https://doi.org/10.17221/32/2025-PPS

A green approach: Effects of organic weed control on weed diversity and phenology

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Citation: Kumar S., Rana S.S., Hetta G., Rana N., Avila-Quezada G.D., Dewidar A., Mattar M.A. (2026): A green approach: Effects of organic weed control on weed diversity and phenology. Plant Protect. Sci.: 280−292.

Abstract: A long-term experiment in the maise-pea cropping system was conducted in Palampur from October 2019 to September 2021 as part of the All India Coordinated Research Project on Weed Management (AICRP-WM). Ten methods for managing weeds, namely, T_1 – hoeing, T_2 – raised stale seedbed + hoeing, T_3 – stale seedbed + hoeing, T_5 – stale seedbed + mulch, T_6 – raised stale seedbed + mulch, T_4 – mulch 5 t per ha, T_7 – intercropping fenugreek in rabi season and soybeans in kharif season, T_8 – crop rotation (soybean, mustard, and maise-peas alternately), T_9 – intensive cropping (additional crops of mustard in the fall and buckwheat in the summer), and T_{10} – chemical check (pendimethalin in rabi season and atrazine in kharif season). A randomised complete block design with three replications was used to assess the weed flora, consisting of eight weed species during kharif 2020, fourteen during kharif 2021, and thirteen during the rabi seasons 2019–2020 and 2020–2021. The weed species composition changed significantly in the second year compared to the first. In contrast to the chemical check, the organic weed control treatments showed a variety of weed flora, as indicated by diversity and phytosociological studies. Long periods of germination/emergence, blooming, and fruiting were found in phenological research. Rabi weeds appeared between October and January and between May and August. They flowered and produced fruits or seeds in March and September, respectively, and matured in April and September. Crop rotation followed by Raised stale seedbed (RSSB) + hoeing + earthing resulted in a much greater yield; however, in the second year, the chemical check was comparable to this treatment. Additionally, crop rotation increased profitability over time.

Keywords: Shannon–Wiener index; cropping system; non-chemical management; maize–pea rotation; yield response

The ongoing decline in soil fertility and the plateauing of crop productivity in intensive farming systems demand a shift toward more ecologically sound and sustainable production strategies.

Supported by the ongoing research funding program – Research Chairs (ORF-RC-2025-5534), King Saud University, Riyadh, Saudi Arabia.

https://doi.org/10.17221/32/2025-PPS

Conventional farming practices, though initially successful in increasing yields, often rely heavily on synthetic fertilisers and chemical pesticides, which adversely affect both environmental and human health (Adeux et al. 2022). Organic farming has emerged as a promising alternative, aligning with the goals of sustainable agriculture by eliminating synthetic inputs, enhancing biodiversity, and promoting soil health.

A major constraint to organic crop production, however, is weed management. Unlike conventional systems that rely on herbicides, organic farming requires non-chemical strategies due to stringent certification regulations (Van der Werf & Bianchi 2022). Practically employed non-chemical weed control methods in organic systems include mechanical practices (e.g., hand weeding, hoeing, mowing, flaming), cultural practices (e.g., crop rotation, mulching, stale seedbed technique), and biological methods (e.g., competitive crop cultivars, allelopathic cover crops, and intercropping). These methods aim to suppress weed growth, reduce the weed seed bank, and create unfavourable conditions for weed establishment, without harming the environment.

Weeds have remarkable adaptive potential and are a crucial biological component of agroecosystems. In organic systems, their phenotypic flexibility and durability need integrative, non-chemical management strategies. Research has shown that both mechanical and cultural weed management methods may successfully suppress weeds and preserve production (Boinot et al. 2024). For instance, Gao and Su (2024) demonstrated that mechanical and rotational techniques can effectively reduce weed pressure in Central European spinach farming. Additionally, compared with conventional systems, organic systems have been shown to sustain greater diversity and richness of weed species (Pearson et al. 2023).

Weed species composition is known to be impacted by changes in input amounts and land-use intensity. Diverse weed communities often flourish in organic settings; however, certain prominent weed species, such as Alopecurus myosuroides Huds. and *Lolium spp.*, are closely linked to traditional herbicide-based systems. Additionally, their analysis found that yield losses in fields with greater weed diversity were much lower (30%) than in fields with lower diversity (60%), suggesting that diverse weed populations may buffer yield losses.

Additionally, compared to conventional farming systems, organic farming systems retain a higher number of weed seeds in the soil seed bank (Szostek et al. 2022). Long-term field data on the composition of the weed community and its management in organic farming are still limited, however. Weed phenology, or the timing of life-cycle events including germination, blooming, and seed set, is a significant but under-studied component that affects the effectiveness of management and the level of competition (Ishfaq et al. 2025). Weed species may exhibit morphological changes across various environmental and management regimes through phenotypic plasticity (Chaudhary et al. 2021). This variation emphasises the need for species-specific and seasonally appropriate weed management strategies.

Therefore, the present study, initiated in 2016 under long-term organic management, was designed to assess weed species diversity and phenological behaviour across five crops – maise (*Zea mays* L.), soybean (*Glycine max* L.), fenugreek (*Trigonella foenum-graecum* L.), coriander (*Coriandrum sativum* L.), and pea (*Pisum sativum* L.) – over two consecutive *rabi* and *kharif* seasons (2019–1920) and (2020–1921). The main objectives were to evaluate the diversity and structure of weed flora under organic weed management. Understand the phenological response of weed species in relation to crops and seasons. Provide insights for developing ecologically sound weed control strategies in similar agroecological settings.

During the *rabi* season, dominant weeds included *Phalaris minor Retz., Stellaria media* (L.) *Vill., Anagallis arvensis* L.*, Poa annua* L.*, Vicia sativa* L.*, Coronopus didymus* (L.) *Sm.,* and *Alopecurus myosuroides Huds*. In the *kharif* season, prevalent species were *Avena ludoviciana Durieu*, *Cyperus rotundus* L.*, Commelina benghalensis* L.*, Poa annua* L.*, and Euphorbia hirta* L. (Sahoo et al. 2025). The present study also evaluated the impact of different non-chemical weed control strategies on crop yield and economic returns.

