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Effects of Mechanical Weed Control and Manual Hoeing on Weed Infestation and Maize Grain Yield: A Three-Year Field Experiment

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Abstract

This study evaluated the effects of different mechanical weed control systems on weed biomass, weed flora composition and maize grain yield during a three-year field experiment conducted from 2021 to 2023 in the Zagreb area, Croatia, using a randomized complete block design with three replications. The following three weed control treatments were compared. T1—mechanical weed control between the crop rows with a motor cultivator combined with manual hoeing within the crop rows. T2—mechanical weed control between the crop rows with a motor cultivator without weed control within the crop rows. T3—without any weed control as control. The weed control system had a statistically significant effect ($p < 0.001$) on weed biomass and maize grain yield throughout the study. The lowest average weed biomass and the highest average grain yield were recorded in T1, whereas the untreated control (T3) had the highest weed biomass and the lowest grain yield. Regression analysis indicated a strong negative association between weed biomass and maize grain yield ($R^2 = 0.833$), demonstrating that higher weed biomass was associated with lower grain yield. During the three-year experiment, 14 weed species were recorded, with *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, *Sorghum halepense* and *Chenopodium album* being the dominant species. The results indicate that combining mechanical weed control between the crop rows with manual hoeing within the crop rows was the most effective weed control strategy under the conditions of this study.

Keywords: maize; mechanical weed control; weed infestation; grain yield; three-year field experiment



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1. Introduction

Maize (*Zea mays* L.) is one of the most economically important field crops worldwide and ranks first among cereals in terms of total production. Due to its high genetic yield potential, broad adaptability to diverse agro-ecological conditions, and wide range of applications in human nutrition, livestock feeding, and industrial processing, maize plays an extremely important role in global agricultural production [1,2]. Owing to its high yield potential, nutritional value, and versatility in terms of end-use products, maize is considered the cereal of the future [3,4]. The yield potential of maize is very high, with yields between 8 and 9 t ha^{−1} being common in many countries [5]. The global average maize yield at the beginning of the 21st century was 4.3 t ha^{−1}; however, an

increasing trend has been observed since then. The average maize yield per hectare reached 5.11 t ha⁻¹ in 2010 and 5.65 t ha⁻¹ in 2016 worldwide [6,7]. Maize yield is influenced by the genetic potential of the hybrid, soil characteristics, agronomic practices, and agro-climatic factors [8]. In the American Corn Belt, where the largest maize production area in the world is located and where soil and climatic conditions are highly favorable for maize production, average yields in favorable years exceed 11 t ha⁻¹, while yields of 20 t ha⁻¹ have also been recorded. Such high maize yields can only be achieved under favorable climatic and soil conditions through the use of high-yielding hybrids and the application of modern production technologies [9]. In contrast, average maize yields in Africa remain considerably lower, ranging between 1.3 and 1.5 t ha⁻¹ [10]. These large differences in maize yield are the result of complex interactions among climatic conditions, soil fertility, socioeconomic factors, and differences in management practices and production intensity [11].

In Croatia, maize is the most widely cultivated field crop and is extensively used in human nutrition, livestock feeding, and the processing industry [12]. Maize is grown in Croatia on more than 300,000 ha annually on average, with considerable variations in annual yields, ranging from 4.2 to 8.0 t ha⁻¹. Weather conditions, particularly the amount and distribution of precipitation and average air temperatures, are the main factors responsible for such differences in maize yield among years [13]. However, in addition to meteorological conditions, achieving high and stable yields depends on several factors, including soil fertility, hybrid selection, agronomic practices, and effective weed management. Weeds represent one of the most important biotic constraints in maize production. Their presence reduces the availability of water, nutrients, and light for the crop and may interfere with field operations and harvesting while also negatively affecting grain quality [14]. It is estimated that weeds cause the greatest potential yield losses among all harmful organisms in agricultural production if adequate control measures are not implemented [15]. In maize, the severity of weed interference depends on weed density, weed species composition, the timing of weed emergence relative to crop development, and weather conditions during the growing season.

Besides climatic and soil conditions, weeds are among the most important factors responsible for maize yield losses. They compete with maize plants for essential resources such as light, nutrients, water, and space, affecting crop morphology and phenological development. Therefore, effective weed control is essential for achieving the maximum yield potential of maize [16]. Worldwide maize yield losses caused by weeds are estimated at approximately 32%, highlighting the importance of weed management in maize production [14]. Weed problems in maize are particularly pronounced due to the relatively wide row spacing, which provides favorable conditions for weed establishment, and the slow early growth of maize plants, which reduces their competitive ability during the initial stages of crop development. Consequently, weeds can overgrow maize plants during emergence or shortly afterward, resulting in substantial yield losses [16]. Depending on weed species and infestation density, weeds can reduce maize yields by 33–50%, while uncontrolled weed competition during critical periods may result in yield losses of up to 100% [17]. Weed species composition and density in maize fields vary depending on geographical location, climatic conditions, soil properties, and numerous other factors influencing the structure of weed communities [18].

