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Impact of Pre- and Post-Emergence Herbicides on Controlling Predominant Weeds at Late-Rainy Season Sugarcane Plantations in Northeastern Thailand

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Abstract

Weeds are a primary factor affecting sugarcane production and productivity in Thailand. During the late-rainy season, when cultivation is carried out under rainfed conditions, weed competition becomes increasingly severe, prompting farmers to perform secondary weed control using post-emergence herbicides. Therefore, to guide farmers on the appropriate use of herbicides for effective weed management and long-term control during the critical period of sugarcane growth, this study evaluates the effectiveness of pre- and post-emergence herbicides. Conducted in Northeast Thailand using a randomized complete block design (RCBD) with four replications, the experiment revealed that several pre-emergence herbicides, namely pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), and sulfentrazone (875 g a.i. ha^{-1}), and a combination of indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) were applied one day after sugarcane planting, demonstrating high weed control efficacy. These treatments significantly reduced the summed dominance ratio (SDR) of both total weed (41.65–78.54%) and dominant weeds (70.13–86.04%), including *Digitaria ciliaris* (Retz.) Koel., *Dactyloctenium aegyptium* (L.), *Brachiaria distachya* (L.) Stapf, and *Cyperus rotundus*, compared with the no-weeding treatment. In summary, effective weed management in sugarcane fields under late-rainy season can be achieved through the application of pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}, which produced the highest sugarcane yield (a 139.00% increasing compared with no weeding) and net profit (a 79.75% increasing compared with hand weeding) in loamy sand soil conditions, where *D. ciliaris*, *D. aegyptium*, and *C. rotundus* were dominant weeds. Similarly, indaziflam at 62.5 g a.i. ha^{-1} yielded the best results (a 71.68% increasing compared with no weeding) and net profit (a 121.04% increasing compared with no weeding) in sandy loam soil, where *B. distachya* was the only dominant weed. This weed management strategy is potentially transferable to sugarcane production systems in other regions that share comparable soil properties, climatic conditions, and dominant weed species.

Keywords: herbicide applications; weed management; summed dominance ratio; critical period

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1. Introduction

Weed control is a major influential factor in sugarcane productivity. Inadequate weed control can lead to yield reductions ranging from 26% to 75% [1]. Fields without weed management can experience yield losses of up to 56.66%, resulting in a lower profit-to-cost ratio [2]. Competition from weeds has been shown to suppress the growth and development of sugarcane by limiting access to essential resources [3–5].

Sugarcane serves as a key raw material for the sugar, ethanol, and energy industries, generating significant economic value [6]. Sugarcane is a vital component of Thailand's agricultural sector, with the sugar and sugarcane industry generating over USD 2.47 billion annually from exports and domestic sales. The total sugarcane cultivation area in Thailand spans approximately 1.82 million hectares, with the majority of sugarcane planting in the northeastern region accounting for 43.43% of the national total in the 2024–2025 growing season [7]. The predominant sugarcane variety cultivated in the country is Khon Kaen 3 (KK3), representing more than 85% of the total cropped area. Moreover, sugarcane cultivation in the northeastern region is primarily based on the late-rainy season system, since more than 78% of the cultivated area in Thailand depends on rainfed conditions [8,9].

Prolonged weed competition is commonly observed in late-rainy season sugarcane cultivation in the northeastern region, primarily due to environmental factors, particularly rainfall-induced moisture, which promotes weed dispersal. This cultivation system is established during the late-rainy season from October to December. Weed problems in sugarcane cultivation are classified into two levels of severity. The first period, representing mild competition, occurs after planting from January to March due to unseasonal rainfall events lasting one to three days. Even light rainfall during this period provides sufficient soil moisture for weed germination [10], leading to weed dispersal within the field and marking the onset of the initial phase of mild competition between sugarcane and weeds. This phase continues until the second period, characterized by severe competition from May onwards, coinciding with the onset of humidity throughout the rainy season, during which increased soil moisture promotes weed seed development [11]. As weed populations expand in both density and biomass per unit area, they adversely affect the sugarcane growth rate, nutrient uptake, and plant height [12,13]. Therefore, sugarcane cultivation under the late-rainy season system in the northeastern region, influenced by the aforementioned environmental factors, results in a prolonged critical period of competition with weeds. A longer critical period prolongs the window for weed competition, which can significantly reduce sugarcane yield. Conversely, maintaining weed control for an extended period can help increase yield [14].

Weed control in sugarcane cultivation can be achieved through various methods. However, given current labour shortages and limited access to agricultural machinery, herbicides remain important components of weed management in sugarcane fields [15]. The effectiveness of herbicide use in weed management depends on multiple factors, including the herbicide's mode of action. The success of herbicides relies on various physiological and biochemical processes within the plant, which occur in a sequence starting with herbicide exposure and absorption by the weed. These processes ultimately lead to weed death while avoiding harm to the crop, due to the herbicide's selectivity and its ability to destroy certain plants while leaving others unaffected [16,17]. Nonetheless, weeds exhibit considerable genetic diversity. Therefore, effective weed management using herbicides necessitates knowledge of the dominant weed species. The summed dominance ratio (SDR), calculated based on the density and dry weight of specific weed species, serves as a useful metric for identifying the key weed species in any given area [18]. Herbicides can be applied as either pre-emergence or post-emergence treatments. In the late-rainy season sugarcane fields in Northeastern Thailand, weed management can be effectively achieved during the early to mid-rainy season with a single application of paraquat [1,1′-dimethyl 4,4′-bipyridinium, IUPAC] photosystem I electron diverters (Group 22) to control the dominant weeds, *D. aegyptium*, *D. ciliaris*, and *Brachiaria,* at the tillering stage. However, the Thai government has banned the import of paraquat, making it unavailable for use in Thailand [19,20]. Currently, herbicides officially recommended by the Department of Agriculture of Thailand and readily accessible to farmers in sugarcane cultivation areas are applied in production systems. Therefore, the identification of herbicides capable of effectively controlling weeds is required to replace those that have been withdrawn from use in late-rainy season sugarcane cultivation. Pre-emergence herbicides suppress weed emergence after planting, while post-emergence herbicides are applied to control weeds before the second fertilizer application, which typically occurs during the tillering and stalk elongation phase. These stages coincide with the early to mid-rainy season, and the recommended herbicides are therefore selected for evaluation in this study under the late-rainy season sugarcane cultivation system.

Glufosinate ammonium [*DL*-homoalanin-4-yl(methyl)phosphinate, IUPAC] is a herbicide classified as an inhibitor of glutamine synthetase (GS) (Group 10). It has been used as a post-emergence herbicide in sugarcane and demonstrated an average 94% control of grass weeds three weeks after application. This rapid herbicidal effect is also initiated by the production of reactive oxygen species (ROS). ROS are generated when oxygen produced during water splitting in Photosystem II (PSII) accepts electrons. This cascade of events leads to lipid peroxidation, which underpins the quick action of glufosinate [21]. It also maintains sugarcane yield, including stalk and sugar production, comparable to that achieved with paraquat [22]. For pre-emergence applications, herbicides such as indaziflam offer broad-spectrum control, effectively suppressing various broadleaf and narrowleaf weeds. Nevertheless, herbicides demonstrated varying levels of weed control effectiveness and selectivity, as well as their capability for eliminating a wide range of weeds [23]. Indaziflam *N*-[(1*R*,2*S*)-2,3-dihydro-2,6-dimethyl1*H*-inden-1-yl]-6-[(1*RS*)-1-fluoroethyl]-1,3,5-triazine-2,4diamine, IUPAC] is a herbicide, classified as an inhibitor of cellulose synthesis (Group 29), that can persist in the soil for over 150 days, providing long-lasting control in sugarcane fields [24–26]. Herbicides like pendimethalin *N*-(1-ethylpropyl) 2,6-dinitro-3,4-xylidine (IUPAC), an inhibitor of microtubule assembly (Group 3), are particularly effective against narrowleaf weeds, including annual grasses and some broadleaf weeds, across various crops, including sugarcane. Pendimethalin is a compound belonging to the dinitroaniline group, and its mode of action involves inhibiting the polymerization of microtubules [23]. Studies show that over 90% of pendimethalin remains in the topsoil of loamy sand after 90 days, indicating prolonged persistence [27–30]. Topramezone [3-(4,5-dihyro-1,2-oxazol-3-yl)-4-mesyl-o-tolyl](5-hydroxy-1 methylpyrazol-4-yl)methanone (IUPAC), an inhibitor of mitosis (Group 23) commonly used as a post-emergence herbicide in maize cultivation to control grasses, is now also used pre-emergence in sugarcane due to its high efficacy against grassy weeds [31,32]. Herbicides targeting broadleaf weeds and sedges include atrazine [6-chloro-N^2-ethyl-N^4 isopropyl-1,3,5-triazine-2,4-diamine, IUPAC], an inhibitor of photosynthesis at photosystem II site A (Group 5) and a widely used pre-emergence triazine herbicide that can maintain a weed-free condition for approximately 50 to 60 days, resulting in high weed mortality in sugarcane fields [33]. Imazapic 2-[(*RS*)-4-isopropyl-4-methyl 5-oxo-2-imidazolin-2-yl]-5-methylnicotinic acid (IUPAC), an acetolactate synthase (ALS) inhibitor (Group 2) and part of the Imidazolinone herbicide group, has been highly effective in controlling broadleaf and grassy weeds when applied pre-emergence. Its mode of action involves inhibiting cellulose synthesis, which affects monocotyledonous weeds [34]. It can achieve up to 95% control up to 120 days after application (DAA) for broadleaf weeds like *Ipomoea hederifolia* and is also capable of reducing tuber density in *C. rotundus* by targeting soil tubers [35,36]. The half-life of imazapic varies from 77 to 85.56 days, depending on environmental conditions and soil type [37,38]. Sulfentrazone [2^1,4^1-dichloro-5^1-(4difl uoromethyl-4,5-dihydro-3-methyl-5-

oxo-1*H*-1,2,4-triazol1-yl)methanesulfonanilide, IUPAC] inhibitors of protoporphyrinogen oxidase (Protox, PPO) (Group 14), when applied pre-emergence, have shown excellent activity against broadleaf weeds and sedges, including *C. rotundus*. Their persistence in the soil is significant, with a half-life of approximately 70.8 days, allowing for prolonged weed suppression [39].