MATERIAL AND METHODS

The study was conducted from winter 2019 to summer 2021 within a long-term experiment initiated in 2016 at the CSK Himachal Pradesh Krishi Vishvavidyalaya's Agronomy Research Farm

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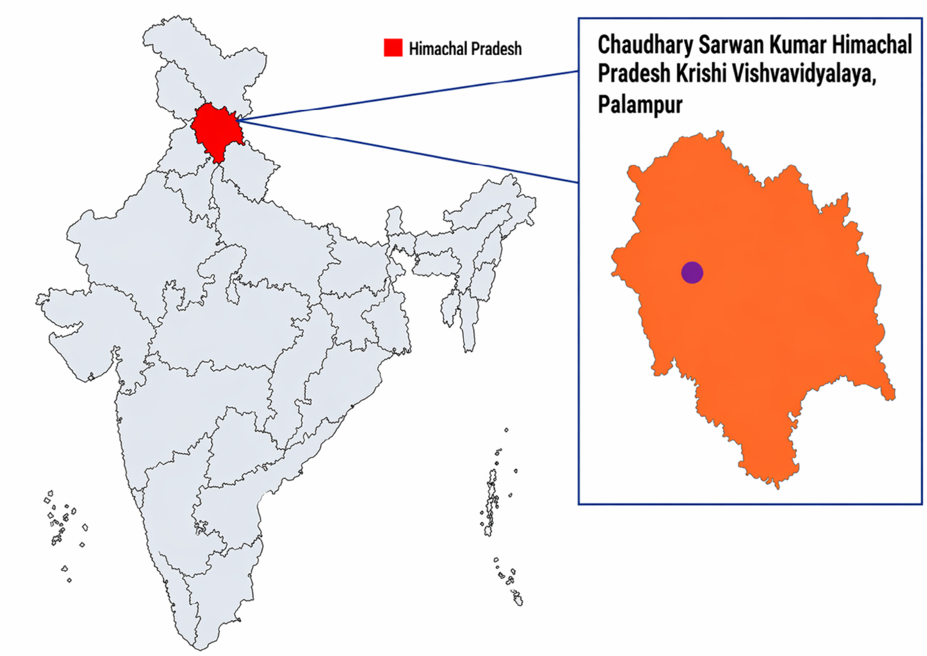

Figure 1. Location of experiment field

(32°06' N, 76°03' E, 1 290 m a.s.l.) in Palampur, India (Figure 1). In the current study, the crop sequence was switched from maise to garlic to maise to peas. In terms of agroclimatology, Palampur is located in Himachal Pradesh's sub-temperate mid-hill zone, characterised by pleasant summers and harsh winters. Rainfall in the area averages 2 332 mm per year; June through September account for about 80% of this total. Figures 2 and 3 show the highest and lowest temperatures, daily rainfall, humidity, and hours of sunlight for the crop-growing season in both years. The soil texture is silty clay loam. It contains 20.4 g, 43.8 g, and 35.1 g of sand, silt, and clay per 100 g of soil, respectively; it is low in available nitrogen (271.4 kg/ha); it is medium in available potassium (196.3 kg/ha) and soil organic carbon (7.4 g per kg); it is high in available phosphorus (42.1 kg/ha) at a soil depth of 0.15 m at the surface; and it reacts acidically (pH 5.6).

A randomised complete block design was used for the experiment, and each of the 10 treatments was replicated three times (Table 1). The gross plot size was 24 m^2 (5 m × 4.8 m). As a basic guideline, the recommended package of practices from

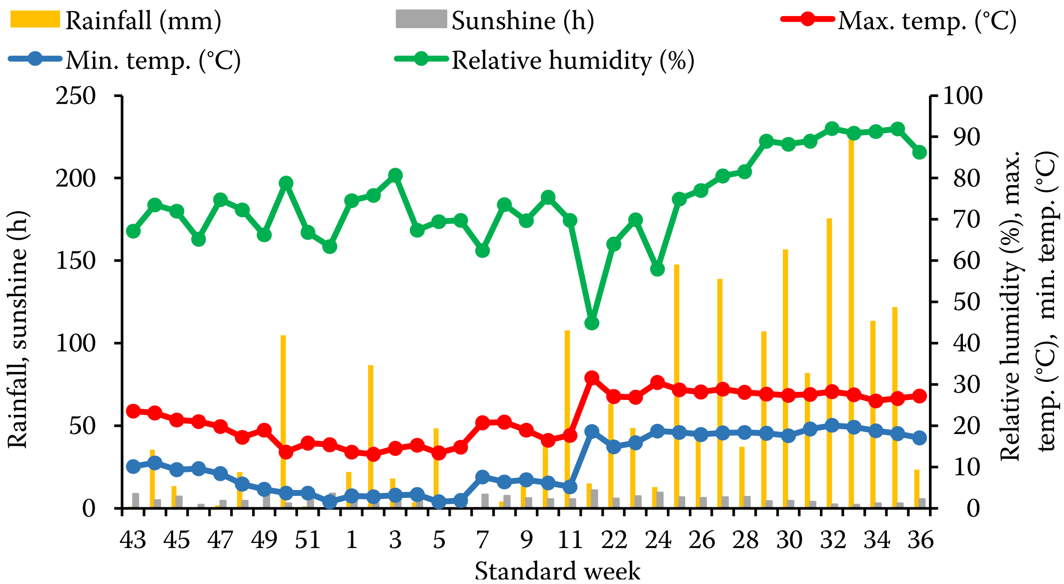

Figure 2. Weekly meteorological data for rabi season (October 2019 to May 2020)

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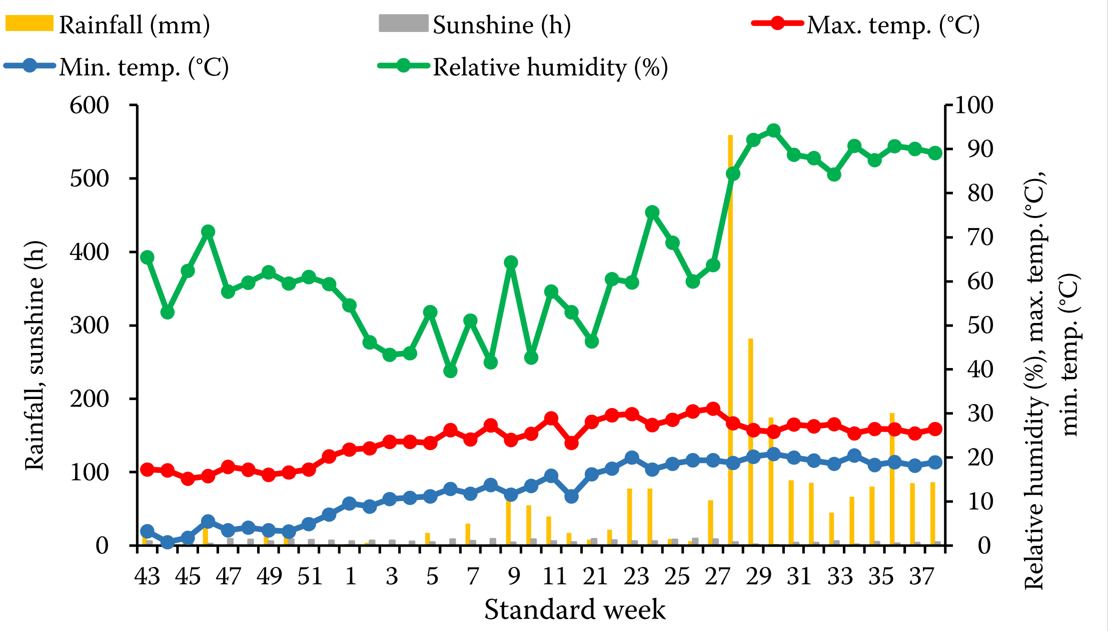

Figure 3. Weekly meteorological data for the kharif season (May 2020 to October 2020)

the agricultural university was followed to calculate nutrient equivalents for crop production. The crops were grown according to the university's recommended package of practices. The varieties used were *GS 10* and *K-25*, respectively, of pea and maise. Varieties of buckwheat were Sangla B1 and KBS-3, and of mustard, KBS-3.

