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Influence of Farming Systems (Organic vs. Conventional) With Crop Rotation and Intercropping on Weed Seedbank in Central Kenya

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ABSTRACT

Weed seedbanks are a key driver of long-term weed pressure and are strongly shaped by farming systems, crop rotation, and intercropping. This study evaluated the influence of organic (ORG) and conventional (CONV) farming systems, each managed under high (113–145 kg N·ha⁻¹, 60–83 kg P·ha⁻¹) and low (31–45 kg N·ha⁻¹ and 13–27 kg P·ha⁻¹) fertilization levels, on weed seedbank density, composition, dominance, and diversity in two long-term trials (established in 2007) at Chuka and Thika in the Central Highlands of Kenya. From 2017 to 2019, across six cropping seasons under a three-year rotation, soil samples (0–20 cm) were collected after each season from four systems: CONV-high, CONV-low, ORG-high, and ORG-low. Weed seedbanks were quantified using the seedling emergence method. Under these conditions, weed species were identified, and density, Shannon diversity (H'), evenness ($E_{H'}$), and principal component analysis were used to assess treatment effects. Crop rotation affected densities of all weed species, with responses dependent on crop sequence and farming system. High-fertilization systems (ORG-high and CONV-high) generally supported higher total weed densities, linked to greater organic and mineral fertilizer inputs and favored high-fertility indicator species such as *Bidens pilosa*, *Amaranthus hybridus*, *Galinsoga parviflora*, *Stellaria media*, and *Commelina benghalensis*. Low-fertilization systems were associated with low-fertility species such as *Portulaca oleracea*, *Tagetes minuta*, and *Schkuhria pinnata*. Dominant species included *B. pilosa*, *G. parviflora*, *S. pinnata*, *Eleusine indica*, and *Setaria verticillata* at Chuka and *A. hybridus*, *B. pilosa*, *E. indica*, and *S. media* at Thika, whose dominance generally declined over successive rotations. Intercropping baby corn/*Mucuna* and maize/*Mucuna* in ORG-high and maize/beans and kales/Swiss chard in ORG-low substantially reduced weed densities compared with corresponding monocrops and CONV-low. Organic systems

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supported higher weed diversity and evenness (H' up to ~ 2.0 ; $E_H > 0.8$) than CONV systems, indicating more functionally diverse, less dominance-driven weed communities. These results highlight that integrating crop rotation, strategic intercropping, and tailored nutrient management can reduce weed seedbank build-up and dominance of problematic species while maintaining diverse weed communities compatible with sustainable, low-herbicide smallholder farming systems.

1 | Introduction

Weeds persist in agricultural soil, and when left unmanaged, they greatly reduce crop yield by competing with crops for nutrients, light, and soil moisture. Globally, weeds are associated with about 40% yield loss per year [1]. Yield loss due to weeds varies by crop, weed species, agroecological location, and farming system, that is, the combination of management practices (e.g., tillage, inputs, and crop diversity) used in a given agricultural production system [2]. For instance, despite advances in control technologies, weeds reduce crop productivity in organic farming systems because they can adapt in response to new management measures [3, 4].

In agricultural soils, weed flora changes over time, with either increasing or decreasing species abundance depending on the farming practices [5, 6]. Weed seed banks reflect the status of weed populations in the present and the past and could be regarded as an indicator of the impact of soil and crop management on weed diversity dynamics [7]. Crop rotation, fertilizer application, tillage practices, agrochemical use, and other agricultural practices affect the soil seedbank and weed flora [8]. Within an integrated farming approach, the development of cropping systems such as appropriate spatial arrangement and efficient tillage helps crops to compete with weeds efficiently [9]. However, changing cropping systems for the purpose of improving integrated weed management requires a good understanding of weed dynamics and influences of crop- and soil-related factors on weed life cycles [1].

As a result of weeds being a major concern in crop production, the majority of conventional farmers have embraced the use of herbicides, which is regarded as the most reliable and effective weed management method [10]. Despite herbicides being effective, their overuse has led to human, animal, and environmental health concerns [1]. Moreover, over-reliance on herbicides has led to increased herbicide-resistant weed species [11, 12]. For instance, 273 weed species (156 dicots and 117 monocots) have developed resistance to 168 different herbicides worldwide [13]. These weed species become dominant and difficult to control over time [14, 15].

Due to herbicide-resistant weeds, farmers have turned to other weed management practices such as crop rotation to manage them [5, 6, 16]. Each crop imposes specific biotic and abiotic constraints on the weed community, favoring some species and suppressing others, acting as a filter for weed survival [17]. Rotating crops changes these selection pressures, reducing the repeated success of any single weed species and increasing weed mortality because different crops require different management practices [18]. Consequently, the likelihood of a weed being tolerant to multiple control methods, such as crop rotation and integrated weed management, is lower than with a single method [19]. Diverse rotations can reduce weed density by up to 49% compared to continuous cropping [20]. Additionally, planting a dense-canopy crop before a more weed-sensitive crop can suppress weed growth [21], as seen with lower weed density of

Amaranthus hybridus and *Chenopodium album* L. when maize follows hay in a rotation [22].

Through long-term variation of crop species and planting times, crop rotation creates a changing environment that disrupts the regeneration niche of different weed species and prevents dominance of a particular weed species [16, 23]. This results in a diverse weed community, which has less effect on crop yield compared to a weed community that is dominated by just a few weed species [24]. Weed-associated yield loss is substantially reduced in diverse weed communities [25]. There is also increasing evidence that a more diverse weed community is less competitive with any given crop [24, 26]. This is because weed species with different phenologies and resource demands are less likely to overlap with those of the crop compared with a low diversity of highly crop-mimicking weed species [25].

Fertilizer use affects crop growth as well as the diversity and composition of weed species by altering soil fertility [27]. Different fertilizer types and rates influence weed species differently due to diverse weeds' demands for various nutrients [28]. High-fertility amendments, particularly nitrogen (N), can lead to an increase in the density of weed species that are both responsive to and competitive under high nutrient conditions [29]. Nitrogenous fertilizer can also stimulate germination and emergence of various weed species [30], and weeds compete with crops for N, reducing its availability to the crop [31]. Phosphorus (P) and potassium (K) fertilizers influence weed species composition; for example, *Cyperus rotundus* L. is often dominant in fields with high P and K application [32]. Therefore, nutrient management strongly shapes weed populations and their interactions with crops, making it an essential consideration in effective weed management strategies [29]. Compost manure, widely used by organic farmers, also presents weed-related challenges [33]. Using immature compost or fresh animal manure inadvertently introduces weed seeds into the farm [34–36].

In the Central Highlands of Kenya, widespread land fragmentation forces farmers to cultivate small plots, relying heavily on hand hoeing for land preparation [15]. Land intensification, adopted to boost food production, has also created challenges for weed management (Barman et al., 2014). Weed composition is shaped by both the crop type in season and the nutrients applied during cultivation [37, 38]. Understanding how organic and conventional nutrient management with rotational practices influences weed composition is important for effective weed control [39].

2 | Material and Methods

2.1 | Study Sites Description

The study was conducted within two ongoing long-term trials established in 2007 at Thika ($0^{\circ}20.864'S$; $37^{\circ}38.792'E$) and Chuka

(1°0.231'S; 37°04.747'E) in Kenya [40]. The two sites lie in the Upper Midlands 3 (UM3) agro-ecological zones and the Upper Midlands 2 (UM2), which are described as main maize (*Zea mays*) and coffee (*Coffea*)–sunflower (*Helianthus annuus*) zones [41], respectively. The areas receive bimodal rainfall, with long rains being received between March and June and short rains from October to December. Thika receives a mean annual rainfall of between 900 and 1100 mm, while Chuka receives rainfall of 1500–2400 mm; temperatures are around 20°C in both sites [42]. The soils at Thika are classified as *Rhodic Nitisols* and Chuka as *Humic Nitisols* [43, 44].

