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Abdulrahman Lado

alado.agr@buk.edu.ng

International Institute of Tropical Agriculture, Ibadan Nigeria. C/o IITA Ltd

Muhammad A. Hussaini

Bayero University Kano

Auwal Abubakar

Bayero University Kano

Ismail I. Garba

Bayero University Kano

Adnan A. Adnan

Bayero University Kano

Bassam L. Abdulrahman

Bayero University Kano

Alpha Y. Kamara

International Institute of Tropical Agriculture, Ibadan Nigeria. C/o IITA Ltd

Fatima Z. Buhari

Bayero University Kano

Nafiu B. Sanda

Bayero University Kano

Ma'amun D. Aliyu

Bayero University Kano

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Weed Dynamics as Influenced by the Cropping Sequence and Season in the Kano River and Hadejia Valley Irrigation Projects of Northern Nigeria

Abdulrahman Lado[1] (corresponding author)*, Muhammad A. Hussaini[1], Auwal Abubakar[1], Ismail I. Garba[2], Adnan A. Adnan[1], Bassam L. Abdulrahman[3], Alpha Y. Kamara[4], Fatima Z. Buhari[1], Nafiu B. Sanda[5] and Ma'amun D. Aliyu[6]

[1]Department of Agronomy, Faculty of Agriculture, Bayero University Kano, 70001 Kano, Nigeria

[2]Centre for Dryland Agriculture, Bayero University Kano, 70001 Kano, Nigeria

[3]Department of Soil Science, Faculty of Agriculture, Bayero University Kano, 70001 Kano, Nigeria

[4]International Institute of Tropical Agriculture, Ibadan Nigeria. C/o IITA Ltd, Carolyn House, 26 10 Dingwall Road, Croydon CR9 3 EE, United Kingdom

[5]Department of Crop Protection, Faculty of Agriculture, Bayero University Kano, 70001 Kano, Nigeria

[6]Hadejia-Jama-are River Basin Development Authority, Kano

*Email of the corresponding author: alado.agr@buk.edu.ng

Abstract:

Background The prolonged practice of monoculture has been associated with the widespread proliferation of weed infestations, which constitute one of the major biotic constraints to food production under both rainfed and irrigated agricultural systems. In an effort to control these persistent pests, farmers frequently apply a range of pesticides. However, the indiscriminate and excessive use of such chemicals poses serious threats to the ecosystem and contributes to the rapid emergence of pesticide-resistant organisms.

Materials and Method Six-season trials were conducted over two years to assess the impact of various cropping sequences and seasons on weed growth, diversity, and composition at the Hadejia Valley and Kano River Irrigation Projects in northern Nigeria's Sudan savannah zone. A total of 38 rotation sequences were selected based on focus group discussions with farmers, community leaders, stakeholders, and literature review. These sequences were categorized into cowpea-based (3), maize-based (12), and rice-based (23) cropping sequences, arranged in a Randomized Complete Block Design with three replications. Data were collected on weed density (m^2), weed dry weight, and weed species composition.

Results Fifty-six weed species of the 71 species found throughout the study were in the maize-based sequence, 54 in the rice-based sequence, and 32 in the cowpea-based sequence. In the wet season, the cowpea-wheat–rice rotation sequence resulted in the highest biomass (231.4 g m^{-2}), whereas the cowpea-onion-rice rotation sequence resulted in the lowest biomass (165 g m^{-2}) in the cold season. The cowpea-tomato-rice rotation sequence resulted in a 13.4% greater weed density than the cowpea-wheat–rice rotation sequence did and a 10.4% greater weed density than the cowpea-onion-rice rotation sequence did during the rainy season. Maize–wheat–fallow had the most weeds (250.3 weeds m^{-2}), whereas maize–wheat–cowpea had the least (170.5 m^{-2}) in the rainy season. In terms of weed biomass, maize-tomato-fallow had the maximum amount (664.8 g m^{-2}) during the hot dry season, whereas maize–wheat-cowpea had the lowest amount (411.8 g m^{-2}). Rice-wheat-maize consistently supported more weeds during all seasons. In the cold season, the rice–wheat–fallow rotation sequence resulted in lower weed biomass (470.1 g m^{-2}), whereas in the hot dry season, the rice–wheat–fallow rotation sequence resulted in the maximum weed biomass (656.3 g m^{-2}).