Weather data for two consecutive years is depicted in Figures 1 and 2. Emergence leads to vegetative growth followed by flowering. Rabi weeds flower mainly from January to March, while kharif weeds flower mostly in July and August. Weeds generally have a short life cycle, with flowering and fruiting occurring simultaneously. The initial flush of weed seedlings was then removed by surface disturbance at sowing. Raised stale seedbed plots, raised to 12–15 cm, were utilised to improve drainage. To reduce weed growth and boost yields,

Table 1. Details of treatments

Treatment	Kharif (maize green cob)	Rabi (peas)	Short title
T_1	One hoeing followed by earthing up at knee high stage	Hoeing (twice) at 30 DAS & 60 DAS	Hoeing
T_2	Stale seedbed (SSB) + hoeing + earthing up	SSB + hoeing + HW	SSB + hoeing
T_3	Raised stale seedbed (*RSSB*)+ hoeing + earthing up	RSSB + hoeing + HW	RSSB + hoeing
T_4	Mulch (*Lantana*) 5t/ha	Mulch (*Lantana*) 5 t/ha	Mulch
T_5	SSB + mulch 5 t/ha	SSB + mulch 5 t/ha	SSB + mulch
T_6	RSSB + mulch 5 t/ha	RSSB + mulch 5 t/ha	RSSB + mulch
T_7	Intercropping (soybean) + hoeing	Intercropping (fenugreek) + hoeing	Intercropping
T_8	*Maize/soybean + hoeing+ earthing up	*Pea/Sarson + hoeing+ HW	Crop rotation
T_9	Maise + mulch + manual weeding fb autumn crop of sarson sag	Peas + mulch + manual weeding fb summer crop of buckwheat	Intensive cropping
T_{10}	Herbicide + HW	Herbicide + HW	Chemical check

*Based on crop rotation, maise-peas in the first year and soybean-sarson in the second year, i.e. in kharif, maise/soybean and in rabi peas/sarson alternatively; T_9 was based on intensive cropping; T_{10} was based on the recommended dose of fertilisers and herbicides

https://doi.org/10.17221/32/2025-PPS

fenugreek was interplanted with peas or garlic, and soybean was interplanted with maise. One method of crop rotation was to plant peas after rabi garlic. Combinations such as green manure crop-buckwheat, oilseed-brown sarson, and pulse-soybean were employed for intensive cropping. In maise and peas, herbicides consisting of atrazine and pendimethalin were used as pre-emergence treatments. Before planting, organic inputs such as vermicompost and farmyard manure were used. Based on the basic requirements, fertilisers were applied, and at monthly intervals, Panchgavya and vermiwash were used to provide additional nutrients. Using 50 × 50 cm quadrates in each plot, weed data, including counts and dry weight, were collected at harvest and monthly. While maise cobs were manually gathered for green fodder, peas were collected when the pods were fully ripe. Market prices were used to translate crop yields into monetary returns, and production costs were subtracted to determine net returns. The kharif season aligns with the southwest monsoon, with sowing usually starting in June or July and harvesting in September or October. These crops thrive in hot, humid climates and are highly dependent on timely, sufficient monsoon rainfall; production may be significantly impacted by either too much or too little rainfall. Because of their tolerance to warm, wet months, common Kharif crops include rice, maise, cotton, soybean, groundnut, bajra, and jowar. The rabi season is the post-monsoon season, with seeds sown in October to November and harvested in the spring, usually in April to June. Warm weather promotes germination, whereas colder weather supports development. These crops need cool, dry growing conditions; they depend less on rainfall and often need irrigation.

Weed diversity

Species diversity. The Shannon index (H), a measure of species variety, was computed. Another name for it is the Shannon Weir index or the Shannon-Wiener index. Species evenness and abundance are taken into account by Shannon's index. The natural logarithm of this percentage (*lnpi*) is then multiplied by the proportion of species (*i*) to the total number of species (p_i). The final result is multiplied by 1 and summed across species:

$$H = -\sum_{i=1}^{n} p_i \ln p_i \tag{1}$$

Similarity index. The relative abundance of the many species that comprise an area's richness is gauged by the similarity index. In the current study, community similarities were calculated using Soverson's coefficient (*SC*) as follows, by Jaccard (1908):

$$SC = \frac{2C}{S_1 + S_2} \tag{2}$$

Where: S_1, S_2 – the total number of species found in communities 1 and 2, respectively; C – the number of species shared by the two communities, this coefficient provides a value between 0 and 1; the closer it is to 1, the more similar the communities are.

Shannon index.

$$H = \frac{\sum(p_i)}{ln\, p_i} \tag{3}$$

Where: p_i – the percentage of the population's total number of individuals belonging to species "1" by Weaver (1963).

Simpson's index. It is the reciprocal of the Simpson's index, which is determined in this way:

$$D = \frac{\sum_{i=1}^{s} n(n-1)}{N(N-1)} \quad \text{or} \quad \sum_{i=1}^{s} (n/N)^2 \tag{4}$$

If 0 denotes infinite diversity, 1 denotes no diversity, s is the number of species with this index, n is the total number of organisms of a certain species, and N is the total number of organisms of all species, according to Simpson (1949):

$$Simpson's\ index\ of\ diversity = 1 - D = 1 - \sum_{i=1}^{s} p_i^2 \tag{5}$$

$$Simpson's\ reciprocal\ index = 1/D = 1/\sum_{i=1}^{s} p_i^2 \tag{6}$$

Evenness/Shannon's equitability (EH). To compute it, divide H by *Hmax* (in this case, *Hmax* = *LnS*). Equitability is predicated on values ranging from 0 to 1, where 1 denotes total evenness, i.e., *EH* = *H*/*Hmax* = *H*/*LnS*. By Pielou (1969).

Weed phenology

Observations on emergence, flowering, fruiting, seed setting and maturity of the major associated weeds have been recorded.

Equivalent yield

By utilising the formula to convert crop/intercrop yield to main crop yield on a pricing basis,

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equivalent yields were computed to compare system performance.

$$Equivalent\ yield\ (\text{kg/ha}) = Y \times \frac{Px}{Py} \quad (7)$$

Where: Y – the yield of other crop/intercrop (kg/ha); Px, Py – prices of another crop/intercrop and main crop, respectively.