2.2 | Trial Design

The study compared conventional (CONV) and organic (ORG) farming systems under two fertilization levels (high and low). For the high fertilization levels, N and P (Table 1) were used according to the recommended rates for the area by the Kenyan Ministry of Agriculture and the Japanese International Co-operation Agency's local and export vegetable growing manual [45] and represented large-scale commercial farmers within the region. For the low levels, the rates of N and P applied (Table 1), and the management practices mimicked that of small-scale farmers in the region [46]. The high fertilization systems received supplementary irrigation during the dry periods, as well as pest and disease control upon identification [44]. The four farming systems assessed were arranged in a randomized complete block design (RCBD) with five replicates in Thika and four in Chuka with plots measuring 8 × 8 m and a net plot for sampling of 6 × 6 m.

The trials were initiated in 2007, but the study was only conducted between 2017 and 2019, with each year including two seasons, that is, short and long rains under a 3-year crop rotation. Selection of the crops for the rotation (Table 1) was done based on farmers' practices within the area, while the crop rotation was recommended by the Kenya Institute of Organic Farming (KIOF) [47].

2.3 | Field Management Practices and Treatment Description

Land was prepared before the onset of rains using a hand hoe in all four farming systems to achieve a fine tilth. Planting was done at the onset of rains at the two sites.

Each farming system involved specific combinations of nutrients tailored to the crops under consideration. In CONV-low, fresh farmyard manure (FYM), diammonium phosphate (DAP), and calcium ammonium nitrate (CAN) were used, ORG-low decomposed FYM was incorporated, and rock phosphate was augmented by *Tithonia* mulch and *Tithonia* plant tea for selected crops (Table 1). The CONV-high treatment encompassed the application of decomposed FYM, DAP, TSP, and CAN with varying amounts customized for specific crops (Table 1). ORG-high featured the utilization of compost, rock phosphate,

Tithonia mulch, and *Tithonia* plant tea (Table 1) [48]. After crop emergence, weeding was conducted once on the fourth week after emergence using a machete following recommended agronomic practices [49].

2.4 | Soil Sampling and Weed Identification

At the end of each cropping season, soil samples were collected from the four farming systems at the two experimental sites. Sampling was done using a soil auger, taking 12 cores per plot at a diameter of 2.7 cm and a depth of 0–20 cm, where most of the weed seeds occur and soil disturbances [50]. Four sampling points were randomly selected using the Y-method within the experimental net plot of 6 × 6 m and mixed thoroughly to come up with a homogenized sample.

The weed seedling emergence method was used to determine weed density and diversity [51, 52]. Before initiating germination, stones and pebbles that could hinder weed seed germination were removed through passing the soils in a 3 mm sieve. To ensure a high germination percentage of the weed seed, samples were treated with gibberellic acid at a concentration of 1000 mg·L⁻¹ [53] to break possible weed seed dormancy. After the preparations, soil samples were taken into the greenhouse and placed in germination trays measuring 375 mm × 300 mm × 30 mm each [54]. The setup mirrored the field design, consisting of four treatments with five replicates each in Thika (20 plots) and four replicates each in Chuka (16 plots). The trays were randomly arranged in the greenhouse. Temperatures inside the greenhouse were not controlled, and each tray was watered using a spray bottle with 300 mL of water on a daily basis to maintain moderate soil moisture favorable for weed seeds to germinate [54]. Lighting within the greenhouse was evenly distributed, giving each tray access to light. Counting and identification of emerged weeds started after 2 weeks at a point where the weed seedlings could be identified and continued on a weekly basis for 3 months.

The identification of weed species was conducted through a thorough examination of reproductive and vegetative elements, encompassing analyses of leaf morphology and leaf arrangement on the stem [55]. For precise identification of weed species, reference materials, such as guidebooks on weeds and specimen vouchers from National Agricultural Research Laboratories (NARL) at KALRO Kabete weed science laboratory, were used.

2.5 | Statistical Analysis

Weed density was calculated as the total weeds per square meter, while the weed species density was the total number of specific weed species per square meter. The following equations (1) and (2) were used to determine weed density and dominance, respectively. Weed species were considered to be dominant if their relative density was more than 10% of the total weed density [15].

$$\text{Weed density (plants m}^{-2}\text{)} = \frac{\# \text{ seedling germinated} * \text{Bulk density (kg m}^{-3}\text{)} * \text{sampling depth (m)}}{\text{Dry weight of soil sample (kg)}}, \quad (1)$$

$$\text{Relative density} = \frac{\text{Species density}}{\text{Total weed density}} \times 100. \quad (2)$$

TABLE 1 | System nutrient management in Chuka and Thika.

System	Year	Season	Crop in season	Nutrient management	Total N (kg·ha ⁻¹)	Total P (kg·ha ⁻¹)
CONV-low	2017	Long	Maize/common bean	Fresh FYM, 50 kg·ha ⁻¹ DAP	31	18
		Short	Common bean	No fertilizer application	na	na
	2018	Long	Maize/common bean	Fresh FYM, 50 kg·ha ⁻¹ DAP	31	18
		Short	Potatoes	Fresh FYM, 100 kg·ha ⁻¹ DAP	27	25
	2019	Long	Maize	Fresh FYM, 50 kg·ha ⁻¹ DAP	45	27
ORG-low	2017	Long	Swiss chard/kale	Fresh FYM, 50 kg·ha ⁻¹ TSP, 60 kg·ha ⁻¹ CAN	20	13
		Short	Maize/common bean	Decomposed FYM, 100 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch	31	18
	2018	Long	Common bean	No fertilizer application	na	na
		Short	Maize/common bean	Decomposed FYM, 100 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch	31	18
	2019	Long	Potatoes	Decomposed FYM, 200 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch	27	25
CONV-high	2017	Long	Maize	Decomposed FYM, 100 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch	45	27
		Short	Swiss chard/kale	Decomposed FYM, 90 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch, and tea	20	13
	2018	Long	Baby corn	Decomposed FYM, 200 kg·ha ⁻¹ DAP, 100 kg·ha ⁻¹ CAN	113	60
		Short	French bean	Decomposed FYM, 200 kg·ha ⁻¹ DAP, 100 kg·ha ⁻¹ CAN	113	60
	2019	Long	Potatoes	Decomposed FYM, 200 kg·ha ⁻¹ TSP, 200 kg·ha ⁻¹ CAN	103	83
ORG-high	2017	Long	Maize	Decomposed FYM, 200 kg·ha ⁻¹ DAP, 100 kg·ha ⁻¹ CAN	113	68
		Short	Cabbage	Decomposed FYM, 200 kg·ha ⁻¹ TSP, 300 kg·ha ⁻¹ CAN	145	64
	2018	Long	Baby corn/ <i>Mucuna</i>	Compost, 364 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch, and tea	113	60
		Short	French bean	Compost, 364 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch, and tea	113	60
	2019	Long	Potatoes	Compost, 364 kg·ha ⁻¹ rock phosphate, <i>Tithonia</i> mulch, and tea	103	83

Note: Maize/baby corn (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), potatoes (*Solanum tuberosum* L.), cabbage (*Brassica oleracea* var. *Pektor* F1), kales (*Brassica oleracea* L. var. *acephala*), and Swiss chard (*Beta vulgaris* L. var. *cicla*), CONV-high, conventional high; ORG-high, organic high; CONV-low, conventional low; ORG-low, organic low. CAN (27%N) = calcium ammonium nitrate, CAN was applied as top dressing in all the crops; in two splits for high fertilization only for specific crops in low fertilization. Compost preparation starts with the indicated amount of fresh farmyard manure (FYM) and is applied at planting. DAP (18% N, 46% P₂O₅) = diammonium phosphate; TSP (46% P₂O₅) = triple superphosphate; RP = rock phosphate. *Tithonia* mulch was applied after crop germination as starter N [44].

Abbreviation: na, not applicable.

Data were log-transformed to maintain normality. ANOVA was performed to estimate the significant differences among means of treatment systems, and Tukey's HSD Test at $p < 0.05$ in RStudio 4.3.2 was used to separate means. The weed species diversity and evenness in each rotational treatment were analyzed using the Shannon diversity index (H'); $H' = -\sum p_i \ln(p_i)$ and Shannon's evenness (E_H); $E_H = (H')/\ln(S)$ [56]. To determine the correlation of weed species and association with the four farming systems, principal component analysis (PCA) was performed on the standardized matrix of individual weed species density and the variance-covariance matrix, and the eigenvalue and eigenvector were determined for the PCA [57]. R Version 4.3.2 was used in all the analysis.