Currently, the aforementioned herbicides lack sufficient research and specific guidelines for weed management in sugarcane fields planted during the late-rainy season under rainfed conditions in Northeastern Thailand. Additionally, environmental factors and the main weed species vary across plantations, making this a critical consideration when selecting effective weed control strategies. Evaluating the effectiveness of the methods discussed above can serve as an alternative approach, providing valuable guidance for sugarcane farmers who continue to face challenges in managing weeds. Therefore, the objective of this study is to evaluate the effectiveness of pre- and post-emergence herbicides in sugarcane fields planted during the late-rainy season under rainfed conditions in Northeastern Thailand.

2. Materials and Methods

2.1. Experimental Site

This study on weed management for the KK3 sugarcane variety was conducted in an upland field during the late-rainy season. The experiment was conducted at two locations during the same growing season, both of which are representative of the characteristic sugarcane cultivation conditions in Northeastern Thailand. The experiment in Location I was carried out from 14 November 2020 to 3 December 2021, while in Location II it took place from 3 December 2020 to 17 December 2021. Location I was situated at Khao Suan Kwang District, Khon Kaen Province, Thailand (16°52′16.7″ N 102°51′52.8″ E). The soil's physical properties consisted of a loamy sand texture. Soil chemicals and attributes included a pH of 5.75, total nitrogen (N) (0.047%), available phosphorus (P) (88.75 mg kg^{-1}), extractable potassium (K) (40.84 mg kg^{-1}), extractable calcium (Ca) (184.02 mg kg^{-1}), extractable magnesium (Mg) (15.53 mg kg^{-1}), cation exchange capacity (CEC) (2.63 mol kg^{-1}), organic matter (OM) (0.57%), and electrical conductivity (EC) (0.026 dS m^{-1}). Location II was in Nong Han District, Udon Thani Province, Thailand (17°20′40.4″ N 103°14′49.9″ E). The soil physical properties exhibited a sandy loam texture. Soil chemicals and attributes included a pH of 5.93, total nitrogen (N) (0.038%), available phosphorus (P) (120.00 mg kg^{-1}), extractable potassium (K) (26.99 mg kg^{-1}), extractable calcium (Ca) (373.38 mg kg^{-1}), extractable magnesium (Mg) (65.69 mg kg^{-1}), cation exchange capacity (CEC) (5.43 mol kg^{-1}), organic matter (OM) (0.80%) and electrical conductivity (EC) (0.042 dS m^{-1}). In addition, soil chemistry parameters facilitate the planning of fertilizer applications according to the nutrient requirements of sugarcane. The plot sizes were as follows: In Location I, each plot measured 105.6 m^2, with a planting length of 11.0 m and a width of 9.6 m. In Location II, each plot covered 86.4 m^2, with a length of 9.0 m and a width of 9.6 m. Six rows of sugarcane were planted in each plot, with a row spacing of 160 cm, while the harvesting area for each plot was 25.6 m^2.

2.2. Weather Data

Weather data were gathered from the meteorological station nearest to the experimental field (Meteorological Center, Upper Northeast Thailand). In Location I, the accumulated rainfall was 1138.80 mm, the average minimum temperature was 22.05 °C, the average maximum temperature was 32.09 °C, and the relative humidity was 70.27%. In Location II, the accumulated rainfall was 1386.60 mm, the average minimum temperature was 21.96 °C, the average maximum temperature was 32.61 °C, and the average relative humidity was 72.43% (Figure 1).

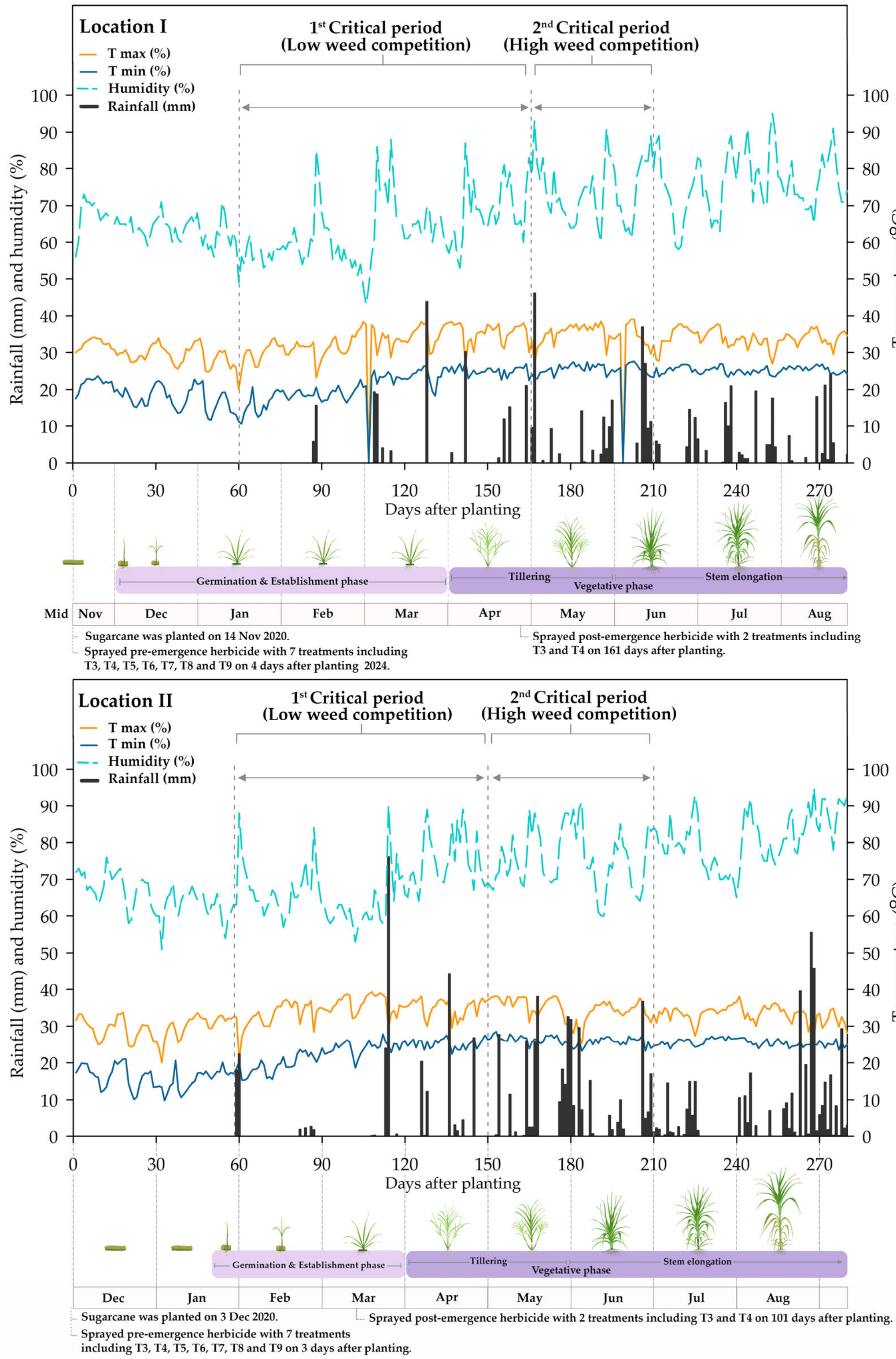

Figure 1. Experiment using meteorological data and sugarcane growth at Location I, Khao Suan Kwang District, Khon Kaen Province, and Location II, Nong Han District, Udon Thani Province, from beginning of sugarcane planting to end of critical sugarcane stage 0 to 210 days after planting (DAP).

2.3. Experimental Design and Plant Material

The experiment was conducted using the randomized complete block design (RCBD), with four replicates and nine treatments (Table 1). The KK3 sugarcane variety was planted using stalks that were paired per row and cut into 30 cm pieces along the planting furrows, with initial fertilizer application and ploughing conducted simultaneously. The study included six pre-emergence herbicides—atrazine, pendimethalin, imazapic, indaziflam, sulfentrazone, and topramezone—applied to one DAP. In Location I, the herbicides were sprayed on 18 November 2020, and in Location II on 6 December 2020. A single post-emergence herbicide, glufosinate ammonium, was performed when weeds had developed no more than four true leaves, using a nozzle cover to minimize drift and contact with leaves and sugarcane stems. In Location I, it was sprayed with 161 DAP (on 24 April 2021), and with 101 DAP in Location II (on 14 March 2021) (Figure 1). Each herbicide application was compared with hand weeding and weed control treatments. Applications were carried out using a calibrated 15 L knapsack sprayer fitted with a battery-powered flooding fan nozzle, delivering a 500 L ha^{-1} spray volume. Fertilizer amounts were calculated based on the soil analysis results using the fertilizer calculation program from the Land Development Department. Fertilizer was applied twice: the first application was conducted simultaneously with planting at a rate of 83.93 kg N ha^{-1}, 18.75 kg P_2O_5 ha^{-1}, and 112.50 kg K_2O ha^{-1} in Location I and one of 76.14 kg N ha^{-1}, 25.25 kg P_2O_5 ha^{-1}, and 152.19 kg K_2O ha^{-1} in Location II. The second fertilization occurred at the beginning of the rainy season, 210 DAP, with an application of 84.32 kg N ha^{-1} in Location I, and one of 75.18 kg N ha^{-1} in Location II.