Herbicides remain the primary choice among farmers for weed control in most countries. Consequently, herbicides account for approximately 60% of all chemical plant protection products used worldwide [19]. The application of herbicides represents the simplest and most economical approach to weed control; however, the long-term effects of chemical products on the environment and human health have raised increasing concerns. The shift in focus from herbicide-based weed control towards non-chemical approaches has been

driven by growing public awareness of environmental issues and concerns regarding the negative consequences of intensive herbicide use. Non-chemical weed control strategies aim to reduce dependence on herbicides and promote more sustainable weed management solutions [20]. Long before the introduction of herbicides, weeds were controlled mechanically using various tools and implements. More recently, increasing interest in organic farming and the implementation of herbicide restrictions in many European countries and other regions worldwide have contributed to the renewed interest in mechanical weed control [21]. This trend began in the 1990s and has accelerated due to further restrictions on herbicide use, the increasing occurrence of herbicide resistance, and limited prospects for the development of herbicides with new modes of action [22]. Today, a wide range of machine designs and tools for mechanical weed control are available. These tools generally rely on three main mechanisms of action: weed burial, cutting, and uprooting. However, inter-row machines, such as cultivators and motorized cultivators, remain the most commonly used solutions [23]. The main limitation of these machines is that they effectively control weeds only in the area between crop rows, while weeds within the crop row and in the immediate vicinity of crop plants often remain unaffected. Numerous studies have shown that weeds growing in these areas can cause substantial crop losses due to direct competition with the crop. Several commercial tools designed for inter-row weed control are available; however, their main limitation is that they can only be applied after crops have reached a certain height and sufficient stem strength. When weeds are similar in size to or larger than the crop, these tools may fail to effectively control weeds within the crop row and may also cause mechanical damage to crop plants [24,25]. Mechanical weed control effectively controls weeds between maize rows, but its effectiveness is limited to the inter-row area, while weeds within the crop rows remain undisturbed and continue to compete with maize plants. Therefore, in some production systems, mechanical weed control between the crop rows is combined with manual weeding within the crop rows to achieve more complete weed control [26,27]. Weeds growing between maize plants within the crop row are commonly removed by hand hoeing; however, this method requires substantial human labor, which is often limited during the early stages of crop development when effective weed control is most critical [28].

Most previous studies on the effectiveness of mechanical weed control have been conducted during a single growing season and have mainly focused on the immediate effects of individual interventions on weed biomass and crop yield. Far fewer studies have evaluated the cumulative effects of repeated application of different mechanical weed control systems on weed biomass, weed flora composition, and maize productivity over several consecutive years. Such studies can provide valuable information on changes in weed flora associated with repeated weed management practices under varying environmental conditions. Therefore, the aim of this study was to determine the effects of different mechanical weed control systems on weed biomass, weed flora composition, and maize grain yield during a three-year field experiment.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted during 2021–2023 near the settlement of Markovo Polje (45°51′43″ N, 16°06′50″ E), located in the eastern part of the City of Zagreb, Croatia. The experiment was set up on pseudogley, whose mechanical composition was determined in the analytical laboratory of the Department of Plant Nutrition, Faculty of Agriculture, University of Zagreb, according to the standard HRN ISO 11277:2011 [29]. According to the soil particle size distribution, the soil of experimental field belongs to silty loam (Table 1).

Table 1. Soil particle size distribution of experimental field.

Depth	Particles Size Distribution (%)				
	coarse sand 2.0–0.2 mm 2.0	fine sand 0.2–0.063 mm 27.2	coarse silt 0.063–0.02 mm 38.8	fine silt 0.02–0.002 mm 24.7	clay <0.002 mm 7.3
0–30 cm					

The basic chemical properties of the soil were determined in the same laboratory using standard analytical methods. The soil reaction was determined according to the HRN ISO 10390:2005 standard [30], the total nitrogen content according to the HRN ISO 11261:2004 standard [31], the humus content according to the Tjurin bichromate method, while the plant-available phosphorus and potassium content were determined by the AL method. The soil had a weak alkaline reaction (pH in H₂O 7.54), weak humus content (2.13% humus), was well supplied with total nitrogen and poorly supplied with available phosphorus and potassium (Table 2).

Table 2. Basic chemical properties of the soil of experimental field.

Depth	pH		%		Al-mg/100 g	
	H ₂ O	KCl	humus	N	P ₂ O ₅	K ₂ O
0–30 cm	7.54	6.71	2.13	0.13	4.0	10.0

The preceding crop on the experimental field was potato. In all three years of the experiment, primary soil tillage was performed in autumn by moldboard plowing to a depth of 25–30 cm, while seedbed preparation was carried out in spring before sowing using disc harrowing. The same agronomic practices for maize production were applied throughout the three-year experiment, while the experimental treatments differed only in the applied weed control method. The timing of the main agronomic field operations during the three-year experiment is presented in Table 3.

Table 3. Dates of the most important agrotechnical field operations during the three-year experiment.

Year	Sowing	Mechanical Weed Control	Harvesting
2021	8 May	8 June	9 October
2022	5 May	8 June	8 October
2023	10 May	12 June	12 October

Before sowing, fertilization was performed in all three experimental years using a complex NPK fertilizer (15-15-15) at a rate of 60 kg N ha^{−1}, 60 kg P₂O₅ ha^{−1}, and 60 kg K₂O ha^{−1}. In addition, nitrogen was applied in the form of urea (46% N) at a rate of 80 kg N ha^{−1}, corresponding to approximately 175 kg urea ha^{−1}. The BC-572 maize hybrid (FAO 520), belonging to the late FAO maturity group, was used in this experiment due to its wide adoption in commercial production in continental Croatia and its good adaptation to the agro-ecological conditions of the experimental area. Maize was sown using a precision pneumatic planter with a row spacing of 70 cm. The target plant density was approximately 65,000 plants ha^{−1}, and seeds were sown at a depth of 5 cm. Mechanical weed control was performed once during the growing season at the BBCH 14–16 maize development stage according to the standardized BBCH scale [32]. This stage was selected because it represents the beginning of intensive vegetative growth in maize, while weeds are still at early developmental stages and more susceptible to mechanical removal. In all experimental years, a single mechanical weed control operation was performed, as this represents the

