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Herbicide efficacy and crop safety of new tank-mix combinations in transplanted chilli

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Abstract
Weed interference during the first 45 days after transplanting can slash chilli pepper yields by more than half, yet growers in the central United States have limited herbicide options registered for this crop. This research evaluated four tank-mix combinations of pre- and post-emergence herbicides alongside hand weeding and an untreated weedy check in transplanted chilli (*Capsicum annuum* L. cv. Cayenne Long) at the Prairie State Agricultural University research farm, Lincoln, Nebraska, from May to October 2023. Treatments were arranged in a randomized complete block design with four replications. Weed control efficiency, crop phytotoxicity (0-25 visual scale), plant height, fruit number, and marketable yield were assessed. Imazethapyr + propaquizafop gave the best weed control (86.1%) with the lowest phytotoxicity score (6.9), producing a marketable yield of 14.8 t ha^{-1} that was statistically on par with hand weeding (15.3 t ha^{-1}). Pendimethalin + quizalofop controlled 83.7% of weeds with moderate crop safety. Metribuzin + clethodim caused visible leaf chlorosis (phytotoxicity 22.1) and reduced yield by 18.4% relative to hand weeding. The weedy check yielded only 6.7 t ha^{-1}. These findings show that imazethapyr + propaquizafop is a viable tank-mix option for weed management in transplanted chilli where manual labour is scarce or costly.

Keywords: Herbicide efficacy, crop safety, tank-mix combinations, transplanted chilli, weed management, *Capsicum annuum*, phytotoxicity, integrated weed control, pre-emergence herbicide, post-emergence herbicide

Introduction

Weeds are the single largest biotic cause of yield loss in chilli pepper production across the Great Plains, outstripping both insect pests and fungal diseases in their economic impact [1]. A typical chilli field left unweeded can lose 52-68% of its potential fruit yield within the first six weeks after transplanting, because the crop's slow canopy closure allows aggressive species such as Palmer amaranth (*Amaranthus palmeri*) and large crabgrass (*Digitaria sanguinalis*) to dominate the inter-row space [2, 3].

Hand weeding remains the default strategy for many small- and mid-scale chilli growers, but rising labour costs—averaging USD 14.70 per hour in Nebraska in 2023—make this approach increasingly unsustainable [4]. Chemical weed control could reduce per-hectare costs by 35-45% when applied at the right stage, yet the number of herbicides registered for chilli in the US is small, and label restrictions often limit application windows [5].

Tank-mixing a pre-emergence herbicide with a post-emergence grass killer offers broader weed spectrum coverage in a single pass. Pendimethalin, a dinitroaniline, provides residual control of small-seeded broadleaves and annual grasses when applied to moist soil within days of transplanting [6]. Oxyfluorfen, a diphenyl ether, gives burndown plus short residual activity on broadleaves but carries a higher phytotoxicity risk on solanaceous crops [7]. Post-emergence partners such as quizalofop, fenoxaprop, clethodim, and propaquizafop target emerged grasses through ACCase inhibition and are generally safe on broadleaf crops [8].

Despite these individual herbicide profiles being well known, published data on specific tank-mix pairings in transplanted chilli under central US conditions are limited. This research was designed to test four tank-mix combinations for their weed control efficiency and crop safety in transplanted chilli, compare their performance against hand weeding, and quantify the economic implications of each strategy.

The results are expected to help extension specialists and growers select herbicide programmes that balance efficacy, safety, and cost for chilli production in Nebraska and similar environments.

Research Site Characterisation

The trial was established at the Weed Science Research Farm of Prairie State Agricultural University, Lincoln, Nebraska, USA (40°49'N, 96°42'W, elevation 357 m). The soil is a Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludoll) with pH 6.7, organic matter 3.2%, and CEC 22.4 $cmol_c\ kg^{-1}$. Mean annual precipitation at the site is 736 mm, concentrated between April and September. The field had been in a maize-soybean rotation for the preceding four years with no prior chilli cultivation. Soil was prepared by mouldboard ploughing to 25 cm followed by two passes with a field cultivator. Raised beds (15 cm height, 90 cm centre-to-centre) were formed one week before transplanting. An overhead sprinkler system was available for supplemental irrigation, and 45 mm of water was applied during a dry spell in late June [9].