In the equivalent yield formula, the yield of the intercrop or secondary crop (Y) is expressed in kilograms per hectare (kg/ha). The price of the intercrop or secondary crop (Px) and the price of the main crop (Py) are both expressed in Indian rupees (INR, equal 0.011USD) per kilogram (e.g., INR/kg). When Y (kg/ha) is multiplied by Px (INR/kg), the result is the monetary value of the intercrop per hectare (INR/ha). This value is then divided by Py (INR/kg) to convert the monetary value back to the equivalent yield of the main crop in kg/ha. Thus, the final unit for equivalent yield remains kg/ha.

Statistical analysis

According to Gomez and Gomez (1984), statistical analysis was performed on the collected data. To assess differences in therapy, the findings were compared at the 5% significance level. Following square root transformation [$\sqrt{(x+1)}$], the weed count and weed dry weight data were examined, and the transformed averages were used to compare the treatment effects.

RESULTS

Shannon–Wiener index

Shannon–Wiener index, reflecting species abundance within a community, peaked with Mulch + HW (T_4) in both years, followed by *SSB* + Mulch + HW (T_5) in rabi 2019-20 and Hoeing (T_1) in the subsequent year. The lowest values were observed in crop rotation (T_8) in the first year and in chemical check (T_{10}) in the second year, indicating dominance by a few species in these treatments. Simpson's reciprocal index was highest under chemical check (T_{10}), followed by crop rotation (T_8), consistently across both years. Shannon's equitability was highest under RSSB + Hoeing/HW (T_3) in Rabi 2019–2020 (Figure 4) and under intensive cropping (T_9) in 2020–2021 (Figure 5), with the lowest values under chemical check (T_{10}) in both years.

In the experimental field, the number of weed species increased from 8 in Kharif 2020 to 15 in Kharif 2021. Treatments like Mulch + *HW* (T_4), *SSB* + Mulch + *HW* (T_5), *RSSB* + Mulch + *HW* (T_6), and intercropping (T_7) supported all 8 weed

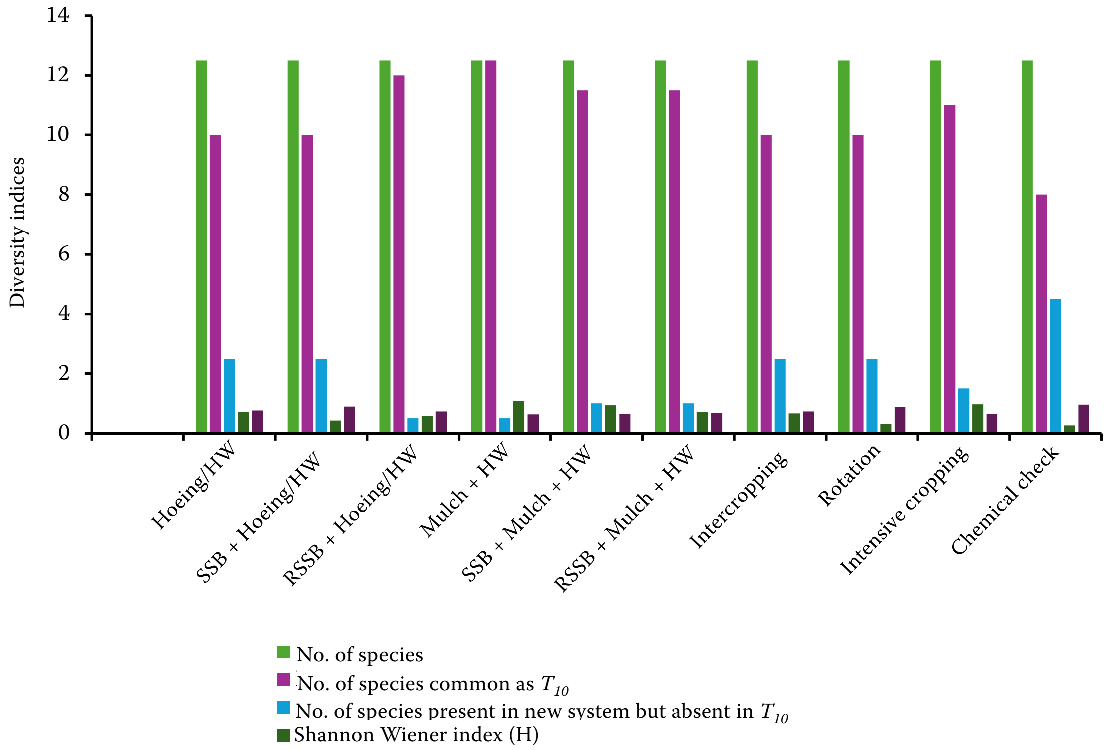

Figure 4. Effect of weed management practices on diversity indices of weeds in Rabi 2019–2020 (pooled)

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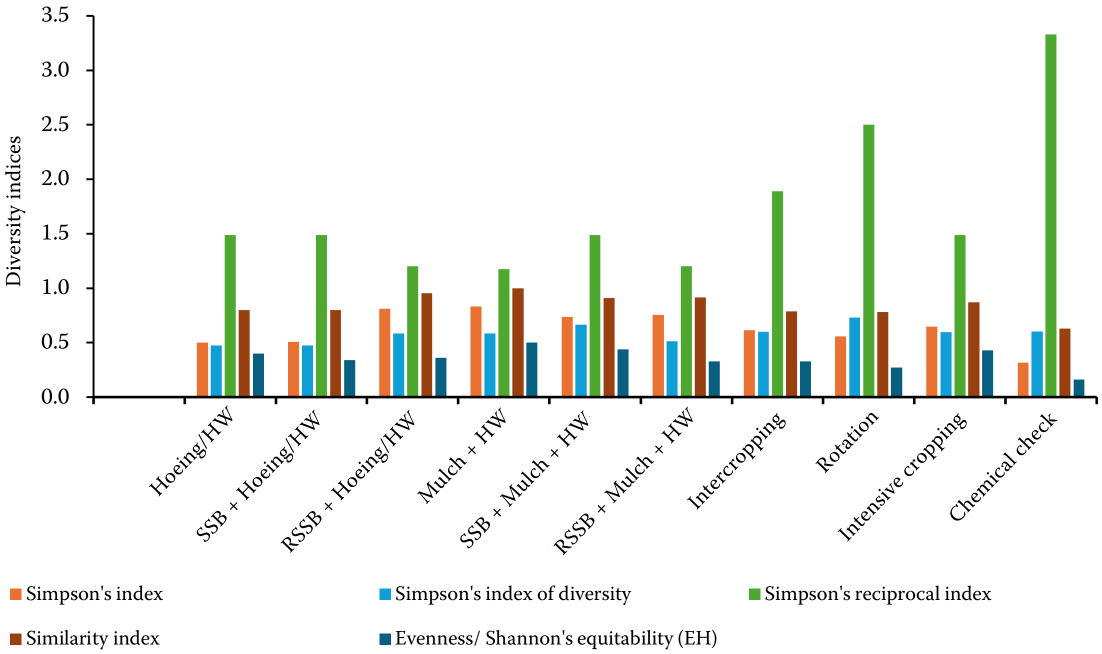