common practice adopted by local farmers in the study area. Mechanical weed control between crop rows was carried out using an MTD T/450 walk-behind motor cultivator (MTD PRODUCTS, Saarbruecken, Germany) equipped with standard cultivating tines. The motor cultivator had an engine power of 6.5 HP (4.8 kW), a working width of 46 cm and an approximate working depth of 5–8 cm. In treatment T1, weeds remaining within the crop row were subsequently removed manually using a hand hoe, whereas no additional in-row weed control was performed in treatment T2. Representative photographs of the motor cultivator in operation and the applied hand hoeing are presented in Figure 1.



Figure 1. Weed control methods used in the experiment: (a) Mechanical weed control between the crop rows with a motor cultivator; (b) manual hoeing within the crop row.

Maize was harvested annually after reaching physiological maturity, when grain moisture content allowed reliable yield determination. Harvest timing was adjusted according to maize maturity dynamics in each growing season and prevailing weather conditions. Due to differences in temperature patterns and precipitation distribution among years, harvest timing varied slightly; however, in all years harvesting was performed at the optimal maturity stage for the BC-572 hybrid.

The experimental site is located in the temperate humid climate zone (Cfb) according to the Köppen–Geiger climate classification [33]. Long-term climatic conditions are generally favorable for maize production; however, considerable year-to-year variability in temperature and precipitation can significantly affect crop development, weed dynamics, and grain yield. Meteorological data, including monthly precipitation totals and mean monthly air temperatures, for the experimental period (2021–2023) and the long-term reference period (2000–2020) were obtained from the nearest meteorological station operated by the Croatian Meteorological and Hydrological Service. These data were used to characterize weather conditions during the experimental period and to assess their potential influence on maize growth, weed development, and yield formation.

2.2. Experimental Design

The experiment was set up according to a Randomized Complete Block Design (RCBD) with three treatments and three replications. The total area of the experimental field was 2700 m², and each experimental plot was 300 m² (30 × 10 m). The same treatment schedule

was maintained throughout this three-year experiment to assess the cumulative effect of different mechanical weed control systems on weed infestation and maize grain yield.

Three weed control systems were applied as follows.

T1—mechanical weed control between the crop rows with a motor cultivator combined with manual hoeing within the crop rows,

T2—only mechanical weed control between the crop rows with a motor cultivator without weed control within the crop rows,

T3—without any weed control as control.

Such an experimental design allowed for a comparison of the effectiveness of complete and partial mechanical weed control and an assessment of the consequences of several years of no weed control on the development of the weed flora and maize grain yield. Representative photographs of the experimental plots under the three weed control treatments are shown in Figure 2.



Figure 2. The experimental plots under the three weed control treatments: (a) T1—mechanical weed control between the crop rows combined with manual hoeing within the crop rows; (b) T2—mechanical weed control between the crop rows only; (c) T3—untreated plot.

2.3. Weed Assessment and Maize Grain Yield Determination

The determination of weed flora and fresh weed biomass was carried out approximately one month before the maize harvest, when the weed vegetation was in full development and the above-ground weed biomass reached or approached its maximum value. Weed biomass was assessed approximately one month before harvest to quantify the cumulative response of weed communities to the different mechanical weed control treatments while avoiding destructive sampling during the period of active grain formation. Five samples were randomly selected from each experimental plot using a metal frame with an area of 1 m². All weed species within the frame were determined to the species level using standard floristic keys [34], after which their total fresh biomass was determined by weighing on a precise laboratory scale. The results are expressed as weed biomass (kg m⁻²). Based on the determined species, a list of weed flora was compiled and their relative abundance in individual treatments was estimated during the three-year study. The relative abundance of individual species is shown on a four-level scale (+ to ++++).

Maize was harvested at the end of the growing season at technological maturity. On each experimental plot, the yield was determined on five representative samples of 1 m². The maize ears were hand-picked, after which the kernels were separated from the cobs and weighed using a PRECIA MOLEN X932-A precision balance (PRECIA MOLEN, Privas,

France). Grain moisture content was measured using a DICKEY-john GAC 2000 grain moisture analyzer (DICKEY-john[®], Auburn, IL, USA). The maize grain yield was calculated on a hectare basis, adjusted to a standard grain moisture content of 14%, and expressed as kg ha⁻¹.

2.4. Statistical Analysis

Statistical analyses were performed using SAS[®] 9.4 software (SAS Institute Inc., Cary, NC, USA) [35]. Means and standard deviations were calculated for all measured variables. Because the same experimental plots were evaluated over three consecutive years, the effects of experimental year, mechanical weed control treatment, and their interaction on weed biomass and maize grain yield were analysed using a linear mixed-effects model (PROC MIXED) with repeated measurements. Treatment, year, and their interaction were specified as fixed effects, while block was included as a random effect. Repeated measurements over years were modelled at the plot level. When significant differences were detected, estimated marginal means (LSMeans) were compared using Tukey's honestly significant difference (HSD) test at $p < 0.05$. The relationship between weed biomass and maize grain yield was additionally examined using simple linear regression analysis. Regression analysis was used only as a descriptive assessment of the association between the measured variables. The strength of the relationship was expressed by the coefficient of determination (R^2), and the significance of the regression model was evaluated at $p < 0.05$.