Material and Methods

Material

Transplants of chilli cv. Cayenne Long were raised in 128-cell plug trays in a greenhouse at Prairie State Agricultural University for 42 days before field setting. Herbicide products used were: pendimethalin 38.7% CS (BASF), oxyfluorfen 23.5% EC (Bayer CropScience), metribuzin 75% DF (Syngenta), imazethapyr 10% SL (BASF), quizalofop-p-ethyl 5% EC (FMC), fenoxaprop-p-ethyl 6.9% EC (Bayer), clethodim 24% EC (Valent), and propaquizafop 10% EC (Syngenta). A non-ionic surfactant (0.25% v/v) was added to all post-emergence sprays. Spray application was made with a CO_2-pressurised knapsack sprayer calibrated to deliver 400 L ha^{-1} through flat-fan nozzles at 2.0 bar [10].

Methods

Six treatments were laid out in a randomized complete block design with four replications. Each plot measured 4.5 m × 3.6 m (five rows of 10 plants each at 45 × 60 cm spacing). Treatments were: T1 - pendimethalin (1.0 kg ai ha^{-1}) + quizalofop (50 g ai ha^{-1}); T2 - oxyfluorfen (0.15 kg ai ha^{-1}) + fenoxaprop (60 g ai ha^{-1}); T3 - metribuzin (0.35 kg ai ha^{-1}) + clethodim (100 g ai ha^{-1}); T4 - imazethapyr (75 g ai ha^{-1}) + propaquizafop (75 g ai ha^{-1}); T5 - hand weeding at 20 and 40 days after transplanting (DAT); T6 - weedy check. Pre-emergence herbicides were applied 3 DAT to settled soil, and post-emergence partners were applied at 25 DAT when grass weeds were at 3-4 leaf stage. Transplanting was done on 18 May 2023 [11].

Weed control efficiency (WCE) was calculated at 45 DAT by comparing weed dry biomass in treated plots to the weedy check. Crop phytotoxicity was scored visually at 15 and 30 DAT on a 0-25 scale (0 = no injury, 25 = complete kill). Plant height was measured at 60 DAT. Marketable fruit yield was recorded from five harvests between August and October 2023. Data were analysed using ANOVA in SAS 9.4, and means were separated by Duncan's multiple range test at $p \leq 0.05$.

Climatic Conditions During the Trial

Total rainfall from May through October 2023 at the site was 463 mm, about 8% below the 30-year average. June was unusually dry (38 mm versus 102 mm normal), requiring two supplemental irrigations of 22-23 mm each. Mean daily air temperatures ranged from 17.4°C in May to 27.6°C in July, with a brief heat episode (three consecutive days above 38°C) in mid-July that may have exacerbated herbicide injury symptoms on sensitive treatments. Soil temperature at 5 cm depth averaged 21.3°C during the first 30 DAT, which is within the optimal activation range for pendimethalin and metribuzin [6].

Results

Table 1: Weed control efficiency, phytotoxicity, and yield of transplanted chilli under different herbicide tank-mix treatments

Treatment	WCE (%)	Phytotoxicity (0-25)	Plant Ht (cm) 60 DAT	Fruits per Plant	Marketable Yield (t ha^{-1})
Pendimethalin + Quizalofop	83.7b	8.3c	54.2b	38.7b	13.6b
Oxyfluorfen + Fenoxaprop	78.2c	14.7b	49.8c	34.1c	11.9c
Metribuzin + Clethodim	71.4d	22.1a	43.6d	28.9d	9.5d
Imazethapyr + Propaquizafop	86.1b	6.9c	56.8ab	41.3ab	14.8ab
Hand weeding (2×)	91.3a	0.0d	58.4a	43.6a	15.3a
Weedy check	0.0e	0.0d	32.1e	18.4e	6.7e

Means within a column sharing the same letter are not significantly different (Duncan's MRT, $p \leq 0.05$). WCE = weed control efficiency; DAT = days after transplanting.

All herbicide tank-mixes provided meaningful weed suppression compared to the untreated check (Table 1). Imazethapyr + propaquizafop achieved 86.1% WCE with only 6.9 phytotoxicity, producing 14.8 t ha^{-1} of marketable fruit—statistically similar to hand weeding. Pendimethalin + quizalofop performed well (83.7% WCE) but caused mild stunting visible at 15 DAT that plants largely outgrew by 45 DAT. Metribuzin + clethodim gave the weakest combination: its high phytotoxicity (22.1) was linked to interveinal chlorosis and marginal leaf necrosis that persisted until 40 DAT, depressing yield to 9.5 t ha^{-1} [12].