Figure 5. Effect of weed management practices on diversity indices of weeds in Rabi 2020–2021 (pooled)

species in 2020, while *SSB* + Mulch + *HW* (T_5) hosted all 15 species in 2021. Mulch + *HW* (T_4) had the highest Shannon–Wiener index in 2020, followed by *SSB* + Mulch + *HW* (T_5) and *RSSB* + Mulch + *HW* (T_6), whereas intensive cropping (T_9) led in 2021. Simpson's diversity index peaked under Mulch + *HW* (T_4) in 2020 and chemical check (T_{10}) in 2021. Shannon's equitability favoured Mulch + *HW* (T_4) in 2020 and *Hoeing/HW* (T_1) in 2021, contrasting with the minimum observed in *SSB* + Hoeing/*HW* (T_2) during both years (Figures 6 and 7).

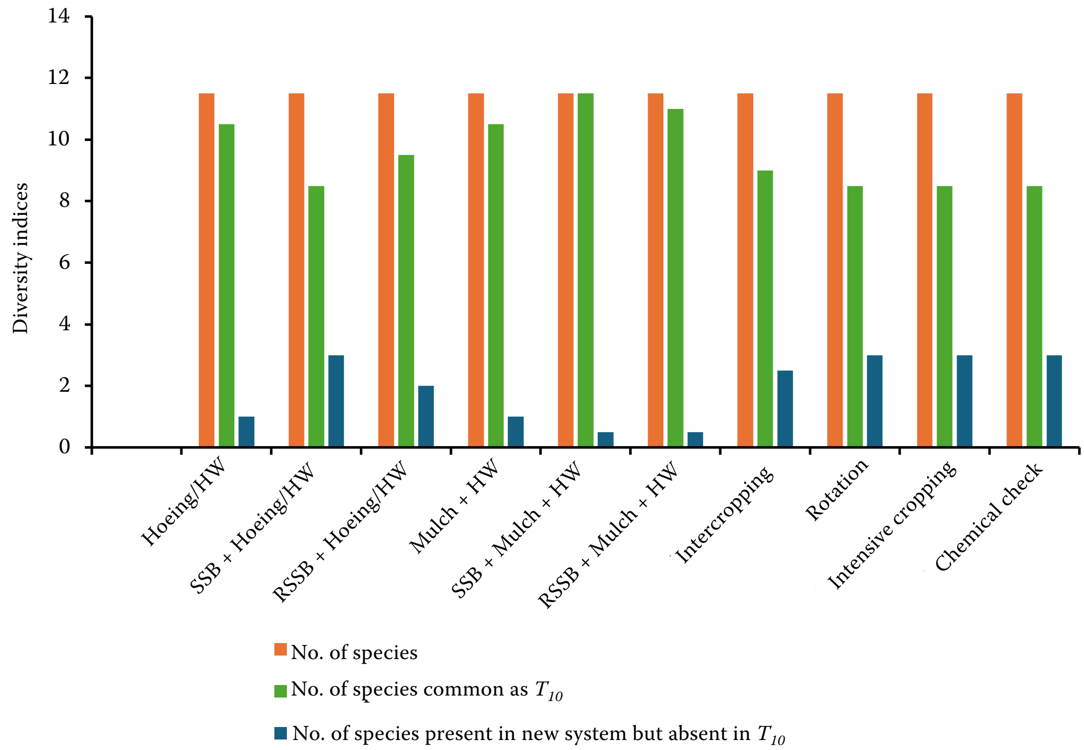

Figure 6. Effect of cropping systems on diversity indices of weeds in kharif 2020 (pooled)

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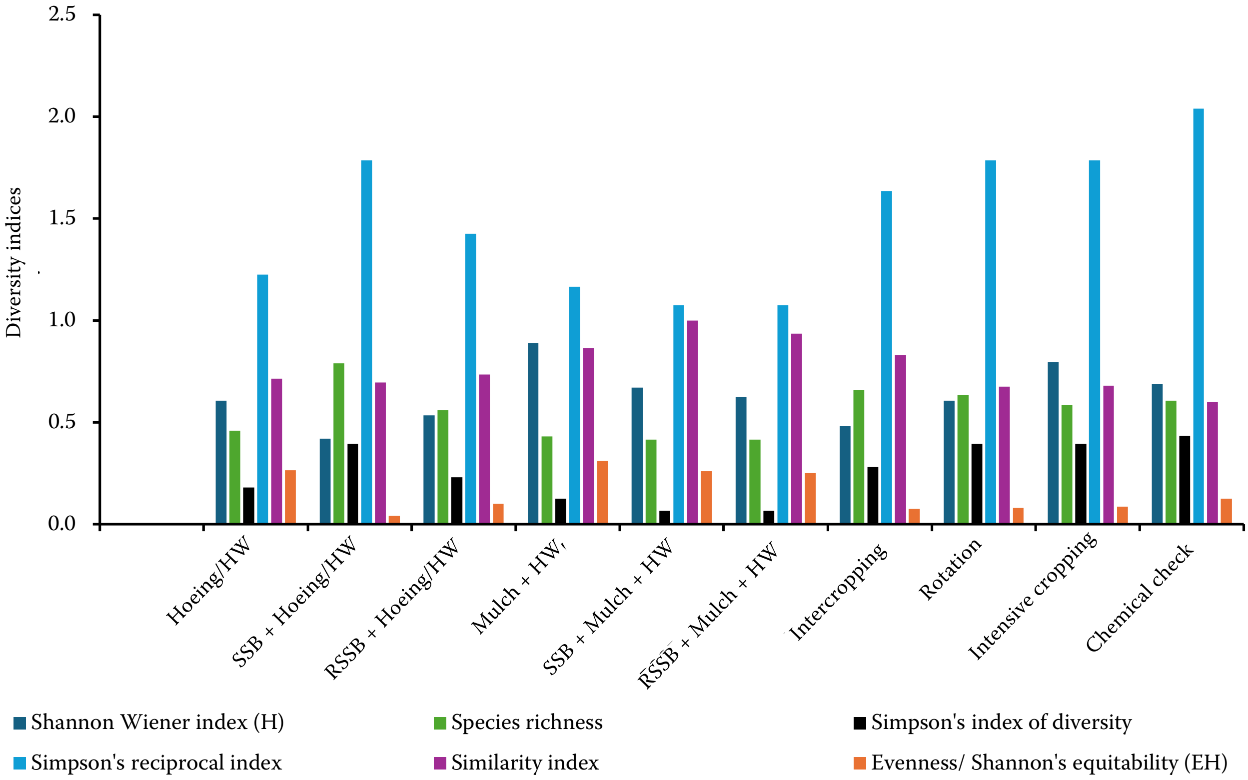

Figure 7. Effect of cropping systems on diversity indices of weeds in kharif 2021 (pooled)

Phenology of the associated weeds

The current study found that weed management strategies did not statistically affect the germination, flowering, and maturity times of the target weeds. Weed phenology is primarily controlled by temperature and light, with vernalisation, day duration, and thermal time accumulation all having significant effects (Maple et al. 2024). As a result, we looked at how environmental factors affected the phenological development of the main weed species, including emergence, branching, flowering, seed setting, and maturity (Figures 8 and 9).