3. Results

3.1. Weather Conditions

Meteorological data on monthly precipitation totals and mean monthly air temperatures during the experimental period (2021–2023) at the experimental site, together with the multi-year averages for the reference period (2000–2020), are presented in Table 4. The multi-year averages were used to assess deviations in weather conditions during the experimental years. Meteorological conditions during the maize growing season differed between the experimental years. Meteorological conditions during the maize growing season differed considerably among the experimental years. The year 2021 was characterized by a pronounced precipitation deficit in June and higher air temperatures during June and July compared with the multi-year average. These unfavorable conditions negatively affected the initial growth and development of maize and reduced yield potential. The 2022 growing season was characterized by higher temperatures than the multi-year average, along with insufficient precipitation during May, July, and particularly August, when only 20.8 mm of precipitation was recorded. Although increased precipitation in September partially alleviated the effects of summer drought, unfavorable conditions during flowering and grain filling reduced the yield potential, resulting in growing conditions only slightly more favorable than those in 2021. In contrast, 2023 was characterized by substantially higher precipitation throughout the growing season, particularly in May, July, August, and September. Air temperatures were close to or slightly above the multi-year average, and the more favorable precipitation distribution combined with adequate soil water availability provided significantly better conditions for maize growth and development. These favorable conditions were reflected in higher yields across all weed control treatments.

Table 4. Weather conditions in the period 2021–2023 and multi-year averages (2000–2020).

Month	Precipitation (mm)				Mean Air Temperature (°C)			
	2021	2022	2023	2000–2020	2021	2022	2023	2000–2020
January	78.4	19.2	155.7	52.5	2.8	2.0	4.9	1.4
February	48.5	31.8	35.4	64.3	5.7	5.6	4.2	3.2
March	41.8	6.4	69.9	48.1	6.8	6.3	9.0	7.7
April	64.9	84.1	91.6	53.8	9.8	11.0	10.8	12.6
May	110.7	46.0	136.1	83.3	14.7	18.5	16.5	17.0
June	7.8	88.5	57.7	85.6	23.3	23.3	21.1	21.0
July	68.9	57.2	145.7	79.1	24.0	24.0	23.5	22.6
August	50.7	20.8	126.0	83.0	21.4	23.6	22.0	22.1
September	53.9	227.4	120.2	102.9	17.8	16.8	19.9	16.8
October	106.4	22.5	62.2	91.7	10.1	14.3	15.6	12.1
November	78.6	97.1	119.5	82.4	6.5	7.9	7.3	7.4
December	79.7	92.7	100.2	65.6	3.6	4.7	4.8	2.4
Sum/ Average	790.3	793.7	1220.2	903.0	12.2	13.2	13.3	12.2

3.2. Weed Biomass Under Different Weed Control Treatments

The average weed biomass differed significantly among the evaluated weed control treatments during all three experimental years (Figure 3). The lowest weed biomass was recorded in treatment T1, where mechanical weed control was performed between the crop rows combined with manual hoeing within the crop rows, while the highest biomass was recorded in the control treatment T3, where no weed control was applied. Treatment T2, in which only mechanical weed control between the crop rows was performed, resulted in intermediate weed biomass values between the two previously described treatments. Throughout the experiment, a gradual increase in weed biomass was observed in treatments T2 and T3, with the highest average biomass recorded in 2023. In contrast, weed biomass in treatment T1 remained consistently low throughout the experimental period, with only minor year-to-year variations. The most pronounced differences among treatments were observed in 2023, when more favorable weather conditions promoted more intensive weed growth and development.

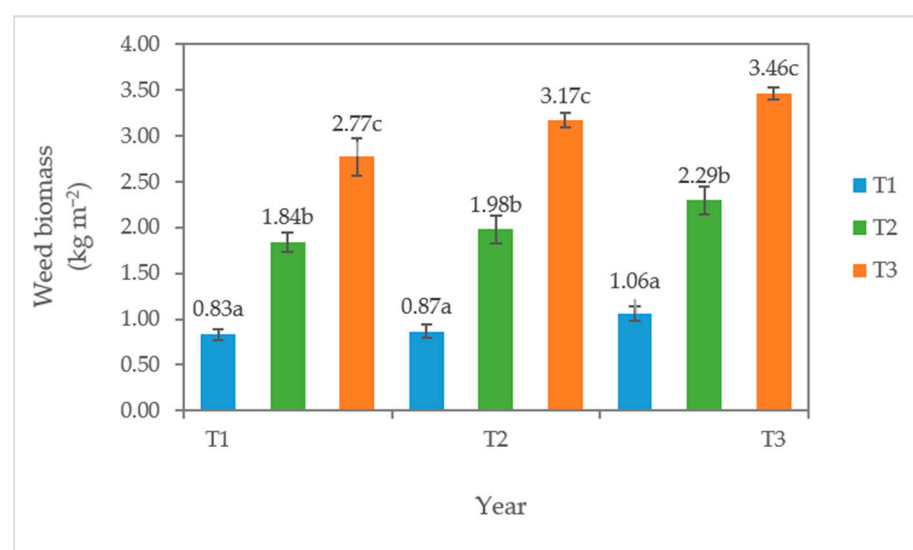


Figure 3. Weed biomass under different weed control treatments during a three-year field experiment (kg m^{-2}). Means followed by different letters differ significantly according to Tukey's HSD.