Conclusions Rotation systems involving legumes, forage, and pasture decrease weed infestations and may be utilized as alternative methods of weed management. The conventional cereal–cereal rotation sequence encouraged weed infestation and should be discouraged.

Keywords: Important value index, weed morphology, weed density, weed biomass

Introduction

The growth of a variety of crop species on the same piece of land is known as crop rotation. This is not the same as continuous monoculture, which is the technique of cultivating a single crop species on the same piece of land, or intercropping, which is the practice of growing two or more crops simultaneously on the same piece of land. The most common rotation practices are one-year rotations, e.g., maize – mustard, rice – wheat. The use of different crops in

rotation sequences can create differences in resource competition and allelopathy, leading to the creation of an unfavorable environment for the growth and development of other plants [1, 2].

In the irrigated areas of the Hadejia Valley Irrigation Project (HVIP) and Kano River Irrigation Project (KRIP), a variety of crops are grown under a range of management circumstances, cropping patterns, and production techniques. Crop intensity has increased in irrigated areas as a result of rapid population growth and the ensuing intensification of agriculture caused by concerns about food security. Inappropriate rotation sequences in agricultural farming systems present several difficulties for farmers in the KRIP and HVIP. There is also a threat of rapid buildup of pests and diseases associated with the current unorganized rotation system. Weeds and other pests from other crops can spread and affect more crops. To control these widespread pests, farmers apply various pesticides that may seriously affect the ecosystem and rapidly build up pesticide-resistant organisms.

The advent of chemical pesticides and fertilizers, as well as improved cultivars, has been linked to a decrease in the use of extended rotation [3]. Currently, long rotations are frequently replaced with short-term rotations and extended monocultures. Although these technologies have proven effective, they are regrettably linked to drawbacks such as an increase in weed infestations, among others. Rotation has had a major impact on weed growth and development. According to Wozniak and Soroka [4], the dry weight of conventional monocultures is 51.1 times greater than that of rotation monocultures and 75% greater than that of rotation monocultures. Monocultures have been shown to worsen the phytosanitary conditions of crop stands and increase weed infestations [5].

Rotation is the most practical and cost-effective way to reduce weeds and other pests

since it breaks the life cycle of weeds [6]. This significantly lessens the need for weed pressure and the likelihood of herbicide resistance, which is a significant worldwide problem in weed control. This has resulted in a more significant shift in the diversity and organization of weed communities [4]. The number of weeds in the field increases significantly when monocultures are maintained. Growing crops in succession is one of the most effective ways to control weeds, but little is known about how seasons and rotation sequences affect weed population dynamics under KRIP and HVIP. To provide an alternative solution to these challenges, this study aimed to determine the effects of rotation sequence and season on weed population and growth under KRIP and HVIP.

Materials and methods

The research was carried out between 2020 and 2021. The trial was carried out in the hot dry season (April–June), cold dry season (December–March), and rainy season (July–November) each year. The sites were situated in the Sudan savannah zone of northern Nigeria, between latitudes 11°31'N to 11°52'N and longitudes 8°20'E to 8°40'E, at an elevation of 361 meters. They were part of the Kano River Irrigation Project (KRIP) and the Hadejia Valley Irrigation Project. Table 1 provides the monthly rainfall and maximum and minimum temperatures obtained from the dataset (from the experimental sites), which spans the period from January 2020 to December 2021. The area received significantly more rainfall in the rainy season, with no rainfall recorded in the cold dry season. Higher maximum temperatures were observed in the hot dry season, and the lowest temperature was observed in the cold dry season.