Between the rabi and kharif seasons, there were significant variations in the patterns of weed emergence. In general, rabi weeds appeared between October and November, and kharif weeds appeared between May and June. In both seasons, a flush emergence pattern was observed, with flowering and fruiting occurring shortly after rapid vegetative growth. Weeds, unlike many crops, often blossom and set fruit at the same time, which helps seeds spread before or during crop maturity. In contrast to kharif weeds, which set seed in August and September and greatly contribute to the soil seed bank and subsequent weed infestations, rabi weeds reached their peak fruiting period in March and April. Weed emergence patterns were significantly impacted by environmental conditions, especially temperature and rainfall. For example, the development of plants that require high soil moisture, such as *Ranunculus arvensis*, *Tulipa asiatica*, and *Spergula arvensis*, was either expedited or delayed by variations in rainfall.

S. arvensis was the most prolific of the major *rabi* weeds, blooming within 8 weeks after germination and dispersing seeds till plant senescence. A common winter weed in deep clay soils, *Vicia sativa* appeared mostly between September and mid-October, when soil moisture was at its highest. Weed growth surged when winter ended, and temperatures rose, driven by lower humidity and a longer photoperiod. In a similar vein, *Poa annua* showed germination patterns that were highly correlated with soil temperature and moisture, with peak seed setting occurring from February to April at temperatures between 17 °C and 21 °C, and best germination occurring in November to December. *Commelina benghalensis*, *Cyperus rotundus*, and *Brachiaria* were the kharif season weeds that first appeared in May 2020. However, due to climate fluctuations, their appearance in 2021 was delayed by 1 month compared

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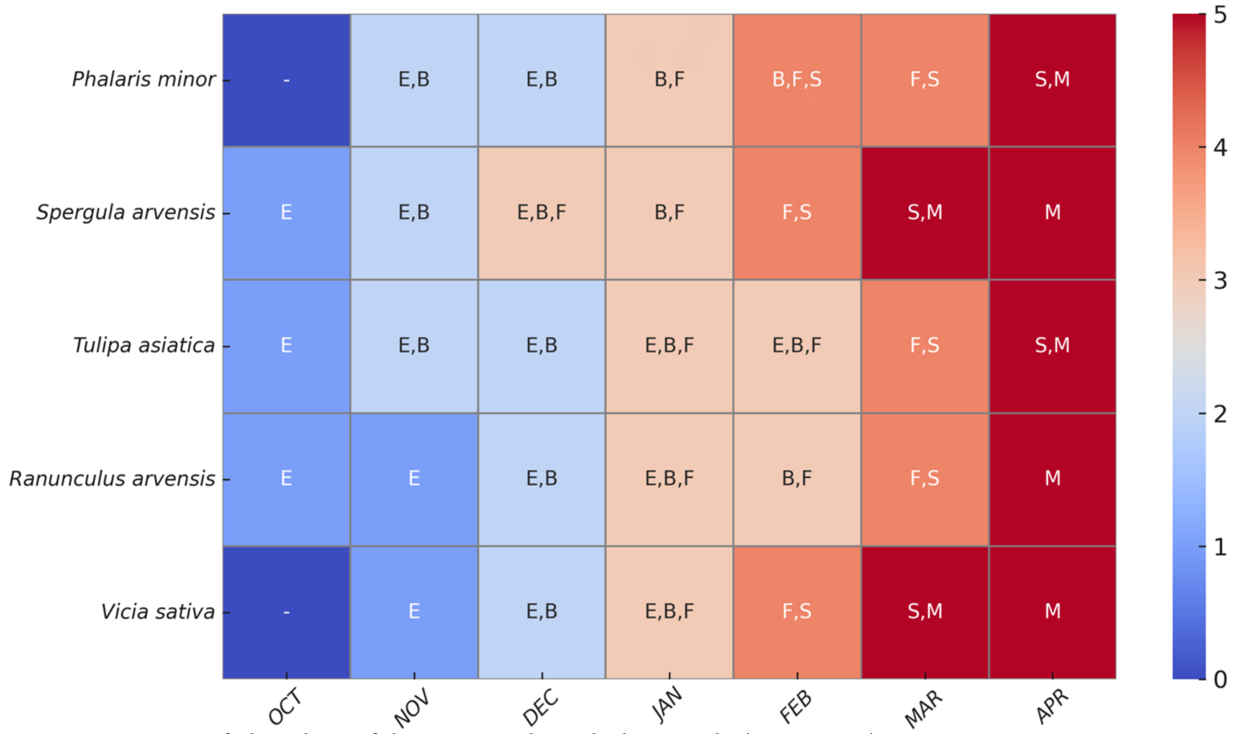

Figure 8. Heat map of phenology of the associated weeds during rabi (2019–2021)
E – emergence; B – branching; F – flowering; S – seed setting; M – maturity

to 2020. In accordance with the reproductive phases of maise, these species began branching in June, blooming in July, and fruiting in August. The majority of seeds were disseminated in May by populations of *Polygonum* and *Echinochloa colona* that coexisted with maise. About 15 days after maise was sown, *C. benghalensis*, *C. rotundus*, and *Brachiaria* began to appear; the impor-