3.3. Weed Flora Composition and Relative Abundance

A diverse weed flora consisting of annual and perennial broadleaf and grass weed species was identified in the experimental field. Based on qualitative field observations of weed abundance, the greatest contribution to total weed biomass during the three-year experiment was made by *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, *Sorghum halepense*, and *Chenopodium album* (Table 5). These species are characterized by high competitiveness and an ability to efficiently utilize available resources. Their abundance was lowest in the treatment with the most intensive weed control (T1), increased in the treatment with inter-row mechanical weed control without weed removal within the crop row (T2), and was highest in the untreated control (T3). This pattern was consistent with the observed increase in total weed biomass.

Table 5. Qualitative occurrence and relative abundance of weed species recorded under different mechanical weed control treatments during the three-year experiment.

Botanical Name	Family	Common Name	T1	T2	T3
<i>Amaranthus retroflexus</i>	Amaranthaceae	Common amaranth	++	+++	++++
<i>Ambrosia artemisiifolia</i>	Asteraceae	Ragweed	++	+++	++++
<i>Sorghum halepense</i>	Poaceae	Johnson grass	+	++	+++
<i>Chenopodium album</i>	Chenopodiaceae	White goosefoot	++	++	+++
<i>Echinochloa crus-galli</i>	Poaceae	Cockspur grass	++	++	++
<i>Setaria</i> spp.	Poaceae	Foxtail	++	++	++
<i>Convolvulus arvensis</i>	Convolvulaceae	Field bindweed	+	+	++
<i>Elymus repens</i>	Poaceae	Couch grass	+	+	++
<i>Cynodon dactylon</i>	Poaceae	Bermuda grass	+	+	++
<i>Cirsium arvense</i>	Asteraceae	Creeping thistle	+	+	++
<i>Polygonum persicaria</i>	Polygonaceae	Lady's thumb	+	+	+
<i>Lolium</i> spp.	Poaceae	Ryegrass	+	+	+
<i>Sinapis arvensis</i>	Brassicaceae	Field mustard	+	+	+
<i>Equisetum arvense</i>	Equisetaceae	Field horsetail	+	+	+

Legend: + sporadic occurrence; ++ moderate abundance; +++ common species; ++++ dominant species.

Amaranthus retroflexus and *Ambrosia artemisiifolia* are highly competitive annual broadleaf weed species characterized by rapid early growth, large leaf area, and the production of substantial above-ground biomass. Both species efficiently utilize available water, light, and nutrients and, under favorable growing conditions, can significantly reduce light availability for young maize plants. Their increased abundance in treatments T2 and particularly T3 may explain the observed increase in weed biomass and the associated reduction in maize yield during the study period. *Sorghum halepense* exhibits a different development strategy compared with annual weed species. In addition to reproduction by seeds, it spreads effectively through rhizomes, which contributes to its increasing importance in crops under conditions of insufficient long-term control. Due to its vegetative propagation ability, a gradual increase in its abundance was observed during the study, particularly in treatment T3. Although the abundance of *Chenopodium album* did not increase as markedly as that of *Amaranthus retroflexus* or *Sorghum halepense* during the experiment, its continuous presence contributed to overall weed infestation, especially in the treatment without weed control.

Annual grass weed species, primarily *Echinochloa crus-galli* and *Setaria* spp., were present in all treatments throughout the experiment. Their relatively stable abundance indicates that they represented a consistent component of the weed community but were not the main contributors to the increase in total weed biomass over the years. In contrast, perennial weed species such as *Convolvulus arvensis*, *Elymus repens*, *Cynodon dactylon*, and

Cirsium arvense showed a gradual increase in abundance over the experimental period. Their ability to propagate vegetatively through underground organs enables gradual spread under conditions of incomplete or absent weed control, making their contribution increasingly important in long-term experiments. Conversely, species such as *Equisetum arvense*, *Lolium* spp., *Sinapis arvensis*, and *Polygonum persicaria* occurred sporadically and contributed less to total weed biomass and competitive pressure on maize.

3.4. Maize Grain Yield Under Different Weed Control Treatments

The average maize grain yield differed significantly among the evaluated weed control treatments during all three experimental years (Figure 4). The highest average yield was achieved in treatment T1, where mechanical weed control between the crop rows was combined with manual hoeing within the crop row, while the lowest yield was recorded in the untreated control treatment T3. Treatment T2, in which weeds were controlled only by mechanical weed control between the crop rows, resulted in intermediate grain yield values between the two treatments. This yield pattern was consistent throughout the three-year experiment, with T1 achieving the highest and T3 the lowest grain yield in each year. Across all treatments, the highest average yield was recorded in 2023, whereas yields in 2021 and 2022 were lower and comparable. Differences among treatments were observed in each experimental year and were particularly pronounced between T1 and T3. The average maize grain yield over the three-year experimental period in treatment T1 was 6683 kg ha^{-1} . Compared with T1, the average yield in treatment T2 was 55.4% lower, while in treatment T3 it was 81.9% lower. These results indicate a consistent positive effect of more intensive weed control on maize grain yield throughout the three-year experiment.