3 | Results

3.1 | Weed Density and Dominance Under Different Farming Systems and Rotations

Crop rotation influenced all the weed species across the four farming systems in Chuka and Thika. However, changes in the density of individual weed species were strongly dependent on the specific crop sequences within each rotation. In ORG-high, B. corn/*Mucuna*-French beans rotation decreased densities of *A. hybridus* (26.9%), *Stellaria media* (25%), and *Tagetes minuta* (57.3%) but led to an increase of the density of *B. pilosa* (48.8%), *Eleusine indica* (133.3%), and *Oxalis corniculata* L. (30.8%) (Table 2). In contrast, B. corn/*Mucuna*-potatoes rotation decreased the density of *B. pilosa* L. (56.5%) and *S. media* (57.8%), while allowing the re-establishment of *A. hybridus* and increasing the densities of *Oxalis corniculata* (60%), *Portulaca oleracea* L. (43%), *S. media* (33.3%), and *T. minuta* (17%).

In ORG-low, maize/beans-common beans rotation resulted in a decrease in density of *A. hybridus* (67.5%), *B. pilosa* (13.4%), and *S. media* (25%) alongside the re-establishment of *Galinsoga parviflora*. This also led to an increase in the density of *E. indica* by 53.4% and the reappearance of *Portulaca oleracea* (Table 2).

Under CONV-high, B. corn-French beans rotation decreased the densities of *E. indica* (28.3%) and *S. media* (53.33%), while enabling the re-establishment of *Fallopia convolvulus* (L.) *A. Love*, *A. hybridus*, and *T. minuta* (Table 2). Baby corn-potatoes rotation similarly reduced *S. media* (53.3%) but increased the density of *A. hybridus* (57%). In the maize-cabbage rotation, *S. media* density decreased by 32%, whereas *B. pilosa* increased by 65% (Table 2).

Within CONV-low, maize/beans-common bean, maize/common bean-potatoes and maize-kales/S. chard rotation resulted in a decrease in density of *A. hybridus* (76.5%), while *B. pilosa* was completely eliminated under the maize-cabbage rotation (Table 2). In contrast, *E. indica* density increased by 53% under both the maize/beans-common bean and maize-kales/S. chard rotations (Table 2).

In Chuka, under the ORG-high farming system, the B. corn/*Mucuna*-French bean, B. corn/*Mucuna*-potatoes, and maize/*Mucuna*-cabbage rotations resulted in a decrease in the densities of *B. pilosa* (5.4%), *Galinsoga parviflora* (33.2%), *Oxalis corniculata* (41.7%), and *Schkuhria pinnata* (88.9%). In ORG-low maize/beans-common beans, maize/common beans-potatoes,

and maize-kales/S. chard rotation led to decreases in the densities of *A. hybridus* (25%) and *G. parviflora* (57.8%) (Table 3).

In CONV-high system, B. corn-French beans, B. corn-potatoes, and maize-cabbage rotation reduced the densities of *S. pinnata* (56.2%) and *Setaria verticillata* (72%). However, this same rotation resulted in an increase in the density of *B. pilosa* (31.7%) (Table 3). Within CONV-low, overall weed densities declined by the end of the rotation sequences, with reduction observed for *G. parviflora* (38%), *S. pinnata* (50%), and *S. verticillata* (47%). In contrast, there was an increase in the weed density of *A. hybridus* (43.5%) and *O. corniculata* (50%).

3.2 | Impact of Farming Systems on Weed Species Density

Weed species density differed among management practices in Thika and Chuka, with responses strongly depending on species (Figures 1(a) and 1(b)). Across most species, the ORG-high input system supported higher mean density relative to the other farming systems, while CONV-low recorded the lowest densities for several species.

At Thika, *A. hybridus*, *B. pilosa*, *E. indica*, and *S. media* showed high density across the systems, while *C. album*, *C. benghalensis*, *F. convolvulus*, *G. parviflora*, *O. corniculata*, *P. oleracea*, *S. oleraceus*, and *T. minuta* showed low density across the systems. *B. pilosa* records a low mean density under CONV-low (0.39) compared to CONV-high (1.02), ORG-high (1.23), and ORG-low (1.09) (Figure 1(a)). Under high-input farming systems, *S. media* recorded higher mean densities in CONV-high (1.23) and ORG-high (1.16) relative to CONV-low (0.99) and ORG-low (0.93) (Figure 1(a)). The occurrence of *C. album* and *C. benghalensis* was only in organic farming systems and absent under conventional farming systems, whereas *P. oleracea* was observed only under the low-input systems and was absent under both conventional and organic high-input systems (Figure 1(a)).

At Chuka, CONV-high resulted in higher weed density compared to ORG-high, ORG-low, and CONV-low. Across the farming system, high weed density was recorded in *A. hybridus*, *B. pilosa*, *G. parviflora*, *O. corniculata*, *S. pinnata*, and *S. verticillata*, while low density was recorded in *C. album*, *C. benghalensis*, *F. convolvulus*, *S. media*, *P. oleracea*, *S. oleraceus*, and *T. minuta*. The mean density of *A. hybridus* was lower under the CONV-high (0.23) system compared to CONV-low (0.77), ORG-high (0.72), and ORG-low (0.64) (Figure 1(b)). The mean density of *B. pilosa* was higher in the conventional and organic high-input systems (CONV-high: 1.30; ORG-high: 1.28) than in the corresponding low-input systems (CONV-low: 0.64; ORG-low: 0.96) (Figure 1(b)). *G. parviflora* recorded higher mean density under CONV-high (1.30) compared with ORG-high (0.21), while *S. pinnata* showed greater mean density under ORG-low (1.13) than under ORG-high (0.27) (Figure 1(b)). The mean density of *S. verticillata* was higher under CONV-high (1.12) than under ORG-high (0.29) (Figure 1(b)). *Chenopodium album* and *S. media* occurred only under the conventional and organic high-input systems and were absent under both conventional and organic low-input systems (Figure 1(b)). In contrast, *C. benghalensis* only occurred under conventional high and low farming systems.

TABLE 2 | Density of weed species as influenced by farming system and crop rotation in Thika.