Table 1. Herbicide and rates applied.

Treatment	Active Ingredient and Formulation	Trade Name Manufactured	Doses (g a.i. ha^{-1})
No weeding (T1)	-	-	-
Hand weeding (T2)	-	-	-
Atrazine fb glufosinate ammonium (T3)	Atrazine 90% WG, Glufosinate ammonium 15% SL	BK Prim/Baka Company (Bangkok, Thailand), BastaX/BASF (Bangkok, Thailand)	3000 fb 562.5
Atrazine fb glufosinate ammonium (T4)	Atrazine 90% WG, Glufosinate ammonium 15% SL	BK Prim/Baka Company (Bangkok, Thailand), BastaX/BASF (Bangkok, Thailand)	3000 fb 750.0
Pendimethalin + imazapic (T5)	Pendimethalin 33% EC, Imazapic 24% SL	BK Ranger/BK Agro Company (Bangkok, Thailand), BKX/BK Agro Company (Bangkok, Thailand)	825.0 + 75.0
Indaziflam (T6)	Indaziflam 50% SC	B Kano/Baka Company (Bangkok, Thailand)	62.5
Sulfentrazone (T7)	Sulfentrazone 48% SC	Authority/Baka Company (Bangkok, Thailand)	875.0
Indaziflam + sulfentrazone (T8)	Indaziflam 50% SC, Sulfentrazone 48% SC	B Kano/Baka Company (Bangkok, Thailand), Authority/Baka Company (Bangkok, Thailand)	46.88 + 750.0
Topramezone (T9)	Topramezone 33.6% SC	Cleo/Chia Tai Company (Samut Prakarn, Thailand)	52.5

fb = followed by. At Location I (Khao Suan Kwang District, Khon Kaen Province), hand weeding was performed at 98, 163, 243, and 320 days after planting. At Location II (Nong Han District, Udon Thani Province), hand weeding was conducted at 102, 149, 221, and 305 days after planting.

2.4. Data Collection

2.4.1. Weed Data

Herbicide efficacy in weed control was evaluated using the weed control efficiency (WCE) index, defined on a scale of 0 to 100% as described by Dear et al. [40]. Weed species were surveyed by representative sampling weeds randomly from subplots with an area of 1 m^2 using two quadrants (each 1.0 m × 0.5 m) per plot, located outside the harvest area. Sampling was conducted during the critical period at 60, 90, 120, 150, 180, and 210 DAA for pre-emergence herbicides and at 0, 1, 7, 14, 21, and 30 DAA for post-emergence herbicides. The weed types were identified, and the number of weeds of each species was counted to calculate the density per m^2. The collected weed samples were then dried in an oven at 80 °C for 72 h, and their dry weight was subsequently measured. The quantitative characteristics of the weeds were analyzed to rank the dominant weeds using the SDR [16].

$$\text{Relative density (RD)} = \frac{\text{DS}}{\text{TDS}} \times 100$$

$$\text{Relative dry weight (RDW)} = \frac{\text{DWS}}{\text{TDWS}} \times 100$$

$$\text{Summed dominance ratio (SDR)} = \frac{\text{RD} + \text{RDW}}{2}$$

DS = density of a given species, TDS = total density of all species, DWS = dry weight of a given species, and TDWS = total dry weight of all species.

The SDR of total weeds in each treatment was determined by defining the RD value as the total number of weeds identified in each treatment and the DWS value as the total dry weight of all weeds found in each treatment at a given time. These values were used to compare the SDR of weeds with different treatments.

The evaluation of weed control efficacy was conducted using the weed control efficiency (WCE) formula [41].

$$\text{WCE\%} = \frac{\text{weed biomass in no-weeding plot} - \text{weed biomass in treated plot}}{\text{weed biomass in hand weeding plot}} \times 100$$

2.4.2. Herbicide Phytotoxicity of Sugarcane

The herbicide phytotoxicity of sugarcane was visually assessed at 0, 1, 7, 14, 21, and 30 DAA of post-emergence, using a 0 to 100% scale, with lower percentages indicating less toxicity to the plants and higher percentages indicating greater toxicity, following the methodology used by Dear et al. [40].

2.4.3. Yield and Yield Components

The harvest area was designated as 25.6 m^2 per plot. The length of 10 randomly selected stalks within this area was measured by cutting the sugarcane stalks near the ground and using a tape measure to determine the distance from the base to the natural breaking point of each stalk. After harvesting, all stalks within the harvest area were counted and weighed to calculate the stalk and cane yield per hectare. Leaves were also cut, weighed fresh, and used to calculate the yield per hectare. Commercial cane sugar (CCS) refers to the amount of sugar extractable from the sugarcane for refinement into white sugar. The CCS content was calculated using the formula provided by Albertson and Grof [42].

$$\text{CCS} = \frac{3\text{P}}{2}\left(1 - \frac{\text{F}+5}{100}\right) - \frac{\text{B}}{2}\left(1 - \frac{\text{F}+3}{100}\right)$$

where P = pol at 20 °C, B = brix at 20 °C, and F = fibre percentage.

Sugar yield is a measurement of the amount of sugar produced from sugarcane, determined using the following formula:

$$\text{Sugar yield (ton CCS ha}^{-1}) = \frac{\text{CCS} \times \text{Cane yield}}{100}$$

2.4.4. Production Costs and Net Profit

Net profit was calculated based on the production cost and determined using the following formula:

$$\text{Production cost} = \text{Fixed costs} + \text{Variable costs}$$

Fixed costs represent the total expenses involved in establishing and maintaining the sugarcane fields that remain consistent across all processes. These costs are calculated per hectare and include expenses such as ploughing, harrowing, turning, seed cutting, planting, and fertilizer application.

Variable costs comprise the expenses for weed control methods, which vary depending on the chosen approach. These costs are also calculated per hectare and include herbicides, labour for herbicide application, manual weed control, human labour for cutting fresh sugarcane, and transportation costs adjusted for different yield levels.

The calculation of net profit was obtained using the following formula:

$$\text{Net profit} = \text{Total income} - \text{Production costs}$$

Total income is determined by multiplying the amount of fresh sugarcane produced by the initial price of 31.85 USD per ton, based on a sugar content of 10 CCS in 2021. The sugarcane price is calculated according to its sugar content quality [43].

2.5. Statistical Analysis

Data were subject to analysis of variance (ANOVA) according to the experimental design to examine variations in treatment effects, weed control efficiency, herbicide phytotoxicity to sugarcane, and sugarcane yield and yield components. Differences among treatment means were determined using the Least Significant Difference (LSD) test at a 5% significance level. The statistical analyses were performed using Statistix® version 10.0 (1985–2013) tool (Analytical Software, Tallahassee, FL, USA). The correlation between weed control efficiency and sugarcane yield was also assessed.

3. Results

3.1. Weed Species, Abundance, and Summed Dominance Ratio (SDR)

The Predominant Weed Species in Locations I and II

In experimental Location I, a total of 16 weed species under all treatments were identified through random sampling during the critical period (60 to 210 DAA). These included three narrowleaf weed species, nine broadleaf species, and four sedges. When assessing the proportion of dominant weeds based on the SDR, three weed species with high SDR were found: two narrowleaf weed species, namely, *Dactyloctenium aegyptium* (L.), and *Digitaria ciliaris* (Retz.) Koel., and one sedge species, *Cyperus rotundus* (Figure 2). In Location II, 27 weed species were recorded, comprising 7 narrowleaf weeds, 19 broadleaf weeds, and 1 sedge. Among these, one species with a high SDR was identified as the dominant weed, *Brachiaria distachya* (L.) Stapf, a narrowleaf weed (Figure 2).