The trial included 38 rotation treatments, as indicated in Table 2. The cropping sequences were selected on the basis of focus group discussions with farmers, community leaders and other stakeholders in the study communities. The selected sequences were categorized into three

categories: cowpea-based (3), maize-based (12) and rice-based (23) cropping sequences. These included the traditional rotation pattern carried out by farmers considered to serve as a check for improved systems. The improved rotation patterns were developed on the basis of an extensive literature search. The seeds of cowpea (IT99K-573-1-1), maize (EVDT99) and soybean (TGX1835) were obtained from International Institute for Tropical Agriculture Kano substation while that of rice (FARO 44), wheat (Noman borlaugh) and groundnut (SAMNUT 24) were from International Crop Research Institute for Semi-arid Tropics, Kano substation. The seeds of fruits and vegetable such as Tomato (Chibil), Onion (Red creole) and watermelon were obtained from National Horticultural Crop Research Institute Bagauda substation, Kano State Nigeria. The seeds of Forage legumes (*Stylosanthesis guianensis*) and pasture grass (Bracharia) were obtained from National Animal Production Research Institute Shika-Zaria, Kaduna State Nigeria. In addition to applying fertilizer optimally for each crop, cultural practices were carried out according to the requirements of each crop in each season. Weeds inside 1 m^2 quadrants were identified [7] counted, removed from ground level prior to each weeding and taken to the herbarium unit of the Department of Plant Science and Biotechnology Bayero University, Kano where they were sorted into broadleaf, grasses, and sedges. The weeds were oven dried at 65°C. On the basis of the percentage of occurrence, the infestation levels of the identified weeds were evaluated as *=1--25%, **=26--50%, ***=51--75%, and ****=76--100%. The experimental research on plants (weed) was conducted in accordance with institutional and national guidelines governing the use of plant materials for scientific research in Nigeria. Field activities and sample collection complied with local agricultural and environmental regulations, and no endangered or protected plant species were involved in the study. Therefore, no special collection permits or licenses were required for the acquisition of the plant materials used.

The plant materials (weed) were formally identified and authenticated by qualified personnel in the Department of Plant Science and Biotechnology, Bayero University Kano, Nigeria. Identification was based on standard taxonomic and morphological characteristics relevant to the plant species under investigation. Accession specimens of the plant materials were prepared and deposited in the departmental herbarium for future reference under Accession Specimen **No. BUKHAN0008** (for *Leptochloa filiformis* (Lam.) P. Beauv*)* **to BUKHAN0691 (***for Cyathula prostrate* (L.) Blume**).** The study was conducted in compliance with relevant institutional, national, and international guidelines for experimental research on plants, including adherence to the principles of the Convention on the Trade in Endangered Species of Wild Fauna and Flora (CITES), where applicable.

Data for weed biomass, weed density and the morphological composition of the weeds were subjected to analysis of variance via Genstat 17th discovery editions, and significant treatment means were compared via HSD at a 5% probability level. The important value index (IVI) of a morphological group of weeds was computed [8] as follows:

$$\text{IVI} = \text{Relativedensity}(\%) + \text{Relativefrequency} + \text{Relativeabundance}(\%), \text{where}$$

$$\text{Relative density (RD)} = \frac{\text{Density of species}}{\text{Total density of all species}} \times 100$$

$$\text{Relative Abundance (RA)} = \frac{\text{Abundance of individual species}}{\text{Total abundance of all species}} \times 100$$

$$\text{Relative frequency (RF)} = \frac{\text{Frequency value of species}}{\text{Sum of frequency of all species studied}} \times 100$$

Results

Weed species composition

Twenty-one grass species, forty broadleaved species, and seven sedges were among the 68 weed species found at the experimental sites (Table 3). Of these, 51 species were found in maize-based rotation sequences, 56 in rice-based rotation sequences, and 32 in cowpea-based rotation sequences. In maize-based systems, 30 species were found during the wet season, 34 during the cold dry season, and as many as 39 during the hot dry season. In systems based on rice, however, 43 species were recorded during the rainy season, 39 during the cold dry season, and 41 during the hot dry season. The rotation sequence for cowpeas included a total of 14 species in the rainy season, 20 in the cold dry season and 17 in the hot dry season.

In the maize-based rotation sequence, no weed species presented a 100% infestation level during any of the seasons. The only species in this series with the highest infestation levels were *C. esculentus, K. erecta,* and *K. squamulatus,* and these only occurred during the wet season. In rice-based systems, infestation levels of *C. difformis* (during the wet and cold dry seasons) and *C. esculentus* (during the hot dry season) reached 100%. Species such as *C. dactylon* (during the rainy season), *O. sativa* (during the cold dry season), *O. barthii* (during the rainy season), *C. olitorius* (during the rainy season), *M. villosus* (during the rainy season), *C. difformis* (during the hot season), *C. rotundus* (during the hot dry season), *K. squamulatus* (during the rainy season), and *K. erecta* (during the hot dry season) recorded 75% infestation levels. None of these species were recorded above the 50% infestation level in the cowpea-based rotation sequence in either season.