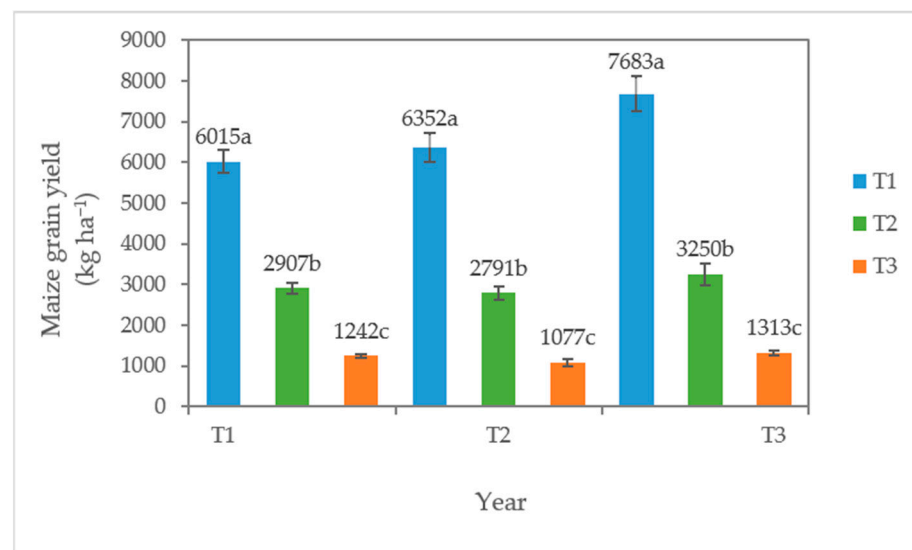


Figure 4. Maize grain yield under different weed control treatments during a three-year field experiment (kg ha^{-1}). Means followed by different letters differ significantly according to Tukey's HSD.

3.5. Relationship Between Weed Biomass and Maize Grain Yield

Figure 5 shows the relationship between weed biomass and maize grain yield based on observations obtained during the three-year field experiment. Regression analysis revealed a strong inverse linear relationship between weed biomass and grain yield ($R^2 = 0.8334$), indicating that plots with higher weed biomass generally had lower grain yields. The regression model explained approximately 83.3% of the variability in maize grain yield, while the remaining variation may be attributed to differences among years, weed control treatments, environmental conditions, and other sources of experimental variability. This relationship should be interpreted as an overall association between the two variables rather

than evidence of a direct causal relationship, as maize grain yield was also influenced by the experimental design and environmental conditions.

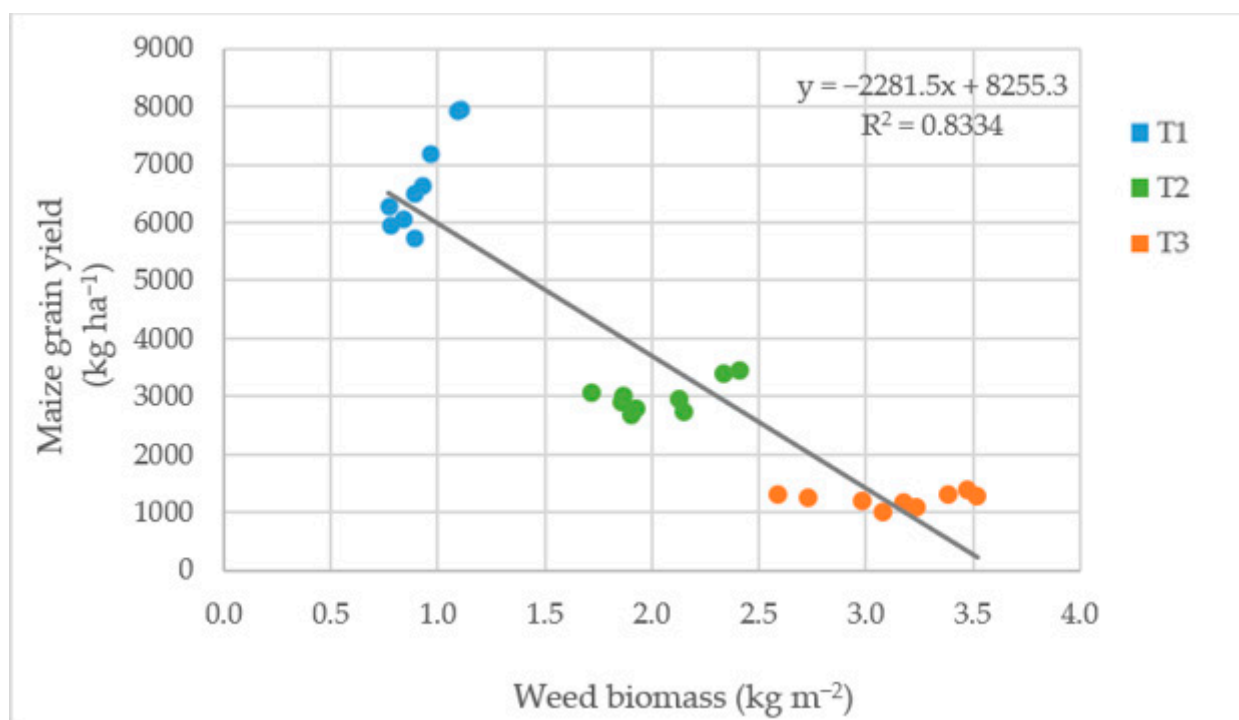


Figure 5. Correlation between weed biomass and maize grain yield during the three-year field experiment.

The linear mixed-effects model with repeated measurements showed that both year and weed control treatment significantly affected weed biomass and maize grain yield during the three-year experiment (Table 6). The treatment effect was highly significant for both response variables, indicating consistent differences in weed biomass and grain yield among the evaluated weed control systems. The significant effect of year reflected year-to-year variability in environmental conditions, while the significant year $\times$ treatment interaction indicated that the magnitude of treatment effects differed among experimental years. Nevertheless, the overall ranking of treatments remained unchanged throughout the experiment, with treatment T1 consistently resulting in the lowest weed biomass and highest grain yield, whereas treatment T3 showed the highest weed biomass and lowest grain yield.