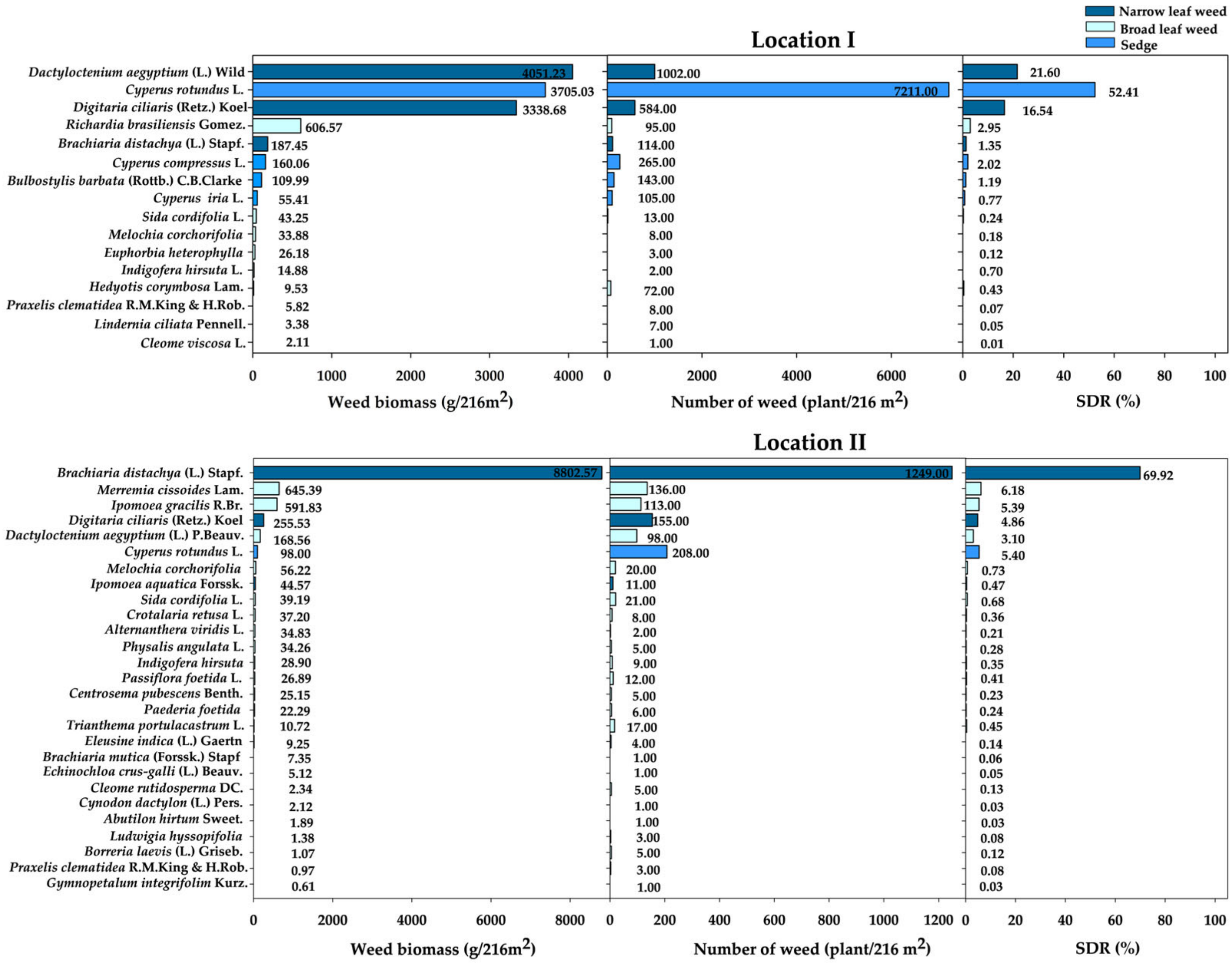

Figure 2. The weed biomass, number of weeds, and SDR of each weed species. The area of 216 m^2 is the cumulative area from 60 to 210 days after herbicide application. Location I, Khao Suan Kwang District, Khon Kaen Province, and Location II, Nong Han District, Udon Thani Province.

3.2. Weed Control Efficiency and SDR of Total Weeds

During the critical period in Location I, the efficiency of weed control and SDR showed statistically significant differences among treatments. The combinations of pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), and sulfentrazone (875 g a.i. ha^{-1}) exhibited moderate to very good levels of weed control efficiency (82–96%, $p < 0.01$), although not always at a generally acceptable threshold. In contrast, the combination of indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) demonstrated fair to moderate control efficiency (71–83%, $p < 0.01$) at 60, 90, and 150 DAA, with slightly reduced effectiveness observed at 120 DAA (63–83%, $p < 0.01$). Notably, all four treatments resulted in significantly reduced weed occupancy, as reflected by SDR values during the 60 to 150 DAA period ($p < 0.01$), when compared with the no-weeding scenario. However, during the later stages of the critical period, when weed and sugarcane competition persisted for a longer period, at 180 and 210 DAA, pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}) continued to provide satisfactory to good weed control (85%) and maintained a low SDR. Although the weed control efficacy of pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}) was slightly decreased over longer critical periods, it still effectively inhibited weed growth (Figure 3).

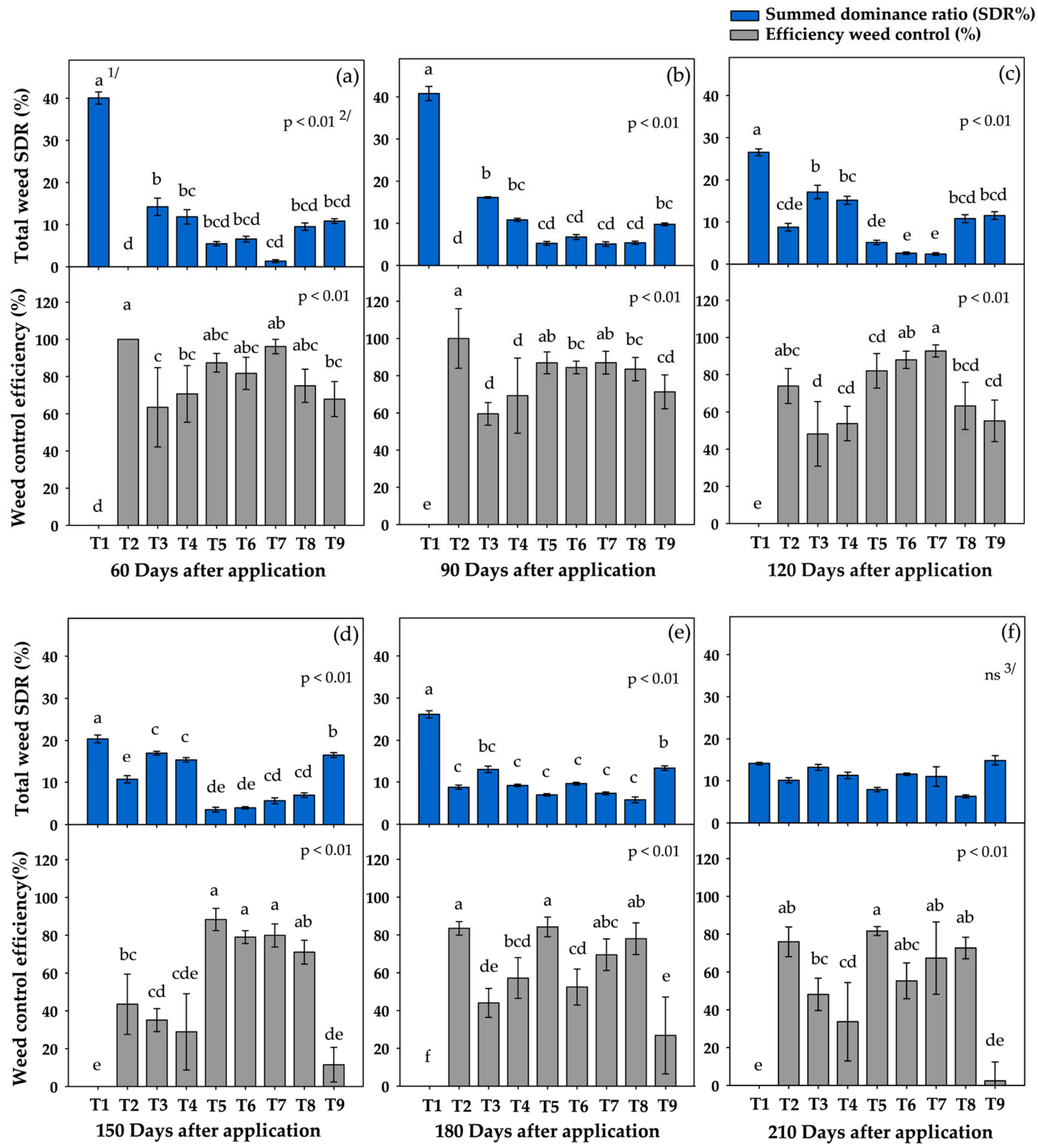

Figure 3. Total weed SDR and weed control efficiency during the critical period of 60 to 210 days after application; 60 DAA (**a**), 90 DAA (**b**), 120 DAA (**c**), 150 DAA (**d**), 180 DAA (**e**), and 210 DAA (**f**). Location I, Khao Suan Kwang District, Khon Kaen Province. T1 = no weeding; T2 = hand weeding at 98, 163, 243, and 320 DAA; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}. [1/] Means followed by the same letter were not significantly different at $p < 0.05$. [2/] significant LSD at $p < 0.01$. [3/] non-significant.

In Location II, weed control efficiency was almost complete for all herbicide applications during the early critical period (60 to 90 DAA). In the early critical period (60–90 DAA), weed control treatments featuring atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (562.5 g a.i. ha^{-1}), atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (750 g a.i. ha^{-1}), pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) significantly suppressed total weed populations (57–99%, $p < 0.01$), leading to a marked reduction in the SDR of total weeds when compared with the untreated control ($p < 0.01$). By 120 to 150 DAA, the previously highly effective treatments, atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (700 g a.i. ha^{-1}), pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) showed a slight decrease in control efficiency but still maintained satisfactory to good weed suppression (78–84%, $p < 0.01$), and still resulted in significantly lower SDR values of total weeds ($p < 0.01$). The atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (562.5 g a.i. ha^{-1}), atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (750 g a.i. ha^{-1}), and topramezone treatment at a rate of 52.5 g a.i. ha^{-1} demonstrated high efficacy, achieving 67% weed control ($p < 0.01$), but only up to 60 days after application (DAA). Following this period, the weed control efficiency significantly decreased ($p < 0.01$) from 90 to 210 DAA), likely due to increased rainfall (Figure 1) that may have caused runoff of the herbicide treatment. Moreover, the stand density reduction (SDR) value for this treatment was comparable to that of the untreated (no-weeding) control. These findings suggest that topramezone may not be suitable for effective long-term pre-emergence weed management in this context. Additionally, under the condition at Location II, indaziflam at 62.5 g a.i. ha^{-1} proved to be an effective herbicide treatment throughout the entire critical period, extending the maintenance of weed control until the end at 210 DAA when compared with the herbicide treatment (Figure 4). Moreover, this method yielded the highest net profit compared with the other weed control treatments.