Crop	Organic high										Organic low										Conventional high											
	A. hybridus	B. pilosa	C. album	C. benghalensis	E. indica	O. corniculata	P. oleracea	S. oleraceus	S. media	T. minuta	A. hybridus	B. pilosa	C. album	C. benghalensis	E. indica	G. parviflora	O. corniculata	P. oleracea	S. oleraceus	S. media	T. minuta	A. hybridus	B. pilosa	C. benghalensis	E. indica	F. convolvulus	G. parviflora	O. corniculata	S. oleracea	S. media	T. minuta	
B. corn/mucuna	16.0 ^e	21.0 ^c	0.0 ^a	1.2 ^a	10.7 ^b	10.7 ^c	0.0 ^a	0.0 ^a	16.0 ^c	15.7 ^f																						
French beans	11.7 ^d	31.3 ^e	7.0 ^d	0.0 ^a	25.0 ^e	14.0 ^d	0.0 ^a	11.0 ^d	12.0 ^b	6.7 ^d																						
B. corn/mucuna	3.0 ^{ab}	23.0 ^d	0.0 ^a	0.0 ^a	13.0 ^c	0.0 ^a	0.0 ^a	3.0 ^b	18.0 ^d	0.0 ^a																						
Potatoes	6.0 ^c	10.0 ^b	0.0 ^a	0.0 ^a	14.0 ^d	6.0 ^b	4.3 ^b	0.0 ^a	23.0 ^e	1.7 ^b																						
Maize/mucuna	2.0 ^a	7.0 ^a	6.0 ^c	3.9 ^c	11.0 ^b	6.0 ^b	0.0 ^a	7.0 ^c	10.7 ^a	2.7 ^c																						
Cabbage	3.7 ^b	21.0 ^c	2.3 ^b	2.0 ^b	9.0 ^a	7.0 ^b	0.0 ^a	7.0 ^c	11.0 ^a	11.7 ^e																						
LSD	1.085	0.86	0.92	0.94	0.86	1.03	0.43	0.94	0.43	0.43																						
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001																						
Maize/beans	12.3 ^f	12.7 ^d	0.0 ^a	0.0 ^a	8.3 ^d	9.0 ^b	0.0 ^a	0.0 ^a	0.0 ^a	12.0 ^e																						
Common beans	4.0 ^c	11.0 ^c	0.0 ^a	0.0 ^a	13.0 ^f	0.0 ^a	0.0 ^a	11.0 ^d	3.0 ^c	9.0 ^c																						
Maize/C. beans	0.0 ^a	21.0 ^e	0.0 ^a	0.0 ^a	12.0 ^e	0.0 ^a	0.0 ^a	5.0 ^c	0.0 ^a	10.7 ^d																						
Potatoes	6.0 ^d	23.0 ^f	0.0 ^a	0.0 ^a	4.0 ^b	9.0 ^b	2.0 ^b	3.0 ^b	2.0 ^b	4.0 ^a																						
Maize	3.0 ^b	6.0 ^a	3.0 ^b	4.0 ^c	7.0 ^c	0.0 ^a	0.0 ^a	3.0 ^b	2.0 ^b	11.0 ^d																						
Kales/S. chard	8.0 ^e	9.0 ^b	4.0 ^c	2.0 ^b	0.0 ^a	0.0 ^a	0.0 ^a	3.0 ^b	2.0 ^b	8.0 ^b																						
LSD	0.92	0.43	0.94	0.94	0.79	0.94	0.74	0.74	0.94	0.86																						
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001																						
B. corn	22.7 ^c	33.7 ^f	0.0 ^a	30.7 ^d	11.7 ^c	20.7 ^b	0.0 ^a	0.0 ^a	45.0 ^e	22.7 ^c																						
French beans	0.0 ^a	31.0 ^e	12.0 ^b	22.0 ^c	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	21.0 ^c	0.0 ^a																						
B. corn	7.0 ^c	9.0 ^c	0.0 ^a	32.0 ^e	4.0 ^b	0.0 ^a	7.0 ^b	7.0 ^b	25.7 ^d	0.0 ^a																						
Potatoes	11.0 ^d	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	12.0 ^b	1.7 ^b																						
Maize	0.0 ^a	7.0 ^b	0.0 ^a	9.0 ^b	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	10.3 ^b	0.0 ^a																						
Cabbage	6.0 ^b	20.0 ^d	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	0.0 ^a	7.0 ^a	0.0 ^a																						
LSD	0.92	0.79	0.74	0.92	0.79	0.43	0.74	0.74	2.95	0.54																						
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001																						

(Continues)

TABLE 2 | (Continued)

	Conventional low									
	<i>A. hybridus</i>	<i>B. pilosa</i>	<i>C. bengalensis</i>	<i>E. indica</i>	<i>O. corniculata</i>	<i>P. oleracea</i>	<i>S. oleraceus</i>	<i>S. media</i>	<i>T. minuta</i>	
Maize/beans	17.0 ^f	21.0 ^d	1.0 ^a	8.0 ^b	0.0 ^a	0.0 ^a	0.0 ^a	18.7 ^f	0.0 ^a	
common beans	12.0 ^e	0.0 ^a	1.3 ^a	14.0 ^d	2.0 ^b	0.0 ^a	0.0 ^a	13.0 ^d	3.7 ^b	
Maize/C. beans	5.0 ^c	6.0 ^c	0.9 ^a	13.0 ^c	0.0 ^a	0.0 ^a	4.0 ^b	5.0 ^a	0.0 ^a	
Potatoes	0.0 ^a	2.0 ^b	1.2 ^a	13.0 ^c	6.0 ^d	4.3 ^b	0.0 ^a	14.0 ^e	0.0 ^a	
Maize	11.0 ^d	0.0 ^a	5.7 ^c	0.0 ^a	3.0 ^c	0.0 ^a	0.0 ^a	6.0 ^b	0.0 ^a	
Kale/S. chard	4.0 ^b	0.0 ^a	3.1 ^b	17.0 ^e	3.0 ^c	0.0 ^a	0.0 ^a	9.0 ^c	0.0 ^a	
LSD	0.74	0.99	0.94	0.74	0.94	0.43	0.74	0.858	0.43	
<i>p</i> value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	

Note: *A. hybridus*, *Amaranthus hybridus* L.; *B. pilosa*, *Bidens pilosa* L.; *C. album*, *Chenopodium album* L.; *C. bengalensis*, *Commelina benghalensis* L.; *E. indica*, *Eleusine indica* L.; *F. convolvulus*, *Fallopia convolvulus* (L.) A. Love; *G. parviflora*, *Galinsoga parviflora* Cav.; *O. corniculata*, *Oxalis corniculata* L.; *P. oleracea*, *Portulaca oleracea* L.; *S. oleraceus*, *Sonchus oleraceus* L.; *S. media*, *Stellaria media* (L.) Vill.; *T. minuta*, *Tagetes minuta* L.; *B. corn*, baby corn; *C. beans*, common beans; *S. chard*, Swiss chard. The mean of values with similar letters in the same column denotes no significant difference at $p \leq 0.05$.

3.3 | Influence of Farming System and Crop Seasons on Dominant Weed Species

Weed species were considered to be dominant if their relative density was more than 10% of the total weed density. *Bidens pilosa* was the most dominant weed species on both sites. Dominant weed species in Chuka were *B. pilosa*, *G. parviflora*, *S. pinnata*, *E. indica*, and *S. verticillata* in the four-farming system (Figure 2). The dominance of *G. parviflora* remained high during long rains in ORG-high and CONV-high farming systems. However, by the end of crop seasons in 2019 long rains, the dominance of *G. parviflora* had reduced by 31.5% and 34.8% in ORG-high and CONV-high, respectively (Figure 2). Cropping seasons influenced the dominance of *S. verticillata* under the CONV-high farming system, resulting in its decrease in dominance by 52% by the end of the 2019 short rain cropping season (Figure 2). The rotational practice resulted in the decline in the weed density of *G. parviflora*, *S. pinnata*, and *S. verticillata* by the end of the cropping season, 2019 short rains, at Chuka (Figure 2). Despite the dominance of *B. pilosa* and *G. parviflora*, their density was highly influenced by the rotation practices under ORG and CONV-low systems.

At Thika, the dominant weed species were *A. hybridus*, *B. pilosa*, *E. indica*, and *S. media* (Figure 3). Under the high fertilization regimes, the relative density of *A. hybridus* declined by 52% and 57% under ORG-high and CONV-high, respectively, while that of *S. media* decreased by 46.2% in CONV-high systems (Figure 2). In contrast, under the CONV-low farming systems, *E. indica* increased in dominance by 25%, whereas *A. hybridus* declined by 25% (Figure 2).

3.4 | Weed Species Diversity as Influenced by Organic and Conventional Farming Systems and Cropping Seasons in Thika and Chuka

There was a significant difference in weed species diversity within the four treatments over the study period. Weed diversity indices at Thika ranged from $H' = 0.92$ to 1.97, while at Chuka they ranged from $H' = 1.33$ to 2.06 (Figure 3). Within the CONV-high farming system, weed species diversity at Thika decreased from $H' = 1.88$ in 2017 to $H' = 0.94$ in 2019 compared with the ORG-high system, where diversity increased from $H' = 1.76$ in 2017 to $H' = 1.89$ in 2019. A similar pattern was observed at Chuka, where diversity under CONV-high decreased from $H' = 1.92$ in 2017 to $H' = 1.43$ in 2019, whereas under ORG-high it remained high, changing from $H' = 2.02$ in 2017 to $H' = 2.04$ in 2019 (Figure 3).

Overall, the ORG-high farming system exhibited higher weed species diversity than the CONV-high system at both sites, with diversity indices of $H' = 1.89$ and $H' = 0.94$ at Thika and $H' = 2.04$ and $H' = 1.43$ at Chuka, respectively (Figure 3). Similarly, under low-input systems, weed species diversity was greater under ORG-low than under CONV-low at Thika ($H' = 1.48$ vs. 1.32) and at Chuka ($H' = 1.87$ vs. 1.55) (Figure 3). The ratios of diversity indices (H') for ORG-high to CONV-high and ORG-low to CONV-low were 2:1 and 2:1.4, respectively, at Thika, and 2:1.8 and 2:1.6, respectively, at Chuka (Figure 3).