Table 6. Results of the linear mixed-effects model with repeated measurements for weed biomass and maize grain yield during the three-year experiment.

Source of Variation	Weed Biomass (F)	<i>p</i>	Maize Grain Yield (F)	<i>p</i>
Treatment	205.64	<0.001	298.06	<0.001
Year	3.49	0.031	165.25	<0.001
Year $\times$ Treatment	3.79	0.004	40.40	<0.001

Legend: F = F-test value; *p* = probability level.

Statistical analysis further confirmed that weed control system was the most influential factor affecting weed infestation level and maize grain yield. Although meteorological conditions differed among the experimental years, particularly regarding precipitation distribution during the growing season, the effect of weed control treatment was more

pronounced than the effect of year. This was reflected by the higher F-values obtained for the treatment factor compared with the year factor for both weed biomass and grain yield. These results indicate that more favorable climatic conditions alone could not compensate for the negative effects of insufficient weed control; rather, they enabled higher yields primarily in plots where weed competition was effectively reduced.

4. Discussion

The results of the three-year experiment clearly demonstrated that the mechanical weed control system was a key factor affecting weed infestation level and maize grain yield. Throughout all three experimental years, the lowest weed biomass was recorded in the treatment where mechanical weed control between the crop rows was supplemented with manual hoeing within the crop rows (T1), whereas the highest weed biomass was observed in plots without weed control (T3). These results indicate that effective mechanical weed management cannot rely solely on mechanical weed control between the crop rows, as weeds remaining within the crop rows continue to compete with maize plants for water, light, and nutrients during critical growth stages. Therefore, combining mechanical weed control between crop rows with weed removal within the crop rows appears to be necessary for achieving more effective and stable weed suppression over multiple growing seasons. In recent years, increasing restrictions on herbicide use, together with growing concerns regarding herbicide resistance and environmental impacts, have renewed interest in mechanical weed control as a sustainable weed management strategy [36].

Three-year monitoring of the experimental field also enabled the assessment of changes in weed flora composition over time. During the study, *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, *Sorghum halepense*, and *Chenopodium album* were the most dominant weed species, which is consistent with the weed flora composition commonly reported in maize production systems in continental Croatia and neighboring countries [37,38]. The most pronounced increases in abundance were observed for *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, and particularly *Sorghum halepense* in treatments with insufficient or no weed control. This development is consistent with the biological characteristics of these species, including high competitiveness, strong reproductive capacity, and good adaptation to disturbed agroecosystems. *Sorghum halepense* deserves particular attention due to its perennial growth habit and ability to reproduce both by seeds and underground rhizomes. Consequently, its abundance may increase when effective control measures are not implemented over several consecutive years [39–41]. In contrast, species such as *Echinochloa crus-galli*, *Setaria* spp., and *Chenopodium album* maintained relatively stable abundance throughout the experiment, whereas perennial species such as *Convolvulus arvensis*, *Elymus repens*, *Cynodon dactylon*, and *Cirsium arvense* showed a gradual increase, particularly in treatments T2 and T3. These changes indicate that incomplete long-term weed control may favor the gradual increase of competitive perennial species, which can make their management more difficult and increase weed control costs in subsequent production cycles [42,43].

According to Glowacka [44], the weed species most frequently occurring in maize crops across Europe include *Chenopodium album*, *Echinochloa crus-galli*, *Setaria* spp., *Amaranthus retroflexus*, *Elymus repens*, and *Polygonum persicaria*. As shown in Table 5, all of these species were also identified in the present study. Bensch et al. [45] conducted a nationwide weed survey in 577 maize fields representing all major maize-growing regions in Germany during 2017 and 2018, identifying 119 weed species. The most frequently occurring species were *Chenopodium album* (82%) and *Echinochloa crus-galli* (50%). However, *Ambrosia artemisiifolia* and *Sorghum halepense*, which are among the most important maize weeds in Croatia and neighboring countries, were not recorded in German maize fields. Essl et al. [46] analyzed weed vegetation in maize fields across Central Europe using

data collected between 2012 and 2022. The species most frequently recorded across the analyzed plots were *Echinochloa crus-galli* (121 plots), *Chenopodium album* (114 plots), and *Convolvulus arvensis* (83 plots). In a maize field experiment conducted in Turkey, the most abundant weed species among the 11 recorded species were *Echinochloa colonum*, *Amaranthus retroflexus*, *Echinochloa crus-galli*, and *Portulaca oleracea* [47]. The weed flora recorded in the present study differed from that reported in several other European maize-growing regions, confirming the observation of Kremer [18] that weed species composition in maize is strongly influenced by geographical location, climatic conditions, soil characteristics and crop management. For example, a field experiment conducted in Romania in 2023 identified *Solanum nigrum*, *Atriplex patula*, *Portulaca oleracea* and *Digitaria sanguinalis* as the dominant weed species, with their relative abundance varying according to previous crop and pedo-climatic conditions [48]. A three-year field trial conducted in Slovakia (2014–2016) reported *Amaranthus retroflexus*, *Chenopodium album*, *Persicaria maculosa*, *Echinochloa crus-galli*, *Cirsium arvense*, *Convolvulus arvensis* and *Cardaria draba* as the predominant weed species in maize [49]. Differences in the overall composition of the weed flora further support the influence of local agroecological conditions on weed emergence. According to Buhler [50], weed species composition and abundance in a particular area are determined by several interacting factors, and in most cases only a limited number of species become dominant. This pattern was also observed in the present experiment, where a relatively small number of weed species contributed most to the total weed infestation.