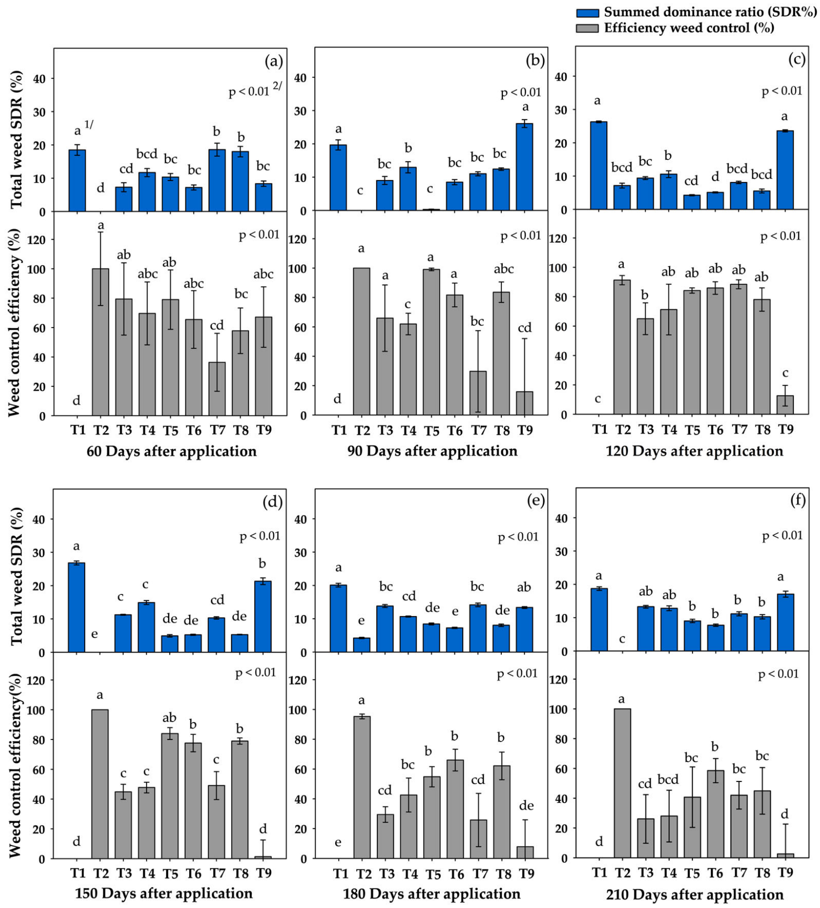

Figure 4. Total weed SDR and weed control efficiency during the critical period of 60 to 210 days after application; 60 DAA (**a**), 90 DAA (**b**), 120 DAA (**c**), 150 DAA (**d**), 180 DAA (**e**), and 210 DAA (**f**). Location II, Nong Han District, Udon Thani Province. T1 = no weeding; T2 = hand weeding at 102, 149, 221, and 305 DAA; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}. 1/ Means followed by the same letter were not significantly different at $p < 0.05$. 2/ significant LSD at $p < 0.01$.

3.3. Summed Dominance Ratio (SDR) During the Critical Period

From Figure 2, it is possible to identify the most dominant weed species, indicated by a high SDR, during the critical period. When the SDR was calculated for each species to determine the distribution of the main weeds in Location I during the critical period, no *D. aegyptium* could be observed at 60, 90, and 120 DAA. This was likely due to the absence of this weed species in the plot during those times, with its presence only beginning to be detected between 150 and 180 DAA.

The use of pre-emergence herbicides, pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), sulfentrazone (875 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}), resulted in the lowest proportion of *D. aegyptium*. In contrast, *D. ciliaris* began to appear from 60 DAA in the treatment without weed control. However, all four herbicide treatments, pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), sulfentrazone (875 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}), were highly effective in controlling *D. ciliaris*, as it was not observed between 60 and 150 DAA. Its presence only reappeared at 180 and 210 DAA, with the SDR remaining quite low during these periods. Therefore, these four weed control treatments were able to effectively manage *D. ciliaris* throughout the entire critical period from 60 to 210 DAA (Figure 5).

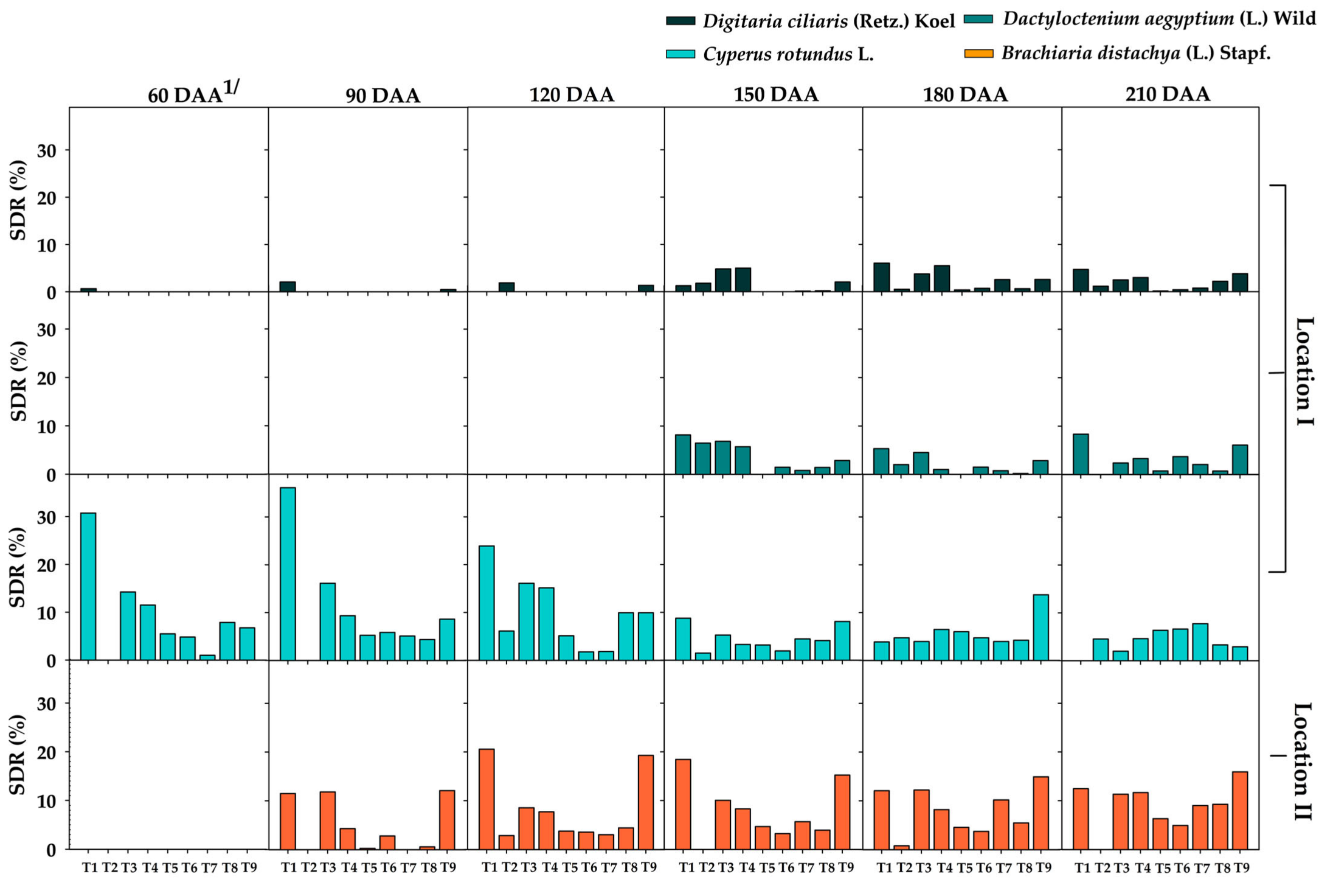

Figure 5. Effect of the nine weed control treatments on the SDR of each dominant weed species during the critical period. Location I: *Digitaria ciliaris* (Retz.) Koel., *Dactyloctenium aegyptium* (L.) and *Cyperus rotundus*. Location II: *Brachiaria distachya* (L.) Stapf. [1/] DAA = days after application; T1 = no weeding; T2 = hand weeding; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}.

The last dominant weed species in Location I, *C. rotundus*, was found to be more abundant than the two previously mentioned species. *C. rotundus* began to appear early in the critical period. The herbicide treatments of pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), sulfentrazone (875 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) significantly reduced both the number and dry weight of this weed, resulting in a low SDR of *C. rotundus* between 60 and 150 DAA (Figure 5). However, from 180 to 210 DAA, the SDR of *C. rotundus* in the no-weeding treatment began to decline, which may have been due to other factors.

In Location II, the dominant weed species, as shown in Figure 2, is *B. distachya*, with the highest SDR. When analysing the SDR of this weed species during the critical period, it was observed that at 60 DAA, no presence of *B. distachya* could be observed in the plot. The weed began to appear at 90 DAA. The treatments resulting in a low SDR of *B. distachya* between 90 and 150 DAA were pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}). These treatments effectively controlled the weed, reducing its number and dry weight, contributing to the low SDR observed during this period (Figure 5).

3.4. Herbicide Phytotoxicity to Sugarcane

Based on the herbicide toxicity assessment for sugarcane, it was observed that sugarcane exhibited toxic symptoms following the application of glufosinate ammonium, a post-emergence herbicide. In both sugarcane fields, toxic symptoms were only seen in treatments such as atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (562.5 g a.i. ha^{-1}) and atrazine (3000 g a.i. ha^{-1}) followed by glufosinate ammonium (750 g a.i. ha^{-1}). In Location I, toxicity appeared at the tips of the lower leaves of the canopy, showing symptoms one day after post-emergence application (158 days after pre-emergence). The symptoms intensified at seven days after post-emergence application (164 days after pre-emergence) and gradually decreased by 14 days after post-emergence application (171 days after pre-emergence) (Table 2). In Location II, sugarcane displayed similar toxic symptoms at the lower leaf tips. Symptoms were clearly visible at seven days after post-emergence application (105 days after pre-emergence), with increasing toxicity observed at 14 days after post-emergence application (112 days after pre-emergence). No phytotoxic symptoms were observed at this later stage, and no such symptoms were detected in sugarcane under any of the other treatments throughout the evaluation period (Table 2).