3.5 | Shannon's Evenness Index ($E_{H'}$) of Weed Species at Chuka and Thika

Weed species evenness ($E_{H'}$) across the four farming systems ranged from 0.78 to 0.99 at Thika and from 0.82 to 0.99 at Chuka,

TABLE 3 | Density of weed species as influenced by farming systems and crop rotation in Chuka.

Crop	Organic high									
	A. hybrid	B. pilosa	F. convolvulus	G. parviflora	O. corniculata	P. oleracea	S. media	T. minuta	S. pinnata	S. verticillata
B. corn/mucuna	12.0 ^e	24.3 ^d	0.0 ^a	19.0 ^e	11.0 ^e	12.0 ^d	0.0 ^a	9.0 ^c	18.0 ^e	23.0 ^d
French beans	0.0 ^a	16.0 ^b	2.0 ^b	12.0 ^a	0.0 ^a	0.0 ^a	2.0 ^b	0.0 ^a	14.0 ^d	14.0 ^c
B. corn/mucuna	6.0 ^c	16.0 ^b	0.0 ^a	16.0 ^d	7.0 ^d	3.0 ^b	9.0 ^d	3.0 ^b	11.3 ^c	11.0 ^b
Potatoes	9.0 ^d	9.0 ^a	8.0 ^c	12.0 ^a	0.0 ^a	11.0 ^c	4.0 ^c	0.0 ^a	7.0 ^b	10.0 ^b
Maize/mucuna	2.0 ^b	35.0 ^e	0.0 ^a	14.0 ^c	4.0 ^b	0.0 ^a	0.0 ^a	3.0 ^b	21.0 ^f	0.0 ^a
Cabbage	12.0 ^e	23.0 ^c	0.0 ^a	12.7 ^b	6.0 ^c	0.0 ^a	0.0 ^a	11.0 ^d	2.0 ^a	24.3 ^e
LSD	0.74	0.86	0.94	0.43	0.94	1.00	1.00	0.94	0.43	1.33
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Crop	Organic low									
	A. hybridus	B. pilosa	G. parviflora	O. corniculata	P. oleracea	S. pinnata	S. verticillata	S. oleraceus	T. minuta	
Maize/beans	12.0 ^d	7.0 ^b	23.0 ^d	21.0 ^e	7.0 ^d	0.0 ^a	3.0 ^a	0.0 ^a	0.0 ^a	
Common beans	0.0 ^a	19.0 ^f	9.0 ^a	1.0 ^a	0.0 ^a	2.0 ^b	11.0 ^c	2.0 ^b	5.0 ^b	
Maize/C. beans	10.0 ^d	8.3 ^c	13.9 ^c	7.0 ^d	6.0 ^d	0.0 ^a	3.0 ^b	0.0 ^a	0.0 ^c	
Potatoes	0.0 ^a	4.0 ^a	8.6 ^a	1.3 ^a	0.0 ^a	2.0 ^b	3.0 ^a	2.0 ^b	7.0 ^a	
Maize	5.0 ^b	15.0 ^e	14.0 ^b	3.8 ^b	2.3 ^b	0.0 ^a	3.3 ^a	0.0 ^a	0.0 ^a	
Kales/S. chard	9.0 ^c	9.0 ^d	9.7 ^a	5.6 ^c	4.0 ^c	4.0 ^c	3.0 ^a	4.0 ^c	0.0 ^a	
LSD	0.93	0.43	0.92	0.94	1.14	1.00	0.43	1.00	0.94	
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	
Crop	Conventional high									
	B. pilosa	C. album	G. parviflora	O. corniculata	S. oleraceus	S. pinnata	S. verticillata	S. oleraceus	S. pinnata	S. verticillata
B. corn	15.7 ^a	0.0 ^a	23.0 ^d	23.0 ^e	23.0 ^e	13.3 ^c	25.0 ^f			
French beans	17.0 ^b	3.0 ^b	21.0 ^c	12.0 ^c	3.0 ^b	13.0 ^c	19.3 ^e			
B. corn	17.0 ^b	0.0 ^a	22.0 ^{cd}	4.0 ^b	5.0 ^c	6.0 ^b	14.0 ^d			
Potatoes	24.0 ^d	21.0 ^c	17.0 ^b	21.0 ^d	14.0 ^d	5.0 ^a	13.0 ^c			
Maize	24.0 ^d	0.0 ^a	21.0 ^c	0.0 ^a	0.0 ^a	5.0 ^a	9.0 ^b			
Cabbage	23.0 ^c	0.0 ^a	15.0 ^a	0.0 ^a	0.0 ^a	6.0 ^b	7.0 ^a			
LSD	0.429	0.939	1.286	0.939	0.939	0.4288	0.4288			
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001			

(Continues)

TABLE 3 | (Continued)

	Conventional low								
	<i>A. hybridus</i>	<i>B. pilosa</i>	<i>F. convolvulus</i>	<i>G. parviflora</i>	<i>O. corniculata</i>	<i>P. oleracea</i>	<i>T. minuta</i>	<i>S. pinnata</i>	<i>S. verticillata</i>
Maize/beans	13.0 ^c	8.0 ^{bc}	6.0 ^b	21.0 ^c	6.0 ^b	23.0 ^c	0.0 ^a	22.0 ^e	17.0 ^d
Common beans	2.0 ^b	7.0 ^b	0.0 ^a	13.0 ^b	0.0 ^a	6.0 ^b	0.0 ^a	13.0 ^d	8.3 ^{bc}
Maize/C. beans	12.0 ^c	13.0 ^d	14.0 ^c	13.0 ^b	8.0 ^c	0.0 ^a	8.0 ^b	6.0 ^b	7.0 ^b
Potatoes	0.0 ^a	9.3 ^c	0.0 ^a	13.0 ^b	0.0 ^a	6.0 ^b	19.0 ^c	3.0 ^a	5.0 ^a
Maize	3.0 ^b	0.0 ^a	0.0 ^a	0.0 ^a	13.0 ^d	0.0 ^a	0.0 ^a	4.7 ^b	7.0 ^b
Kales/S. chard	23.0 ^d	0.0 ^a	0.0 ^a	13.0 ^b	12.0 ^d	0.0 ^a	0.0 ^a	11.0 ^c	9.0 ^c
LSD	0.742	0.92	0.94	0.74	0.939	0.996	0.939	0.858	0.858
<i>p</i> value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Note: *A. hybridus*, *Amaranthus hybridus* L.; *B. pilosa*, *Bidens pilosa* L.; *C. album*, *Chenopodium album* L.; *F. convolvulus*, *Fallopia convolvulus* (L.) A. Love; *G. parviflora*, *Galinsoga parviflora* Cav.; *O. corniculata*, *Oxalis corniculata* L.; *P. oleracea*, *Portulaca oleracea* L.; *S. pinnata*, *Seckuhria pinnata* (Lam.) Thell.; *S. verticillata*, *Setaria verticillata* (L.) P. Beauv.; *S. oleraceus*, *Sonchus oleraceus* L.; *S. media*, *Stellaria media* (L.) Vill.; *T. minuta*, *Tagetes minuta* L. Values of mean followed by the same letter within the same column show no significant difference at $p \leq 0.05$.

with values varying according to farming system and cropping season over the study period (Figure 4). At Thika, weed species evenness declined under the CONV-high system from 0.99 to 0.89, representing a reduction of 10% over the 3-year crop-rotation cycle. In contrast, the ORG-low system at Thika showed an increase in weed species evenness, rising from 0.91 to 0.96 (5.5%) by the end of the rotation period (Figure 4).