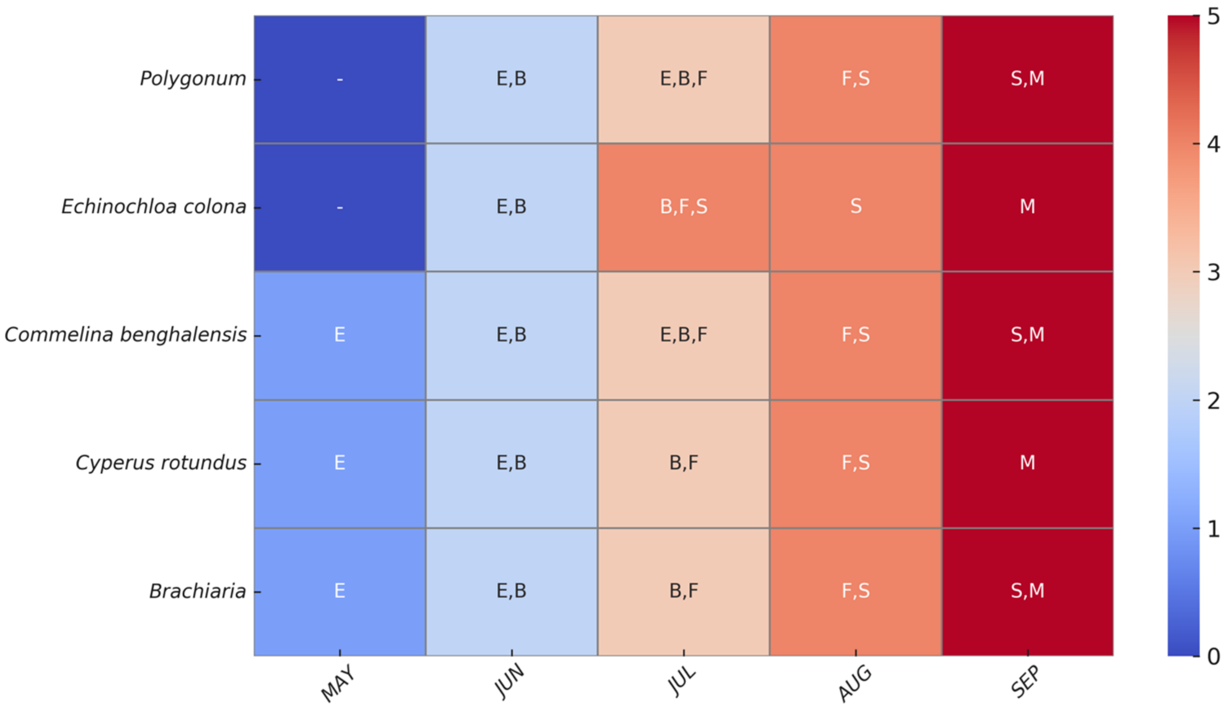

Figure 9. Heat map of phenology of the associated weeds during kharif (2020–2021)
E – emergence; B – branching; F – flowering; S – seed setting; M – maturity

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tant phenophases (flowering, fruiting) took place in February, March, and April.

Yield

Maise equivalent yield of pea in rabi 2019–2020 was significantly greater in crop rotation (2.04 t/ha) and lowest in intensive cropping (0.752 t/ha). In the second season, yield was significantly higher in chemical check (13.71 t/ha) and significantly lowest in mulch + HW (Figure 7). Significantly higher maise cob yield (20.2 t/ha) was in RSSB + Hoeing/HW (T_3) in kharif 2020. In kharif 2021, RSSB + Hoeing/HW (T_3) and RSSB + Mulch + HW (T_6) had significantly higher yields but were at par with mulch + HW (T_4), intercropping (T_7), and chemical check (T_{10}). The other treatments were comparable. In kharif 2020, Hoeing/HW (T_1) and Intercropping (T_7) had significantly lower maise yield (9.64 t/ha) as compared to other treatments. System maise equivalent yield was significantly higher in RSSB + Hoeing/HW (21.60 t/ha) and significantly lowest in intercropping (10.80 t/ha). In the second season, the chemical check gave a significantly higher yield (24.57 t/ha), which was at par with RSSB + mulch + HW, and the lowest was in SSB + Hoeing/HW (14.53 t/ha) (Figure 10).

DISCUSSION

Shannon–Wiener index

Stale seedbed methods allowed weed seeds to germinate freely without crop competition, significantly reducing species richness. Species variety and richness were often higher in organic agricultural systems than in chemical ones. Weed occurrences, particularly *Spergulla* sp. and *Tulipa asiatica*, were consistently higher across all treatments than in chemical controls (Gurusinghe et al. 2022). Environmental factors, such as rainfall, influenced weed fluctuations more directly than the slower-reacting soil seed bank, which reflects farming intensity over several years (Figure 4). Combining hand hoeing with soil cover (*HH + SC*) produced the lowest Shannon–Wiener and evenness indices, indicating successful weed suppression, according to a study on ecological weed control. Weed diversity was greater in treatments lacking these combinations, as reported by Nagargade et al. (2024). Species richness was notably high under *SSB* + Hoeing/*HW* (T_2) in both years, with organic farming showing the highest richness and abundance. Species like *Cyperus sp.* and *Ageratum conyzoides* thrived in intensive farming during spring. Overall, organic farming enhanced species numbers and diversity indices compared to conventional methods, suggesting a positive impact on the arable seed bank and weed community dynamics over time (Psyllos et al. 2022).

The number of species and Shannon Diversity in organically managed fields were much higher than in conventionally managed fields. According to other research, prolonged, intense farming conditions cause the soil's arable weed seed stock to be depleted (Saulic et al. 2022). Compared with

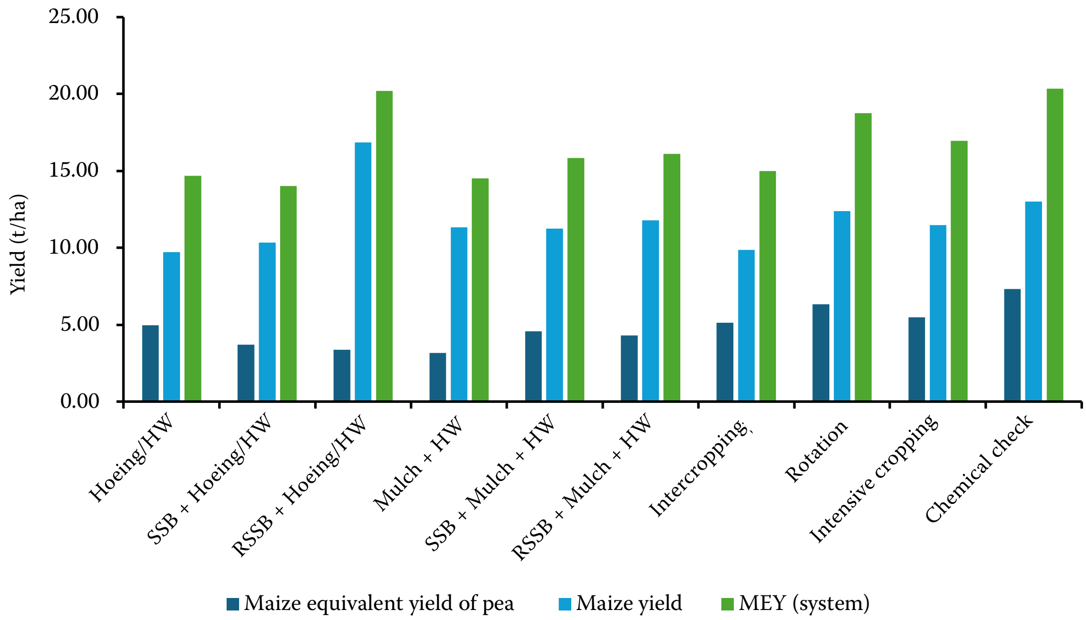

Figure 10. Effect of weed control treatments on system (MEY) maise equivalent yield (t/ha) (pooled)

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conventional farming methods, which typically have 10 species per field, organic farming might increase the average number of seed bank species in the project fields, resulting in 20 species per field. Kollman and Waldhardt (2022) found that crops significantly influenced the distribution of arable weeds, with lower diversity indices in spring-grown crops and higher diversity in winter-grown crops. The number of species was also significantly influenced by season, with the summer months showing the highest numbers.