However, the herbicide toxicity symptoms observed for sugarcane in both locations remained minor, the post-emergence herbicides presenting as slight crop discoloration or stunting, with an estimated severity of 0.01–20.00%. This level is regarded as not adversely affecting sugarcane growth or yield when compared with data obtained from the hand weeding treatment. Additionally, no toxicity symptoms were detected in the pre-emergence herbicide treatments.

Table 2. Phytotoxicity of herbicides to sugarcane in the two experimental fields.

Treatment [1/]	Phytotoxicity of Herbicides to Sugarcane											
	Location I [2/]						Location II [3/]					
	0	1	7	14	21	30	0	1	7	14	21	30
	Days After Post-Emergence Application						Days After Post-Emergence Application					
T1	0.00	0.00 c [4/]	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
T2	0.00	0.00 c	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
T3	0.00	6.25 b	27.50 a	16.25 a	0.00	0.00	0.00	0.00	8.75 a	20.00 a	0.00	0.00
T4	0.00	8.75 a	30.00 a	20.00 a	0.00	0.00	0.00	0.00	10.00 a	25.00 a	0.00	0.00
T5	0.00	0.00 c	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
T6	0.00	0.00 c	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
T7	0.00	0.00 c	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
T8	0.00	0.00 c	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
T9	0.00	0.00 c	0.00 b	0.00 b	0.00	0.00	0.00	0.00	0.00 b	0.00 b	0.00	0.00
F-test	ND [5/]	** [6/]	**	**	ND	ND	ND	ND	**	**	ND	ND

[1/] Nine weed control treatments: T1 = no weeding; T2 = hand weeding; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}. [2/] Location I, Khao Suan Kwang District, Khon Kaen Province. [3/] Location II, Nong Han District, Udonthani Province. In Location I, the post-emergence herbicide was applied at 157 days after pre-emergence applications. The dates for 158, 164, and 171 days after pre-emergence correspond to 1, 7, and 14 days after the post-emergence applications, respectively. In Location II, the post-emergence herbicide was applied 98 days after the pre-emergence applications. The dates for 99, 105, 112, and 120 days after pre-emergence correspond to 1, 7, 14, and 21 days after the post-emergence applications, respectively. [4/] Means followed by the same letter were not significantly different at $p < 0.05$. [5/] not determined. [6/] significant LSD at $p < 0.01$.

3.5. Sugarcane Yield, Yield Components, and Economics

Weed control efficacy during the critical period of 60–210 DAA, characterized by high control levels and low SDR, had a significant indirect effect on the sugarcane yield components in both areas, including the number of canes, cane yield, and sugar yield. Pre-emergence herbicides applied in the study, including pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), sulfentrazone (875 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}), resulted in the highest number of cane stalks per harvested area. Among these, pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}) was particularly effective in suppressing weed competition throughout the critical period, thereby minimising constraints on sugarcane growth and development. Consequently, this treatment yielded the highest number of plants per harvested area, leading to the maximum cane and sugar yields in both experimental locations. All weed control methods contributed to increased stalk and sugar yields per hectare, with no statistically significant differences observed among treatments, except in the case of topramezone (52.5 g a.i. ha^{-1}). Notably, indaziflam (62.5 g a.i. ha^{-1}) produced the highest cane yield per hectare in Location II (Table 3). Specifically, both pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}) and indaziflam (62.5 g a.i. ha^{-1}) promoted superior cane yield components. In terms of production cost, these treatments were comparable to other chemical control methods, yet lower than hand weeding, while still generating the highest net profit (Table 4).

Table 3. Sugarcane yield and yield components at the two locations.

Treatment [1/]	Stalk Length (cm)		Number of Stalk (stalk ha^{-1})				Cane Yield (ton ha^{-1})				Sugar Yield (ton CCS ha^{-1})				CCS [7/]	
	Location I [2/]	Location II [3/]	Location I		Location II		Location I		Location II		Location I		Location II		Location I	Location II
T1	211.51	339.42	28,125	e [5/]	54,688	c	35.98	e	91.49	d	4.78	f	12.37	c	13.50	13.50
T2	240.31	337.83	52,214	abc	80,273	a	85.25	ab	149.65	ab	11.95	a	21.13	a	14.09	14.09
T3	199.84	334.88	43,099	bcd	77,865	a	51.32	d	138.54	abc	7.53	de	20.44	ab	14.72	14.72
T4	214.30	352.15	42,839	cd	74,414	a	50.27	d	134.24	bc	7.00	e	18.78	ab	14.31	14.10
T5	246.46	320.25	56,641	a	76,563	a	86.05	a	147.56	ab	11.94	a	20.52	ab	13.89	13.89
T6	223.54	344.55	52,979	ab	79,427	a	64.07	cd	157.07	a	8.28	cde	20.24	ab	12.93	12.93
T7	217.81	331.95	54,297	a	78,906	a	71.84	bc	144.25	ab	9.71	bc	19.78	ab	13.75	13.75
T8	232.47	340.08	57,031	a	78,386	a	73.24	abc	138.37	abc	10.52	ab	19.83	ab	14.34	14.34
T9	232.44	332.83	39,063	d	64,193	b	61.39	cd	119.18	c	9.18	bcd	17.79	b	14.96	14.96
F-test	ns	ns [4/]	**		** [6/]		**		**		**		**		ns	ns

[1/] Nine weed control treatments: T1 = no weeding; T2 = hand weeding; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}. [2/] Location I, Khao Suan Kwang District, Khon Kaen Province. [3/] Location II, Nong Han District, Udon Thani Province. [4/] = non-significant. [5/] Means followed by the same letter were not significantly different at $p < 0.05$. [6/] significant LSD at $p < 0.01$, [7/] CCS = commercial cane sugar.

Table 4. Production costs and net profit of sugarcane production at the two locations.

Treatment [1/]	Cost of Production (USD ha^{-1})		Total Income (USD ha^{-1})		Net Profit (USD [4/] ha^{-1})	
	Location I [2/]	Location II [3/]	Location I	Location II	Location I	Location II
T1	1440.08	1790.28	1377.52	3726.29	−62.56	1936.02
T2	2616.26	2941.65	3338.67	5992.32	722.41	3050.67
T3	1685.43	2245.41	2022.56	5621.46	337.12	3376.05
T4	1690.53	2227.98	1927.63	5429.03	237.10	3201.05
T5	2081.60	2383.69	3380.11	6125.57	1298.51	3741.88
T6	1769.44	2349.15	2301.03	6628.51	531.60	4279.36
T7	1856.59	2267.14	2639.07	5985.56	782.48	3718.42
T8	1888.01	2241.17	2931.44	5437.48	1043.44	3196.31
T9	1775.92	2096.00	2490.93	4881.33	715.01	2785.33

[1/] Nine weed control treatments: T1 = no weeding; T2 = hand weeding; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}, [2/] Location I, Khao Suan Kwang District, Khon Kaen Province. [3/] Location II, Nong Han District, Udon Thani Province. [4/] USD = United States dollars in 2021.

3.6. Correlations Between Weed Control Efficiency and Sugarcane Yield

The correlation analysis between weed control efficacy and sugarcane yield revealed that, in Location I, cane yield was positively and significantly correlated with manual weeding and with the application of highly effective herbicides during the critical period at 60, 90, 120, 150, 180, and 210 days after herbicide application (r = 0.84, r = 0.86, r = 0.80, r = 0.73, r = 0.88, and r = 0.82, respectively; $p < 0.01$). Similarly, in Location II, cane yield exhibited strong positive and significant correlations with manual weeding and with the application of effective herbicides during the same critical periods (r = 0.72 and r = 0.81, r = 0.94, r = 0.85, r = 0.78, and r = 0.76, respectively; $p < 0.01$). These results indicate that effective weed management during the critical period contributes to increased sugarcane yield at harvest. (Figure 6).

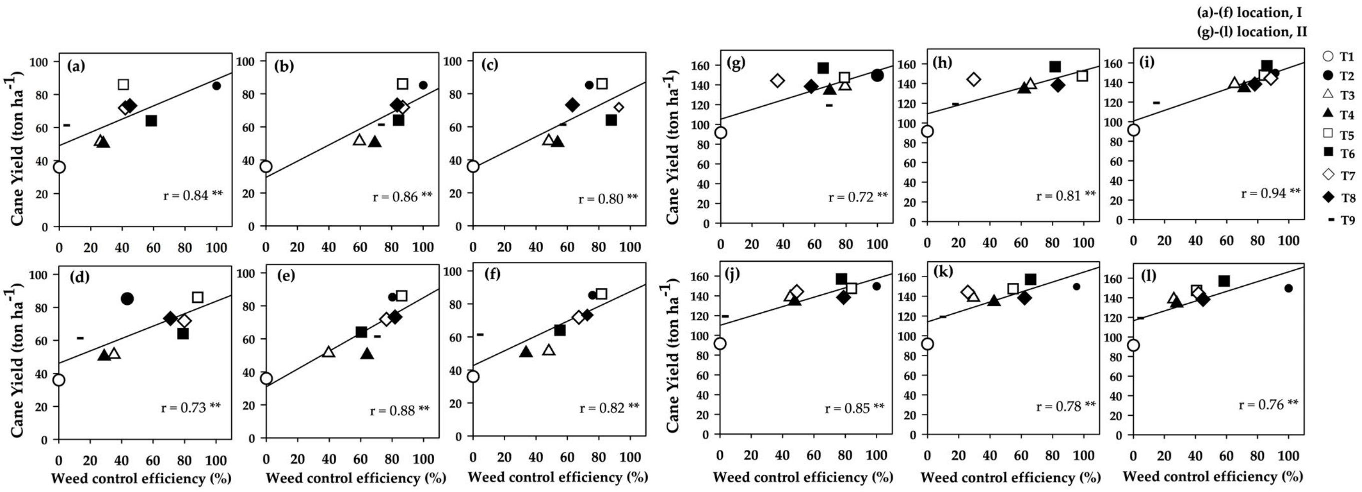

Figure 6. Correlation between weed control efficiency during the critical period (60–210 days after application [DAA]) and sugarcane yield at the harvest stage for Location I, Khao Suan Kwang District, Khon Kaen Province and Location II, Nong Han District, Udon Thani Province; (**a**,**g**) 60, (**b**,**h**) 90, (**c**,**i**) 120, (**d**,**j**) 150, (**e**,**k**) 180, and (**f**,**l**) 210 DAA; ** significant at $p < 0.01$. T1 = no weeding; T2 = hand weeding; T3 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 562.5 g a.i. ha^{-1}; T4 = atrazine at 3000 g a.i. ha^{-1} fb glufosinate ammonium at 750 g a.i. ha^{-1}; T5 = pendimethalin + imazapic at 825 + 75 g a.i. ha^{-1}; T6 = indaziflam at 62.5 g a.i. ha^{-1}; T7 = sulfentrazone at 875 g a.i. ha^{-1}; T8 = indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}; T9 = topramezone at 52.5 g a.i. ha^{-1}.