At Chuka, a similar pattern was observed, although the magnitude of change differed among systems. Weed species evenness under CONV-high declined from 0.97 to 0.86 (11.3%), while organic systems maintained relatively higher evenness values across seasons. By the end of the 2019 short rain season, differences in weed species evenness were evident between the ORG-low and CONV-low systems at Chuka, whereas at Thika, evenness under low-input systems remained comparatively stable (Figure 4). This indicates that high-input conventional management tended to reduce weed species evenness over time, while organic systems, particularly under low-input conditions, maintained or enhanced evenness across seasons.

3.6 | Clustering of Weed Species as Influenced by Farming Systems

PCA was used to examine the relationship between weed species composition and farming systems at Thika and Chuka (Figure 5). At Thika, the first two principal components explained 80.4% of the total variation in the weed species composition (Figure 5). The conventional high fertilization showed a negative correlation for PC1 and PC2 at both sites, indicating a distinct weed assemblage associated with this management practice (Figure 5). Species such as *E. indica*, *S. media*, *A. hybridus*, *F. convolvulus*, and *C. benghalensis* were closely associated with CONV-high management. In contrast, ORG-high was positively associated with PC2 and was linked to species such as *S. oleraceus*, *C. album*, and *O. corniculata*, while ORG-low was associated with *P. oleracea*.

At Chuka, the first two principal components explained 80.9% of the total variation (Figure 5). Similar to Thika, the CONV-high farming system was negatively associated with both PC1 and PC2 and was linked to species such as *C. benghalensis*, *O. corniculata*, and *F. convolvulus* (Figure 5). In contrast, ORG-high was positively associated with PC2 and showed a close relationship with *S. media* and *C. album*, while ORG-low was associated with *A. hybridus* and *T. minuta*. PC2 showed a positive correlation to *B. pilosa*, *C. album*, and *S. media* and a negative correlation with *F. convolvulus* (Figure 5).

4 | Discussion

The composition of weed species and density across the study sites varied in response to fertilizer application rates, crop rotation sequences, and crop species. Notably, the ORG-high and CONV-high farming systems at both Chuka and Thika exhibited significantly higher weed density compared to ORG-low and CONV-low fertilization systems, which can be associated with high rates of fertilizer inputs applied in these farming systems. This can be associated with the addition of FYM, which at some point may contain weed seed, resulting in weed seed addition in the soil [58]. Moreover, fertilizer application also increases nutrient availability, which benefits not only the crop but also

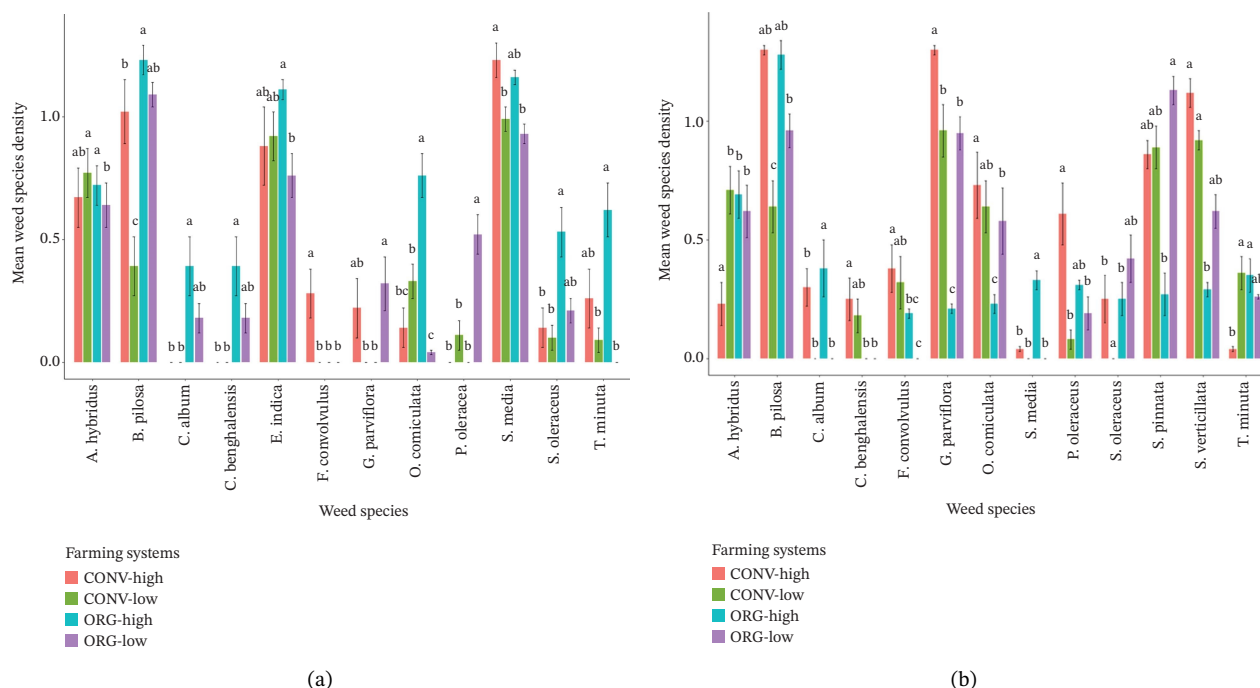


FIGURE 1 | (a, b) Mean weed density ($\pm$ SE) at Thika and Chuka under four management practices (CONV-high, CONV-low, ORG-high, ORG-low). Bars represent means, and error bars indicate standard errors. For each species, different letters above denote significant differences among treatments ($p < 0.05$).

weeds, thus resulting in an increase in their density in subsequent seasons, as also observed by Allan et al. [59].

Fertilizer application influenced the density of *B. pilosa*, *A. hybridus*, and *S. media* in Thika and *A. hybridus*, *B. pilosa*, and *G. parviflora* in Chuka. Fertilizer application affects not only the crop growth but also the diversity of the associated weed species [60]. The effect of fertilizer on weed density and diversity is also influenced by the rates of application and the nutrient composition of the fertilizer [61].

High fertilizer applications under ORG-high and CONV-high farming systems favored the growth of *S. media*, *S. oleraceus*, *A. hybridus*, *B. pilosa*, *C. album*, *F. convolvulus*, *C. benghalensis*, and *G. parviflora*. These weeds have also been reported in other studies as high soil fertility indicators [62, 63]. At Chuka, farmers use *A. hybridus*, *B. pilosa*, *G. parviflora*, and *C. benghalensis* as major indicators of high soil fertility in farms [64]. This shows that high fertilizer application rates enable the weed species to grow faster and produce more seeds [65].

Low fertilization in both organic and conventional systems was associated with *P. oleracea*, *T. minuta*, and *S. pinnata*; these weed species thrive under low soil fertility, and they are used as indicators of low soil [66]. Increased fertilizer application rates resulted in a decrease in the density of *P. oleracea*, indicating that the weed thrives well under low soil fertility [67, 68]. Research done in Chuka indicated that *S. pinnata* establishes well in low-fertile soils and is used as an indicator for low soil fertility [64].

The use of intercrops during cropping seasons enhances the utilization of resources such as light, soil moisture, and uncovered spaces on the farm that give room to emerging weeds. The effectiveness of weed management by use of intercrops was observed in the ORG-high farming system, where weed density

was low during the intercrop of *B. corn/Mucuna* and maize/*Mucuna* seasons. The effectiveness of *B. corn/Mucuna* intercrop in reducing weed density in the ORG-high farming system compared to *B. corn* monocrop in CONV-high has also been observed in other publications [69, 70]. *Mucuna*, being a cover crop, reduced weed density by 52% when intercropped with maize [71]. This reduction is attributed to the ability of *Mucuna* to suppress weeds [72]. Intercropping of maize and beans in ORG-low proved to be a better method to control *B. pilosa* compared to a maize monocrop [73].

Different management practices under the four farming systems influenced the density of eight dominant weed species differently. The dominance of *B. pilosa* within the four farming systems in both sites indicated its adaptability within two different geographical regions [74]. Its dominance can be linked to its vigorous growth, high nutrient use efficiency, high seed production over a short growth period, and efficient seed dispersal mechanism [75]. *Bidens pilosa* produces more seed under nitrogen-rich soils [76], and this can be associated with its high density under CONV-high and ORG-high farming systems in the two-trial sites.