Maize grain yield was strongly negatively correlated with measured weed biomass. Regression analysis revealed a very high coefficient of determination ($R^2 = 0.833$), indicating that variation in weed biomass explained a large proportion of the variability in maize grain yield. This relationship was expected because weeds compete with maize for water, light, nutrients, and space throughout the growing season, with competition being particularly important during the early stages of crop development. Numerous studies have confirmed that weeds remaining within the crop row have the greatest negative impact on yield, as they grow in close proximity to maize plants and compete directly for the same resources during critical growth periods.

The omission of weed control within maize rows through manual hoeing resulted in an average yield reduction of 55.4%, supporting the conclusion that weeds growing within the crop row and in close proximity to maize plants cause substantial yield losses [24]. The absence of weed control resulted in an even greater yield reduction, reaching 81.9% compared with the integrated weed control system combining mechanical weed control between the crop rows and manual hoeing within the crop rows. Although some authors [17,51] have reported that maize yield losses can reach up to 100% under uncontrolled weed infestation, such a complete yield loss was not observed in the present experiment. Similar maize grain yields under conditions without weed control (1.31 and 1.39 t ha⁻¹) were reported by Takim et al. [52] and Silva et al. [53]. In the present study, weed control was performed only once during the growing season, whereas Damian [54] applied multiple weed control operations by combining mechanical cultivation and manual hoeing. This author concluded that repeated weed control (two or three operations) can significantly increase maize yield. Similar conclusions regarding the benefits of repeated weed control were reported by Silva et al. [53]. However, labor availability is often limited during the early stages of maize growth, when weed competition must be controlled. Furthermore, weeds that are allowed to develop extensively require greater labor inputs for effective removal, while delayed weed control can result in substantial yield losses [28].

Maize yields obtained in plots with the most effective weed control system during the first two experimental years were significantly lower than the average maize yield of approximately 8 t ha⁻¹ reported for Croatia [13], which was mainly attributed to un-

favorable climatic conditions during the growing seasons. In 2023, substantially higher precipitation during the vegetation period created more favorable conditions for maize growth and development. However, these conditions also promoted more intensive weed development, resulting in the highest weed biomass across all treatments. Despite the increased weed growth, the greatest yield improvement was achieved in treatment T1, where effective weed suppression allowed maize plants to fully utilize the favorable environmental conditions. In treatments T2 and T3, increased weed competition limited the positive effects of favorable weather conditions, resulting in yield increases that were not proportional to the improved growing conditions. According to Landau et al. [55], favorable meteorological conditions alone are insufficient for achieving high yields if weed competition is not effectively controlled, which was also demonstrated in the present study.

The results obtained in this experiment indicate that effective weed control not only reduces current weed abundance and biomass but also prevents long-term changes in weed community structure that may favor the development of highly competitive annual species and the gradual spread of perennial weeds. Such changes are particularly pronounced in years with favorable meteorological conditions, when increased availability of water and nutrients promotes not only maize growth but also intensive weed development. Therefore, the positive effect of favorable climatic conditions on yield can be fully realized only in production systems where weed competition is effectively controlled [56]. Mechanical weed control represents a non-chemical alternative to herbicide-based weed management and, due to its compatibility with established agricultural practices in many regions, can be effectively incorporated into integrated weed management systems [54]. The present study evaluated a single mechanical weed control operation, reflecting common agricultural practice in the study region. Although this approach effectively reduced overall weed biomass and increased maize grain yield, it cannot completely suppress late-emerging weed cohorts or perennial species capable of regrowth after cultivation. This was particularly evident for species such as *Sorghum halepense*, which remained present in the untreated and partially treated plots. Consequently, additional mechanical interventions or integration with other non-chemical weed management practices may be necessary under conditions of prolonged weed emergence or high perennial weed pressure. A limitation of the present study is that weed biomass was assessed only once, approximately one month before harvest. Consequently, the measurements represent the cumulative outcome of weed development under each treatment rather than the intensity of weed competition during the critical early growth stages of maize. Future studies including repeated weed assessments throughout the growing season would provide a more detailed understanding of the temporal dynamics of crop–weed competition.

5. Conclusions

The weed control systems evaluated in this three-year field experiment significantly affected weed biomass and maize grain yield. The lowest weed biomass and the highest grain yield were achieved in Treatment T1, which combined inter-row mechanical cultivation with manual hoeing within the crop row, whereas the untreated control (T3) showed the highest weed biomass and the lowest yield. Inter-row mechanical cultivation alone (T2) reduced weed biomass compared with the untreated control but was less effective than the combined treatment because weeds remaining within the crop row continued to compete with maize. Qualitative assessment of the weed flora indicated differences in the occurrence of dominant weed species among treatments, particularly *Amaranthus retroflexus*, *Ambrosia artemisiifolia* and *Sorghum halepense*. Although more favourable weather conditions in 2023 increased maize grain yield in all treatments, they did not eliminate the negative effect of weed competition. Under the agroecological conditions of this study, effective

weed control both between and within the crop rows proved essential for reducing weed biomass and achieving high maize grain yield. Because the experiment was conducted at a single location using one maize hybrid and one weed control operation per season, further multi-location studies are needed to confirm the wider applicability of these findings.

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