4. Discussion

4.1. Dominant Weeds in Sugarcane Fields

An analysis of weed distribution across the fields revealed that in Location I, the dominant species were *D. aegyptium*, *C. rotundus*, and *D. ciliaris*. In Location II, *B. distachya* was prevalent (Figure 2). The high density and dry weight of these weeds contributed to elevated weed importance values, indicating the abundance of these species [44]. The presence of these four weed species was previously documented across sugarcane plantations in Thailand's central, western, eastern, and northeastern regions. This widespread distribution explains why these four dominant weed species were found in both Locations I and II of the sugarcane fields [45]. Similarly, Aekrathok et al. [19] reported that *D. aegyptium*, *D. ciliaris*, and *B. distachya* were highly abundant at sugarcane fields in Khon Kaen Province, Northeastern Thailand.

4.2. Assessment of Weed Control Effectiveness

Weed control involves implementing strategies to reduce weed competition and prevent outbreaks [46]. The SDR of pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), sulfentrazone (875 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) treatments result indicated that the percentage of weed control differed across critical periods, reflecting the herbicides' effectiveness during these times. Combined pendimethalin and imazapic showed high weed control efficacy in both locations, suggesting its suitability for effective weed management in sugarcane crops.

A study on the effectiveness of the pendimethalin rate of 900 g a.i. ha^{-1} demonstrated its success in controlling the dominant narrowleaf weed, *Phalaris minor*, with a reduction of up to 70.92% at 60 days after sowing (DAS). However, it was less effective against broadleaf weeds at the same stage [47]. Furthermore, the experimental results indicated that the combination of pendimethalin with an imazapic rate of 825 + 75 g a.i. ha^{-1} was highly effective in controlling key narrowleaf weeds, namely *D. aegyptium* and *D. ciliaris* in Location I, and *B. distachya* in Location II. Additionally, the consistently low SDR throughout the critical period (Figures 3 and 4) suggests that the density and dry weight of the main weeds could be significantly reduced compared to hand weeding treatment (Figure 5). Nevertheless, from 180 to 210 DAA, the SDR of *C. rotundus* in the no-weeding treatment began to decrease, potentially due to other factors. During the elongation stage, sugarcane growth covers the ground area, and canopy development decreases light penetration to the soil surface [48] and thereby suppresses weed growth [49].

In the treatment pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), imazapic is used in combination due to its specific mode of action. In sugarcane plantations, imazapic is employed to control *Cyperaceae* species, with application rates of 60–120 g ha^{-1} effectively reducing the leaf and tuber density, biomass, and viability of *C. rotundus* [15,50]. Consequently, in the sugarcane plot at Location I, imazapic helps to enhance the control of sedge weed like *C. rotundus*. Additionally, the post-emergence application of imazapic at 36 g ha^{-1} has achieved 92% control of the narrowleaf weed *Digitaria sanguinalis* in maize fields [51]. Therefore, applying imazapic at the rate of 75 g a.i. ha^{-1} improved the overall effectiveness of the herbicide combination pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}). This enhanced weed control targets both common weeds and dominant sedge and narrowleaf weed species in Location I, as well as the narrowleaf weeds predominant in sugarcane fields at Location II (Figure 5).

Additionally, the treatment combining indaziflam and sulfentrazone—comprising indaziflam at 62.5 g a.i. ha^{-1}, sulfentrazone at 875 g a.i. ha^{-1}, and indaziflam + sulfentrazone at 46.88 + 750 g a.i. ha^{-1}—was effective in controlling total weeds and reducing the SDR of total weeds and major weeds in both sugarcane fields. Weeds in the Poaceae family, including *Digitaria horizontalis*, *Sorghum halepense*, *Urochloa plantaginea*, and *Eleusine indica*, have been found to be more sensitive to indaziflam than broadleaf weeds [52]. Furthermore, applying indaziflam at 75 g a.i. ha^{-1} proved highly effective in controlling annual bromegrasses, *Bromus squarrosus* L. and *Bromus tectorum*, reducing biomass and density by over 90%, with residual effects lasting up to three years [53]. In addition, indaziflam at a rate of 29 g a.i. ha^{-1} resulted in the complete death of *C. rotundus* by 87 days after treatment (DAT), with the herbicide capable of regulating up to 50% of the root mass and 80% of the shoot mass [54].

Sulfentrazone effectiveness has been demonstrated in controlling sedge weeds, particularly *C. rotundus*, which was the dominant weed in Location I. Sulfentrazone, applied at 800 g a.i. ha^{-1}, was highly effective in controlling weed richness in the sugarcane fields under study, although its effectiveness lasted only up to 45 days after planting. At the same rate, sulfentrazone significantly reduced the epigeal emergence of *C. rotundus*, with the control rate ranging from 79 to 97% depending on weed density per square meter [36,55]. Additionally, sulfentrazone has been shown to inhibit tuber development, with its application at 768 g a.i. ha^{-1} being capable of reducing the number of aerial parts and increasing the number of dead *C. rotundus* tubers. Furthermore, at 15 and 35 DAA, the tubers' dry matter and emergence numbers were reduced. Sulfentrazone was applied at the rate of 350 g a.i. ha^{-1} for 28 days after treatment resulted in a 44% reduction in final tuber weight compared to untreated *C. rotundus* [56,57]. Moreover, sulfentrazone at the rate of 800 g a.i. ha^{-1} is effective against certain narrowleaf weeds in the Poaceae family, such as *Urochloa decumbens*, with control efficiency ranging from 81.2 to 100% and with significant reductions observed in shoot dry mass. These control percentages and biomass reductions are higher than those observed for *Cenchrus echinatus* and *D. horizontalis*, and also higher than those seen for narrowleaf weeds within the same Poaceae family [58]. However, in some cases, a higher rate of sulfentrazone (576 g a.i. ha^{-1}) has shown relatively low efficacy against *C. echinatus*, indicating that herbicides can be selective and may not uniformly control all weeds within the same species or family [59].

The results regarding the efficacy of sulfentrazone align with the findings from both sugarcane fields, demonstrating that the herbicide was highly effective in controlling a wide range of weeds (Figures 3 and 4). In both sugarcane fields, narrowleaf grasses were the most prevalent weeds, while sedge was the dominant weed in Location I. Sulfentrazone significantly reduced the number and dry weight of the main narrowleaf weeds, resulting in a low SDR (Figure 5) during the critical growth period. Overall, sulfentrazone (875 g a.i. ha^{-1}) demonstrated excellent weed control performance.

The previous research reported in Ma et al. [60] indicated that post-emergence application of topramezone at 36.0 g a.i. ha^{-1} applied post-emergence effectively controlled both common grass and broadleaf weeds in sugarcane including *Cynodon dactyl*, *Eleusine indica*, *Solanum nigrum*, and *Amaranthus viridis*. Furthermore, the combined application of topraezone + atrazine (67.2 g a.i. ha^{-1} + 0.9 kg a.i. ha^{-1}) provided high-control *Cynodon dactylon* during 19–40 days after application, whereas only atrazine (0.9 kg a.i. ha^{-1}) resulted in the low control of *Cynodon dactylon* [61]. Consistent with this experiment in Figure 4, atrazine treatments (T3 and T4), and topramezone (T9) exhibited low-control weed during 90 DAA. However, specific research on the effect of topramezone on *C. rotundus* in sugarcane is limited. Under field conditions, the half-life of topramezone ranges from 10.8 to 69.3 days [62]. Loddo et al. [63] suggested that *C. rotundus* had a short life cycle of 3–6 weeks (21–42 days); afterward, it damages the below-ground parts. The rhizome of *C. rotundus* have a mechanism that inhibits the development of apical dominance [64]. In addition, these tubers can survive under low temperatures up to −10 °C and undergo a regenerative phase throughout summer seasons [65]. Therefore, this half-life of topramezone enables the effective control of *C. rotundus* in sugarcane. Otherwise, sugarcane occurred at low levels *C. rotundus*, whereas *Eleusine indica* persisted after 180 DAA in this experiment. Because of *Eleusine indica* competition for growth factors and as canopy covers the soil surface, other weeds are prevented from receiving full light. These findings are consistent with Souza et al. [66], who showed that *Digitaria ciliaris* has a higher leaf area and growth rate than *Digitaria nuda*, indicating a greater efficiency in converting light energy into carbohydrates. However, comparisons of growth rates between *D. ciliaris* and other weed species have not been reported. Additionally, *D. ciliaris* may have allelopathic effects. This not only occurs on crops, such as cucumbers, but also on other weeds [67]. In this research, topramezone treatment showed lower sugarcane yield than other herbicide treatments (Figure 6). The similar response seen in the work of Ducca et al. [61] demonstrated that the combination of topramezone + atrazine reduced tiller number compared to hand weed control. In contrast, topramezone herbicide was found to be safe for sugarcane cultivars [60]. Topramezone applied alone at rate of 25 and 50 g ai ha^{-1} displayed no responses on chlorophyll fluorescence, and total chlorophyll, which did not affect to yield in sugarcane [32]. Thus, the reduction in sugarcane productivity under topramezone treatment is more likely attributed to insufficient weed control rather than direct herbicide toxicity to the crop.