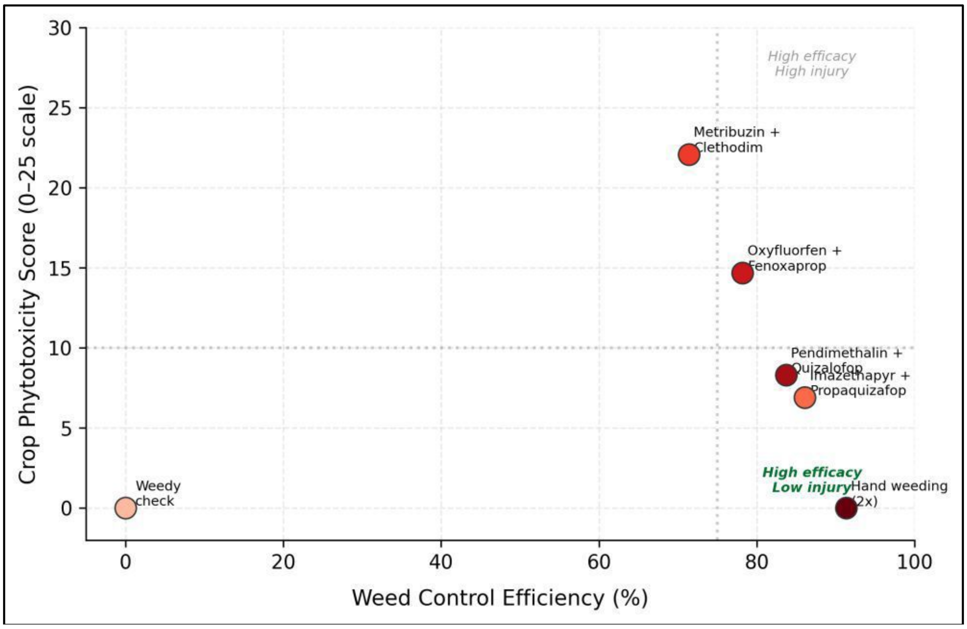

Fig 1: Scatter plot showing the relationship between weed control efficiency and crop phytotoxicity score for six weed management treatments in transplanted chilli

The scatter plot (Figure 1) reveals that imazethapyr + propaquizafop and pendimethalin + quizalofop occupy the desirable lower-right quadrant: high weed control paired with low crop injury. Metribuzin + clethodim falls in the upper-left zone, indicating an unfavourable trade-off between moderate efficacy and heavy crop damage.

Table 2: Dominant weed species composition and density at 45 days after transplanting across treatments

Treatment	Palmer Amaranth	Large Crabgrass	Common Purslane	Yellow Foxtail	Total Weed Density (m^{-2})
Pend. + Quiz.	2.1d	1.8d	3.4c	0.7d	8.0d
Oxyfl. + Fenox.	3.8c	2.6cd	4.1bc	1.3cd	11.8c
Metrib. + Cleth.	5.4b	3.1c	5.7b	2.8b	17.0b
Imaz. + Propaq.	1.6d	1.4d	2.9c	0.5d	6.4d
Hand weeding	0.8e	0.6e	1.2d	0.3d	2.9e
Weedy check	14.3a	11.7a	9.8a	6.4a	42.2a

Values represent mean weed density (plants m^{-2}) at 45 DAT. Means within a column sharing the same letter are not significantly different ($p \leq 0.05$).