At Chuka, *G. parviflora* was highly adaptive across all the four farming systems, which can be associated with a wide range of environmental and soil conditions, lack of seed dormancy, high seed germination rates, and rapid growth [77]. In Thika, dominance of *A. hybridus* and *S. media* within the four farming systems can be related to their high growth rate, high number of seeds produced with high germination percentage, and tolerance to stress [78–80].

High weed densities of *G. parviflora*, *S. pinnata*, and *E. indica* were observed in conventional farming systems where fertility was maintained using inorganic fertilizers [81]. *Galinsoga*

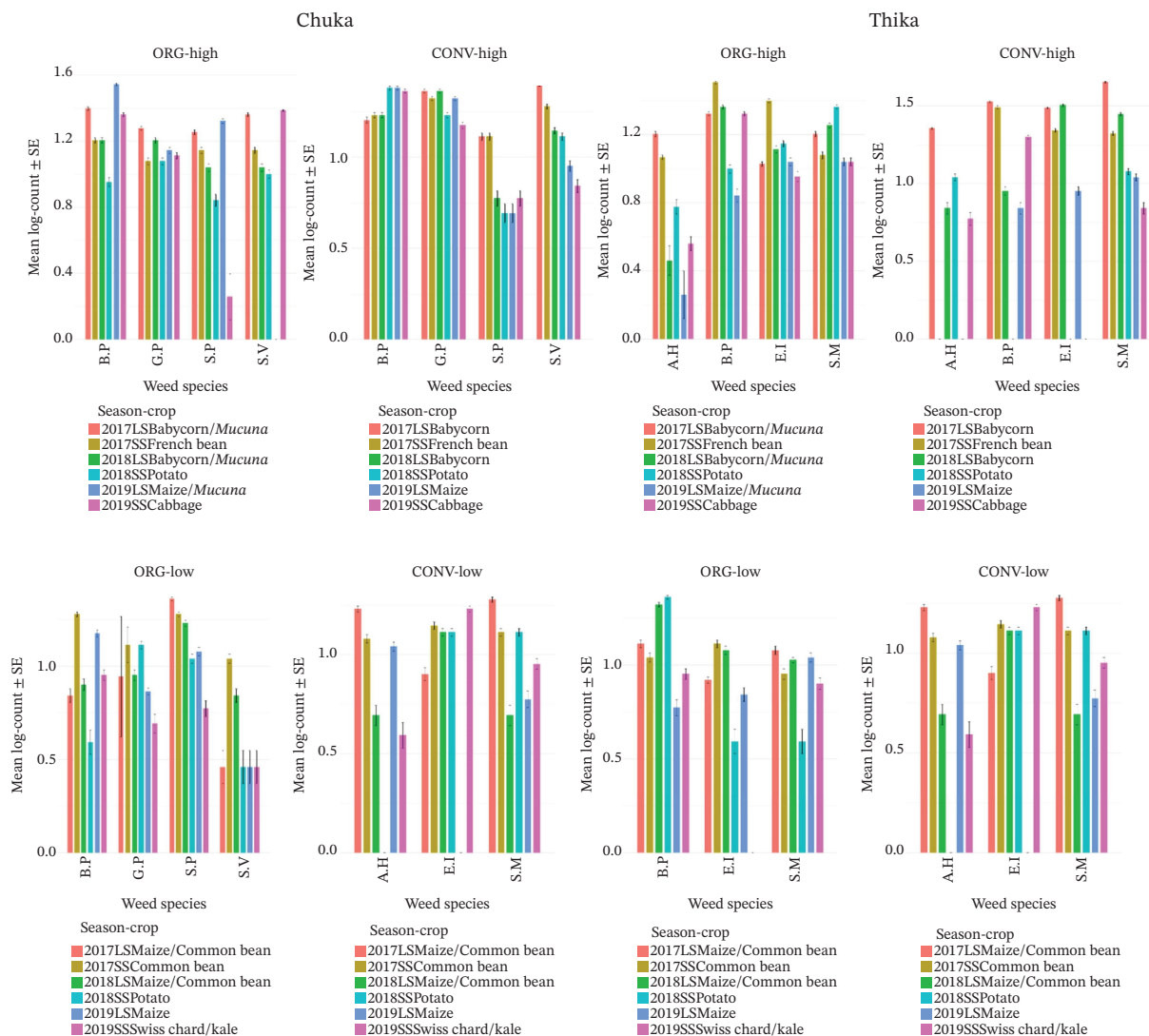


FIGURE 2 | Bar plot showing the mean of the weed density ($\pm$ SE) of dominant weed species within the four farming systems at Chuka and Thika between 2017 and 2019 long rains and short rains. Abbreviations: B.P., *Bidens pilosa* L.; CONV-high, conventional high; CONV-low, conventional low; E.I., *Eleusine indica* L.; G.P., *Galinsoga parviflora* (Cav.); ORG-high, organic high; ORG-low, organic low; LRS, long rain season; S.M., *Stellaria media* (L.) Vill.; S.P., *Schkuhria pinnata* (Lam.) Thell; S.V., *Setaria verticillata* (L.); A.H., *Amaranthus hybridus* L.; SRS, short rain season; SS, short season; LS, long season.

parviflora and *E. indica* were dominant in plots with inorganic fertilizers compared to those with organic inputs [81]. In a three-course crop rotation, *G. parviflora* showed 16.6% dominance [82], while in bean fields its dominance exceeded 50% [83]. *Schkuhria pinnata* was also reported as the most dominant weed species under different weed management practices in maize farms [84].

Integration of different management practices, intercropping and crop rotation helps to destabilize weed species that are resistant to a particular management practice [85, 86]. This can be associated with the reduction in the weed density of *S. verticillata*, *S. pinnata* and *S. media* by the end of six cropping seasons. Variation of crop species and rotation creates a changing environment that disrupts the regeneration niche of different weed species and prevents dominance of a particular weed species [16].

Intercropping enhances resource use efficiency by reducing available light, soil moisture, and space for weed establishment, thereby suppressing weed emergence [87]. In the ORG-high

farming system, intercropping B. corn/*Mucuna* and maize/*Mucuna* resulted in low weed density compared with maize monocropping, consistent with previous studies reporting strong weed suppression by the *Mucuna* cover crop [69, 70]. The weed-suppressive effect of *Mucuna* has been attributed to its rapid ground cover and smothering ability, reducing weed density by 52% when intercropped with maize [71, 72]. Similarly, maize-beans intercropping in ORG-low and CONV-low reduced the dominance of *B. pilosa* and *G. parviflora* compared to common beans or maize monocrops in 2017 and 2018, supporting evidence that cereal-legume intercropping effectively lowers weed density [73].

Organic farming systems supported high Shannon diversity compared to conventional farming systems [88, 89]. Shannon diversity in organic farming systems has been observed being twice higher compared to conventional farming systems [90]. Organic fertilizers encourage weed diversification compared to