Sugarcane cultivation under the rainfed system in Northeastern Thailand is greatly affected by prolonged drought conditions during the early growth stage. In most parts of the northeastern region, the dry season begins in November, with monthly rainfall remaining below 40 mm. During December and January, there is virtually no rain. However, in February, considered to be the middle of the dry season, some rainfall occurs [68]. This pattern is consistent with the observed rainfall after 60 DAA or in February in both experimental plots (Figure 1). Consequently, it is reasonable to conclude that the critical period for sugarcane growth begins around 60 DAA, coinciding with the onset of rain (Figure 1). The increased soil moisture during this period is likely a key factor stimulating weed seed germination. Studies have shown that soil water content significantly influences the germination of grass and forb seeds in grasslands [69]. In the northeastern region, competition between sugarcane and weeds intensifies at the start and end of the rainy season (April and October), as the canopy develops and begins to block sunlight between the rows. This shading delays the onset of competition between the crop and weeds. Furthermore, herbicides with longer half-lives persist in the soil for a longer period than those with short half-lives, which can extend their period of weed control [70].

The half-life of herbicides varies depending on soil temperature and moisture content. For pendimethalin, the half-life ranges from 44 to 101 days. Imazapic has an average half-life of approximately 120 days; that of indaziflam exceeds 150 days; and the half-life of sulfentrazone ranges from 121 to 302 days [23]. Given these relatively long half-lives, it takes a significant amount of time for half the active ingredients to degrade. These values are consistent with the observed high weed control efficacy. Herbicide applications with all four herbicides remained highly effective under loamy sand soil conditions with cumulative precipitation 1–210 days after the pre-emergence application of 426.60 mm in Location I, and under sandy loam soil conditions with cumulative precipitation 1–210 days after the pre-emergence application of 590.60 mm in Location II, with lower SDR values for all weeds and dominant weeds throughout the critical period (60–210 DAA) in both sugarcane plots (Figures 3–5).

4.3. Toxicity of Herbicides to Sugarcane

Based on the herbicide toxicity assessment results for sugarcane, no toxicity symptoms were observed following pre-emergence applications. However, toxicity symptoms were evident after the use of the post-emergence herbicide glufosinate ammonium at both tested rates. It remains to be determined whether repeated exposure to glufosinate ammonium exerts cumulative effects on sugarcane health and yield across multiple growing seasons [71]. Glufosinate can be applied post-emergence at rates ranging from 0.35 to 1.7 kg a.i. ha^{-1} (0.32 to 1.56 kg acid equivalent [ae] ha^{-1}) in non-crop areas and as a directed spray in field-grown and nursery stock. It is non-selective and effective against a broad spectrum of broadleaf weeds, as well as annual and perennial grasses [23]. According to reports, short-term phytotoxicity tests showed that glufosinate applied at 166.88 g a.i. ha^{-1} affected maize, reducing biomass by over 50% compared to untreated controls [71].

However, in both sugarcane field experiments (Table 2), sugarcane exhibited toxic symptoms following the application of glufosinate. The symptoms were only observed on the lower leaves of the canopy directly exposed to the aerosol, displaying chlorosis due to the herbicide's mechanism of action.

4.4. Crop Yield and Its Components

4.4.1. Difference in Sugarcane Yield Between Locations I and II

The observation that Location II tends to produce more sugarcane than Location I indicates that the use of pre-emergence and post-emergence herbicides is not the sole factor influencing yield. Placing greater emphasis on other potential contributing factors e.g., rainfall or irrigation, soil type, and crop management practices, would offer a more comprehensive interpretation of the results. Plant growth is strongly influenced by rainfall intensity and distribution, as high-intensity rainfall events play a critical role in replenishing soil water reserves, mitigating drought stress, and enhancing nitrogen uptake [72]. The rainfall intensity values in both locations were consistent with the standardized precipitation index (SPI). In 2021, Location I (Khon Kaen Province) was more prone to drought due to its lower SPI compared to Location II (Udon Thani Province) [73]. This difference is associated with rainfall intensity and distribution, corresponding to both the accumulated rainfall during the critical period and the total rainfall throughout the growing season (late 2020 to the end of 2021). The accumulated rainfall in Location II (Udon Thani Province) was 590.60 mm during the critical period and 1386.60 mm for the entire growing season, values which were both higher than those observed in Location I (Khon Kaen Province), at 426.60 mm and 1138.80 mm, respectively (Figure 1). This lower rainfall exposure in Location I was a contributing factor to the significantly lower sugarcane yields observed compared to Location II. Adequate soil moisture promotes canopy development, which helps shade out weeds and reduces competition. Furthermore, soil type affects water retention and, consequently, the amount of plant-available water (PAW). Research has demonstrated that soils with higher clay content tend to retain more water and maintain higher residual moisture levels compared to sandy soils with lower clay content [74].

Additionally, water stress significantly reduces the leaf area index (LAI), as it is closely related to the soil water content and the rate at which leaf area per shoot declines [75]. This reduction can influence canopy development, thereby decreasing light competition with weeds and impacting overall productivity. Similarly, the soil at sugarcane Location II contains 7.34% clay, which is higher than the 1.87% clay found in Location I. When rainfall occurs during the critical period, the sugarcane in Location II tends to have a greater capacity for water absorption, leading to faster canopy development.

Moreover, when plants grow more vigorously than weeds, they can absorb nutrients more effectively, which is another factor that influences crop yield [76]. This likely contributed to the higher sugarcane yield measured by the stalk number, cane yield, and sugar yield in Location II compared to Location I (Table 3). During the critical growth period, the dense growth and canopy development of sugarcane can block a significant amount of light in the inter-row areas, affecting the photosynthesis of weeds in those regions. Light plays a crucial role in photosynthetic carbon assimilation and variations in light quality and intensity significantly impact C4 photosynthesis, requiring coordinated activity between the mesophyll and bundle sheath cells. This is supported by experimental findings showing that prolonged shading reduces the chlorophyll content in maize leaves, and low light intensity decreases photosynthetic activity [77,78]. In both sugarcane locations, the dominant weeds were C4 plants, which exhibited better growth and canopy development in Location II than in Location I. This minimized competition between sugarcane and weeds during and after the critical period, likely contributing to higher sugarcane yields at harvest across all treatments (Table 3).

4.4.2. Impact of Weed Control on Sugarcane Yield

Herbicides greatly enhanced the growth, yield, and quality of sugarcane compared to the untreated control, while also improving weed management effectiveness [79]. The use of pre-emergence herbicides has demonstrated high control efficiency at 60 and 90 DAA, leading to improved yield characteristics and increased sugarcane production [80]. For example, pendimethalin, a pre-emergence herbicide, was found to increase sugarcane yields, and when combined with other herbicides, the yields were comparable to those achieved through hand weeding [81]. The application of sulfentrazone at the rate of 800 g a.i. ha^{-1} provided excellent weed control, with *C. rotundus* being the dominant species, along with other weeds, during the first 15 to 45 DAP [55]. However, despite higher sugarcane yield at 240 DAP with herbicide treatment, it was still significantly lower than yields obtained through dedicated weed control methods.

The above report indicates a consistent correlation between high weed control efficiency and increased sugarcane production in both locations (Figure 6). Treatments involving pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}), indaziflam (62.5 g a.i. ha^{-1}), sulfentrazone (875 g a.i. ha^{-1}), and indaziflam + sulfentrazone (46.88 + 750 g a.i. ha^{-1}) demonstrated high efficacy in weed control during the critical period, contributing to a reduction in weed density and consequently the intensity of competitive growth. Thus, effective weed control is an indirect factor contributing to high sugarcane yield.

Moreover, the presence of *D. aegyptium*, *C. rotundus*, and *D. ciliaris* as the dominant and widely dispersed weed species in Location I resulted in a 58.19% reduction in cane yield (ton ha^{-1}) and a 104.82% loss in profit when comparing treatments with the highest and lowest weed control efficiency. Similarly, the occurrence of only *B. distachya* as the dominant species in Location II caused a 38.86% reduction in cane yield (ton ha^{-1}) and a 54.76% decrease in profit under the same comparison. These findings are consistent with Mobarak et al. [2], which reported that ineffective weed control leads to reduced sugarcane yield and decreased profitability.

5. Conclusions

Weed management under rainfed sugarcane cultivation indicated that a single application of pre-emergence herbicide after planting was sufficient to maintain effective weed control throughout the critical period. The application of pendimethalin + imazapic (825 + 75 g a.i. ha^{-1}) markedly reduced the dominance of *D. ciliaris*, *D. aegyptium*, while *C. rotundus* was associated with the highest sugarcane yield and net profit under loamy sand soil conditions with accumulated rainfall of 1138.8 mm during the growing season. Similarly, indaziflam (62.5 g a.i. ha^{-1}) effectively suppressed *B. distachya* and generated both the best sugarcane yield and the highest net profit under sandy loam soil with accumulated rainfall of 1386.6 mm. This weed management strategy may be applicable to sugarcane production systems in other regions characterized by comparable climatic conditions and similar dominant weed species. However, the application of all three herbicides should adhere to the recommended rates in order to minimize herbicide accumulation and residues in sugarcane fields. In addition, prolonged reliance on the same herbicides within a given area should be avoided. The incorporation of alternative herbicides with different modes of action is recommended to mitigate the risk of herbicide resistance development in weed populations in the future.

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