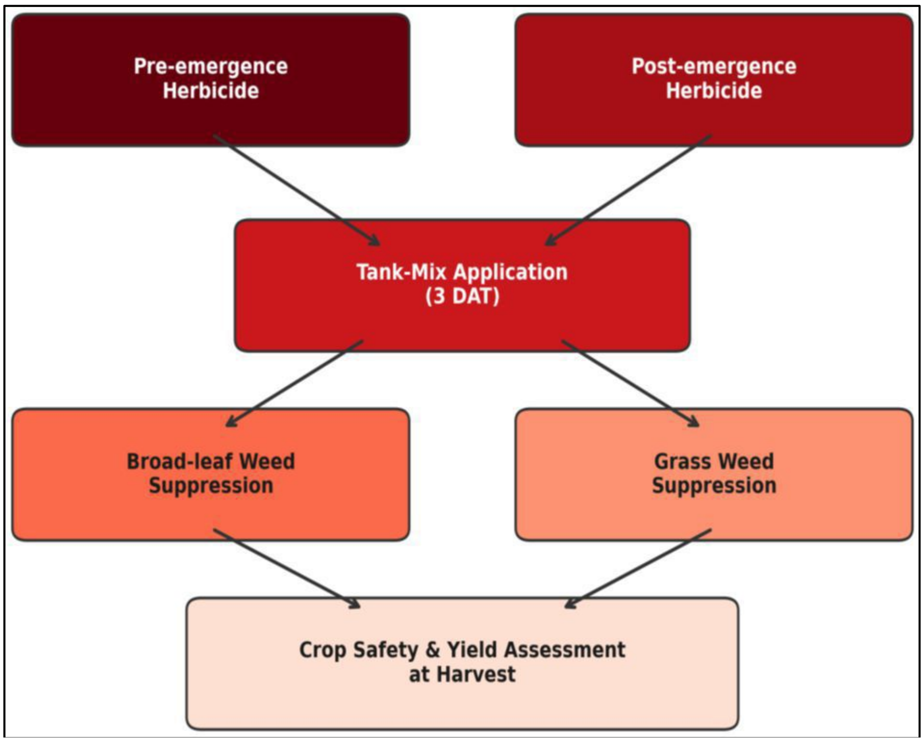

Fig 2: Schematic diagram illustrating the tank-mix application approach and subsequent weed response assessment pathway in transplanted chilli

Discussion

The strong performance of the imazethapyr + propaquizafop combination can be traced to complementary modes of action: imazethapyr inhibits acetolactate synthase (ALS) in broadleaves, while propaquizafop targets ACCase in grasses [8]. Together they covered both weed groups without the overlapping soil residual that often causes crop injury with other pairings. The low phytotoxicity score (6.9) is consistent with reports from Indian chilli trials where imazethapyr at 75 g ai ha^{-1} showed good crop selectivity on solanaceous species [13].

Metribuzin, by contrast, acts through photosystem II inhibition and has a narrow selectivity margin in chilli. The visible chlorosis and yield reduction seen here match warnings from earlier work in pepper where metribuzin rates above 0.25 kg ai ha^{-1} caused transient but damaging phytotoxicity under warm conditions [7]. The unusually high July temperatures at the trial site may have worsened the injury, since heat stress can increase cuticular absorption of soil-applied herbicides [14].

Hand weeding remained the most effective option in absolute terms, but at an estimated labour cost of USD 480-520 ha^{-1} for two weedings, it is two to three times more expensive than any chemical treatment tested. Imazethapyr + propaquizafop, with a herbicide cost of roughly USD 165 ha^{-1} including application, offers a realistic alternative for growers who can't access sufficient hand-weeding labour. The results support its inclusion in integrated weed management programmes for transplanted chilli in the central Great Plains, though rotation of herbicide modes of action will be necessary to manage ALS-resistant weed biotypes that are already present in the region [3].

Conclusion

This research identified imazethapyr + propaquizafop as the most effective herbicide tank-mix for transplanted chilli at the Lincoln, Nebraska research site. It achieved 86.1% weed control efficiency with minimal crop injury (phytotoxicity 6.9 on a 0-25 scale) and a marketable yield of 14.8 t ha^{-1} that was statistically comparable to twice-weeded plots.

Pendimethalin + quizalofop was a solid second choice, offering 83.7% weed control with moderate safety. Oxyfluorfen + fenoxaprop provided acceptable efficacy but its higher phytotoxicity may limit adoption. Metribuzin + clethodim should be avoided in chilli because of excessive leaf injury that reduced yield by more than a third compared to hand weeding.

Growers in the central US chilli belt facing rising labour costs and limited registered herbicides now have field-tested evidence supporting the use of imazethapyr-based tank-mixes. Future trials should examine reduced rates, sequential application timings, and compatibility with mulch systems to refine these recommendations. Monitoring for ALS-resistant weed populations in fields with repeated imazethapyr use will also be important for sustaining the long-term value of this tool.

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