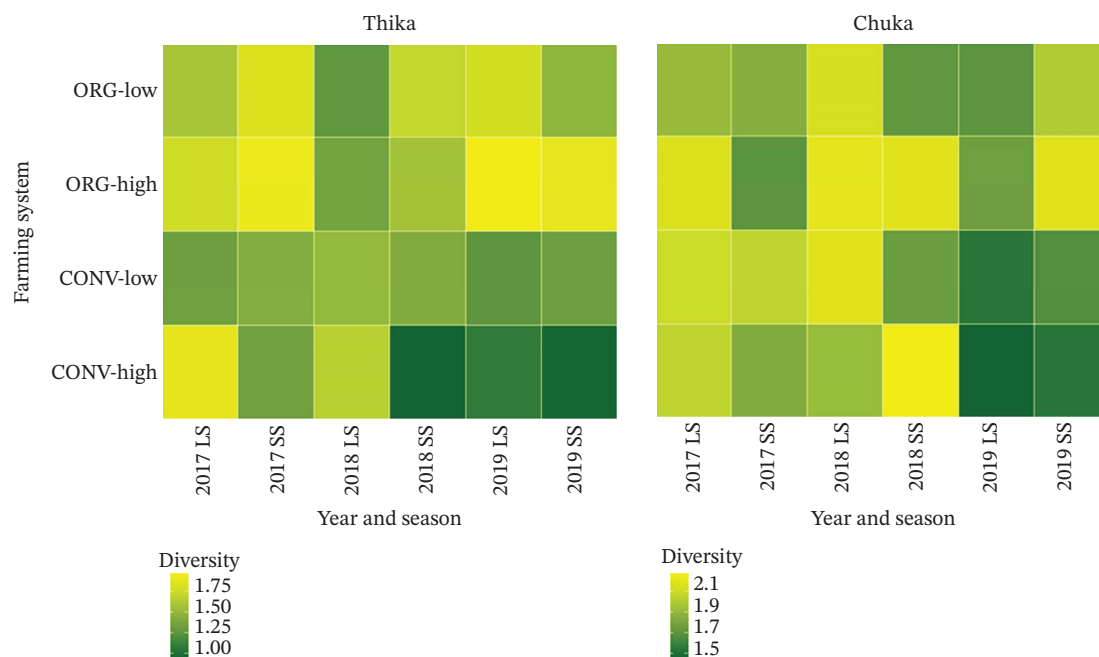


FIGURE 3 | Heat map showing weed species diversity (Shannon index) across farming systems and seasons at the Thika and Chuka sites from 2017 to 2019. Rows represent farming systems; abbreviations: CONV-high, conventional high; CONV-low, conventional low; ORG-high, organic high; ORG-low, organic low, while columns represent the combined year–season periods (long rains and short rains). Color intensity indicates the magnitude of weed species diversity, with darker colors representing higher diversity values.

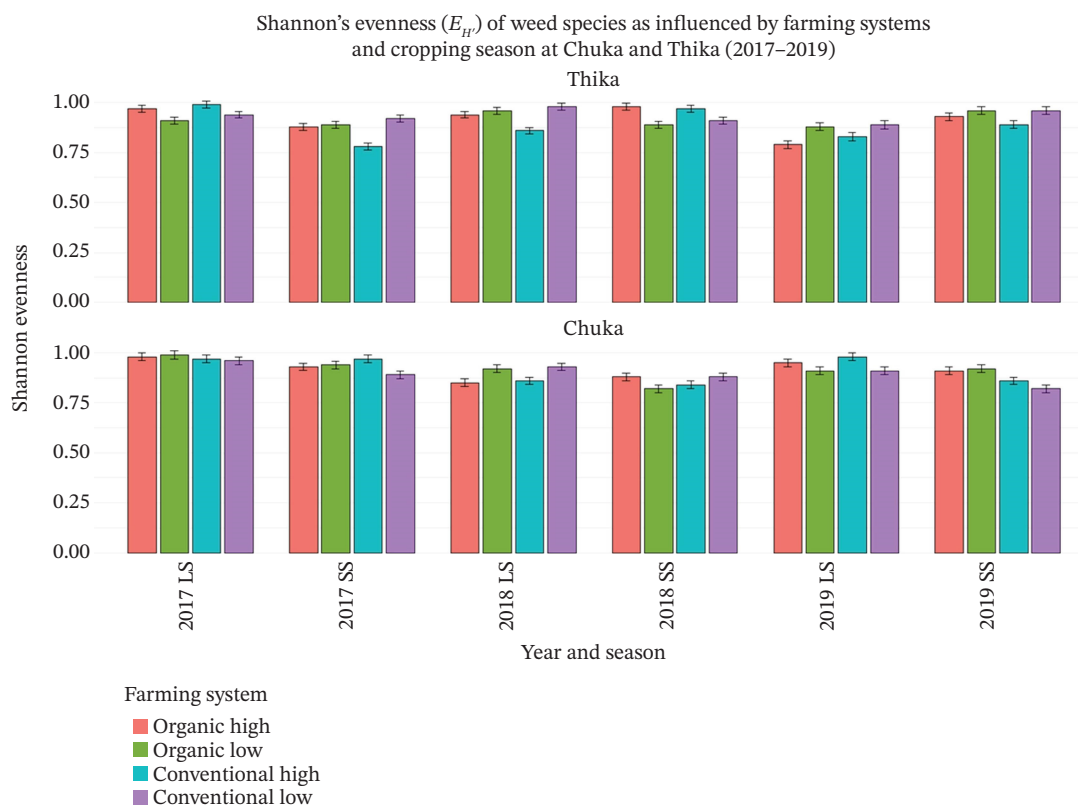


FIGURE 4 | Shannon evenness of weed species under four farming systems at Chuka and Thika across the long (LS) and short (SS) rainy seasons from 2017 to 2019. Bars represent mean evenness values, while error bars indicate the least significant difference (LSD). Farming systems are distinguished by color, and panels are separated by site to facilitate comparison of temporal and management-related patterns in weed species evenness.

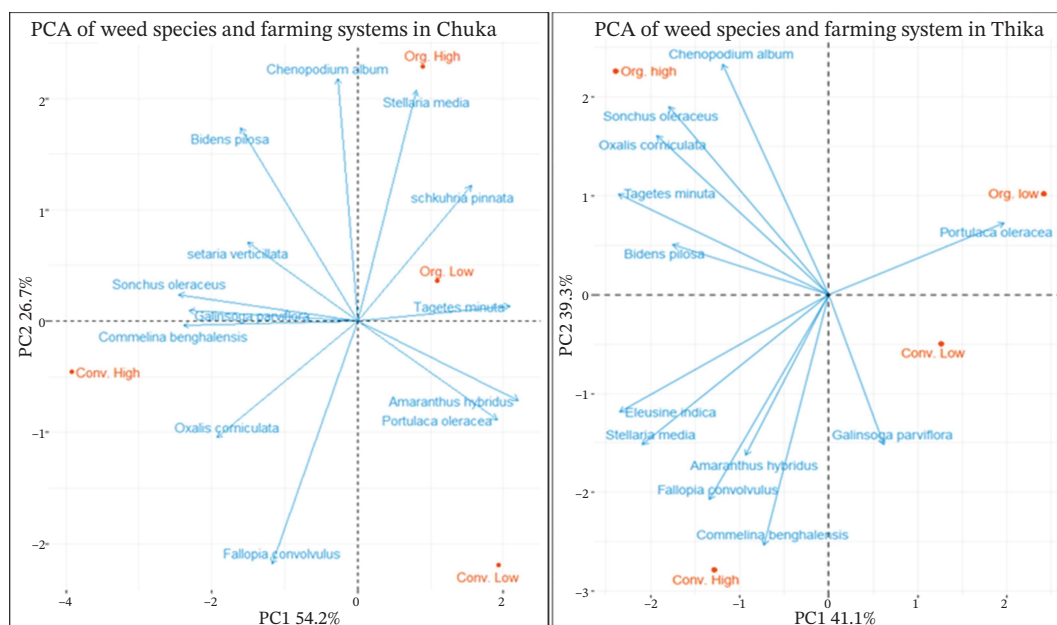


FIGURE 5 | Principal component analysis ordination biplot from correlation matrix with 13 weed species under four farming systems within six cropping seasons at Chuka and Thika. The farming system is labeled in orange and weed species in blue color. Farming systems: ORG-high, organic high; CONV-high, conventional high; ORG-low, organic low; CONV-Low, conventional low.

inorganic fertilizers, which hinders the growth of some weed species while encouraging the growth of others [91, 92].

High Shannon's evenness (> 0.8) across all farming systems reflects the effect of crop rotation in reducing weed species dominance [93]. However, organic systems consistently exhibited higher evenness than conventional systems, indicating more balanced weed communities [70, 94].

In conclusion, the composition of weed species is highly influenced by the type of fertilizer applied, the amount, and the management practices in place. Integration of crop rotation and intercropping demonstrated a reduction in weed density and disrupted dominant weed species, with crop choice playing a vital role. Baby corn/*Mucuna* and maize/*Mucuna* intercropping worked best in weed management in the ORG-high farming system. Organic farming practices lead to higher weed diversity and evenness compared to conventional farming practices. These findings emphasize the importance of precision in weed management strategies, considering fertilizer application and farming practices, to strike a balance between effective weed control and maintaining soil fertility.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The weed data used to support the findings of this study are available from the corresponding author upon request.

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