant Cost (€ ha^{-1})	Lint Yield (kg ha^{-1})	Lint Yield Price (€ kg^{-1})	Lint Gross Revenue (€ ha^{-1})	Net Lint Revenue (€ ha^{-1})	Cost-Effectiveness Ratio
2023	PELACID D1	12	240	975	1.315	1282.13	1042.13	4.34
2023	PELACID D2	16	320	759	1.315	998.09	678.09	2.12
2023	PELACID D3	18	360	699	1.315	919.19	559.19	1.55
2023	PYRAFETH D1	1.5	56.25	1136	1.315	1493.84	1437.59	25.56
2023	PYRAFETH D2	2	75	1083	1.315	1424.15	1349.15	17.99
2023	PYRAFETH D3	2.5	93.75	974	1.315	1280.81	1187.06	12.66
2024	PELACID D1	12	240	1093	1.315	1437.30	1197.30	4.99
2024	PELACID D2	16	320	1131	1.315	1487.27	1167.27	3.65
2024	PELACID D3	18	360	868	1.315	1141.42	781.42	2.17
2024	PYRAFETH D1	1.5	56.25	1196	1.315	1572.74	1516.49	26.96
2024	PYRAFETH D2	2	75	1087	1.315	1429.41	1354.41	18.06
2024	PYRAFETH D3	2.5	93.75	954	1.315	1254.51	1160.76	12.38

* Treatment (PELACID = Pure pelargonic acid; PYRAFETH = Pyraflufen-ethyl).

Although the results clearly underscore the economic limitation of PELACID—namely, that high application volumes reduce cost-effectiveness compared with PYRAFETH—it is important to recognize that the CER does not capture externalities such as national regulations, eco-labels, or market premiums for sustainable fibers. These factors could, in practice, support the adoption of PELACID despite its apparently lower CER.

The second limitation concerns fiber quality, as the potential impact of pelargonic acid on technological parameters remains largely unexplored. It is well established that PELACID acts as a contact desiccant, inducing rapid membrane disruption and necrosis of green tissues [27]. When such effects occur before physiological boll and fiber maturation, they may reduce carbohydrate availability for secondary cell-wall deposition, thereby negatively affecting micronaire, fiber length, and strength. This concern is supported by studies on harvest-aid timing, which indicate that prematurely applied defoliants can alter micronaire and other fiber parameters, whereas appropriately timed applications generally avoid measurable quality penalties [72].

In this context, where no data are currently available on the use of PELACID as a cotton defoliant, future studies should investigate its potential influence on fiber quality. Such research should consider not only the effects of early defoliant application but also those of treatments applied at advanced phenological stages (e.g., BBCH 88). A comprehensive fiber-quality assessment—including upper-half mean length, length uniformity index, strength, elongation, micronaire, fineness, and maturity ratio—would be particularly valuable to distinguish direct phytotoxic effects of pelargonic acid from indirect quality changes associated with assimilate limitation.

5. Conclusions

The results of this two-year study demonstrate that PELACID represents a viable organic alternative to PYRAFETH, offering comparable efficacy with clear environmental advantages. Field trials in southern Sicily, Italy, confirmed that the D3 dosage (18 L ha^{-1}) matched the performance of the benchmark synthetic defoliant PYRAFETH. More significantly, the D1 dosage (12 L ha^{-1}) still delivered over 90% leaf drop, revealing substantial potential for cost-efficient optimization without compromising effectiveness.

From a physiological perspective, PELACID ensures a superior safety profile. Unlike PYRAFETH, whose systemic action can impair root development, PELACID's contact-based mechanism—disrupting cellular membranes—preserves root growth and function. This was evident from the larger root diameters recorded under PELACID treatments (up to 9.87 mm), especially at moderate doses (D1–D2), maintaining the plants' water and nutrient uptake capacity—an essential trait under Mediterranean drought-prone conditions.

On the agronomic side, while high doses of PYRAFETH (D3) led to phytotoxicity and yield reductions of up to 47%, PELACID at 16 L ha^{-1} (D2) showed remarkable performance. In 2024, a season marked by lower rainfall, it matched the fiber yield of the best conventional treatment (1136 vs. 1196 kg ha^{-1} for PYRAFETH D1) and exceeded it in boll number per plant by 73%, underscoring its superior resilience to high thermal stress.

Environmentally, rapid soil degradation (DT_{50} < 48 h) eliminates toxic residue risks associated with persistent synthetic defoliants, and the compound's natural origin enables sustainable deployment. Economically, the feasibility of reducing application rates of PELACID to 12 L ha^{-1} could lower costs to approximately €240/ha, making it a competitive option, especially when combined with complementary defoliation practices.

Future research should explore integrated approaches combining reduced pelargonic acid doses with pre-harvest irrigation termination to further enhance defoliation efficiency and support the adoption of more sustainable agronomic practices for cotton cultivation.

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

Funding: This research was supported by OVS S.p.A. (Via Terraglio 17, 30174 Mestre, Venice), which funded the PhD student enrolled in the Doctoral Program in Agricultural, Food and Environmental Science at the University of Catania. The drip irrigation system was provided by Irritec S.p.A. (Via Gambitta Conforto, Contrada Santa Lucia, 98071 Capo d'Orlando, Messina), CUP: B13D21011580004.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank OVS S.p.A. for supporting the PhD student enrolled in the PhD program in Agricultural, Food, and Environmental Sciences at the University of Catania. Giuseppe Salvatore Vitale is currently conducting a research project titled "Agronomic and Qualitative Aspects of Cotton Cultivation under Organic Farming".

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

Abbreviations

The following abbreviations are used in this manuscript:

CER	Cost-Effectiveness Ratio
ETc	reference crop evapotranspiration
FC	Field Capacity
ET_0	daily reference evapotranspiration
Kc	crop coefficients
PELACID	Pelargogic Acid
PLACEBO	Placebo solution (water)
PYRAFETH	Pyraflufen-ethyl
PPO	protoporphyrinogen oxidase

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