Phenology of the associated weeds

Weeds' phenological development was very consistent throughout the active growth phase, although there was a notable amount of variation at the start and finish of the growing season (Kumar et al. 2024). As long as there was enough moisture, these species flourished in wetland-adjacent locations, including swamps, pond margins, and riverbanks. They showed that they could adapt to both heavy clay soils and sandy substrates. This study offers a thorough assessment of weed phenology across the rabi and kharif seasons, emphasising how different weed species respond to variations in temperature, precipitation, and photoperiod. The results highlight how crucial it is to implement timely weed control plans that take seasonal variations into account (Gharde et al. 2018). When used with integrated weed control methods, early-season emergence monitoring can help reduce weed infestations and prevent excessive seed bank build-up. With some significant exceptions in the early and late phases of the growing season, a comparative study of summer weed phenology showed that seedling emergence for the majority of species happened about 10 days following crop sowing Fantle et al. (2022). Flower bud initiation for *E. colona* took place in June, while peak flowering took place in July.

Yield

The higher yield in the 'chemical check' treatment in the second season could be due to the immediate availability of nutrients through chemical fertilisers, ensuring consistent and adequate supply to the maise plants, compared to the nutrient release rate from organic sources in *RSSB* + mulch + *HW*. Reduced competition for essential nutrients, water, and light is responsible for the increased yields in these treatments, enabling the crops to develop to their full genetic potential. The increased yield observed under these treatments suggests that the selected weed control strategies successfully reduced weed interference, especially throughout the crucial phases of both maise and pea growth. In addition to improving crop establishment, effective weed removal promotes greater photosynthetic efficiency, increased nitrogen absorption, and better root growth.

Hoeing/hand weeding and intercropping treatments had lower maise yields, possibly due to increased competition for nutrients and space between crops, which can limit individual plant growth and overall yield potential (Sharma & Rayamajhi 2022). The low yield in both treatments suggests that either weed reinfestation occurred at critical stages of crop development or the weed management techniques used were insufficient to inhibit weed growth. Weeds hinder light interception, reduce nutrient availability, and deplete soil moisture, resulting in reduced crop development and decreased biomass accumulation. Furthermore, weed pressure can worsen production losses by increasing the prevalence of pests and diseases (Nath et al. 2024).

Robust and integrated weed control tactics are essential, as evidenced by the yield discrepancies between high- and low-performing treatments (Gage & Schwartz-Lazaro 2019; Kumar et al. 2022; Kumar 2023). While treatments with insufficient weed management led to significant production declines, treatments with improved weed suppression increased grain output and system productivity. To maintain increased production in maize-based cropping systems, it is crucial to use prompt and efficient weed management strategies, such as a mix of mechanical, chemical, and cultural methods (Kumar et al. 2020; Reuter et al. 2025).

The study's findings show how crucial it is to use integrated weed control techniques to increase the production of maize-based cropping systems. It has been demonstrated that a complex system of various factors, including local climate, altitude, soil properties, management, seasonality, and landscape factors, shapes the performance of weed communities in agricultural ecosystems. These factors may also significantly affect the diversity and distribution of weed species (Hussain et al. 2021; Van der Werf & Bianchi 2022). It is well acknowledged that the primary determinants of agricultural weed vegetation are environmental and weed-management factors (Andert 2021; Pavlovic et al. 2022).

The findings of this study offer valuable insights for the development of ecologically sustainable

https://doi.org/10.17221/32/2025-PPS

weed management strategies in real-world agricultural systems, particularly under organic farming. The enhanced weed diversity observed under practices such as mulch application, crop rotation, and stale seedbed preparation suggests these methods foster more resilient agroecosystems. While weed presence is often perceived negatively, higher species richness can provide key ecosystem services – including improved soil health, increased pollinator activity, and habitats for beneficial organisms – thereby contributing to ecological stability. Avoiding synthetic herbicides also protects non-target flora and fauna, reducing risks to surrounding ecosystems, including soil biota and aquatic environments.

Crucially, weed control tactics may be directly optimised by using the phenological findings from this research, which follow phases such as emergence, branching, blooming, seed setting, and maturity. Interventions like mechanical weeding, mulching, or delayed planting may be more effectively targeted to weed species at their most vulnerable phases, reducing their capacity to compete with crops or replenish the soil seed bank by pinpointing the crucial growth windows of dominant weed species. For instance, early actions may significantly limit the establishment of fast-emerging species like Vicia sativa or Spergula arvensis. Additionally, crop competitiveness and resource efficiency may be improved by scheduling crop planting to coincide with unfavourable times for weed emergence or blooming.

Incorporating phenological data into region-specific weed calendars or decision support tools can shift weed control from reactive to predictive, reducing the frequency of interventions, labour costs, and environmental impact. Altogether, these findings support the development of integrated, low-input weed management approaches that maintain productivity while enhancing agroecosystem biodiversity, ecological services, and long-term sustainability.

CONCLUSION

The present study highlights that organic weed management strategies – including mulch application, crop rotation, stale seedbed preparation, and hoeing—significantly affect weed diversity, phenology, and crop productivity in maise–pea cropping systems. Treatments such as mulch + *HW* (T_4) and *RSSB* + Hoeing/*HW* (T_3) proved effective in enhancing ecological balance while maintaining yields, demonstrating the potential of such practices as sustainable alternatives to chemical herbicides. However, the broader adoption of these approaches in real agricultural settings presents challenges. Labour intensity, economic feasibility, and performance variability across different agro-climatic conditions may limit their large-scale applicability. Additionally, while organic systems promote species richness, they also require continuous monitoring to prevent dominance by aggressive weed species and to respond to ecological shifts that may reduce long-term control efficacy. There is also the potential for adaptive resistance within weed communities, even in the absence of herbicides. Therefore, implementing a well-integrated, flexible weed management strategy tailored to local environmental and socio-economic contexts is essential. Future research should focus on validating the scalability and adaptability of these organic practices, integrating weed phenology into predictive control tools, and addressing the long-term sustainability of weed suppression under changing climate and farming conditions.

Acknowledgement: The authors extend their appreciation to Ongoing Research Funding program – Research Chairs (ORF-RC-2025-5534), King Saud University, Riyadh, Saudi Arabia. The authors feel privilege to thank CSK Himachal Pradesh Agricultural University, Palampur, HP, India.

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Received: March 2, 2025
Accepted: October 10, 2025
Published online: April 28, 2026