Effects of Rotation Sequence and Season on Weed Biomass and Density

Table 4 shows the likelihood that weed density and biomass are affected by the rotation sequence (rice, cowpea, and maize-based rotation sequences) and season (rainy, cold, and hot

dry seasons). Weed density and biomass were significantly affected by rotation sequence, season, and their interactions.

Weed biomass

Season and crop sequence had an impact on weed biomass. In the cowpea-based rotation sequence, cowpea followed by wheat followed by rice (CWR) presented the highest weed biomass, which was 9.83% greater than that of cowpea, followed by tomato and then the rice sequence (CTR), and it was 18.03% greater than that of cowpea, followed by the rice rotation sequence (COR) (Figure 1).

Among the rotation sequences observed in the maize-based system, maize followed by tomato followed by fallow (MTFL) had the highest biomass (Figure 1). Maize followed by wheat and cowpea (MWC), on the other hand, had the lowest biomass, which was statistically comparable to that of maize onion-soybean (MOS), maize onion-groundnut (MOG), maize onion-cowpea (MOC), maize tomato-soybean (MTS), maize tomato-groundnut (MTG), and maize tomato-cowpea (MTC).

Compared with the other rotation sequences, the rice-onion-fallow (ROFL) sequence presented the highest weed biomass in the rice-based system, whereas the rice-onion-cowpea (ROC) sequence presented the lowest (Figure 1). Additionally, the data revealed that the biomasses of the weeds in the two rotation sequences were not significantly different. The results also revealed that neither of the two rotation sequences had statistically similar weed biomasses.

In the rotation sequences based on rice and cowpea, the wet season yielded the greatest weed biomass. Nonetheless, in the maize-based rotation cycle, greater biomass was noted throughout the hot season (Figure 2). Compared with the hot and cold dry seasons, the rainy

season in the cowpea-based rotation sequence had 37.83% and 31.75% more biomass, respectively. The rainy season had the biomass was 3.4% and 17.24% greater in the rice-based rotation sequence than in the hot and cold seasons, respectively. In the maize-based rotation sequence, the hot season presented 33.9% and 6.4% greater weed biomass than did the cold and wet seasons, respectively.

In rotation sequences based on rice, maize, and cowpeas, the relationships between the season and rotation sequence on weed biomass were significant. The COR rotation sequence in the cowpea-based rotation sequence presented the lowest biomass in the cold and hot dry seasons, which differed from all the other rotation sequences (Table 5). Compared with those in the other seasons, significantly greater weed biomass was observed in the CTR, COR and CWR treatments in the rainy season.

During the cold season, weed biomass ranged from 411.8 to 471.1 g m^{-2}, with relatively small differences observed among the rotation sequences (Fig 3). Biomass levels were generally moderate and showed no pronounced peaks across treatments. A similar trend was observed during the rainy season, when weed biomass ranged from 465.1 to 503.1 g m^{-2}. Although the values were slightly higher than those in the cold season, the variation among the rotation sequences remained comparatively narrow. In contrast, substantial divergence among rotation sequences occurred during the hot season. While several sequences maintained moderate biomass levels (approximately 433–470 g m^{-2}), three sequences, i.e., MWFL, MOFL, and MTFL, presented markedly greater weed biomass, exceeding 600 g m^{-2}. The highest biomass was observed under MTFL (664.8 g m^{-2}), followed by MOFL (647.6 g m^{-2}) and MWFL (626.8 g m^{-2}).

The effect of rotation sequence on weed biomass varied across seasons, indicating a strong sequence × season interaction in rice-based systems (Fig. 4). During the cold season, weed biomass ranged from 470.1 to 600.2 g m^{-2} across rotation sequences. Most sequences presented moderate biomass (470–500 g m^{-2}), whereas the RWF sequence presented the highest biomass (600.2 g m^{-2}). During the rainy season, the biomass values were more evenly distributed, ranging from 472.9 to 572.5 g m^{-2}. Although slightly greater than the cold-season values, differences among sequences were less pronounced. During the rainy season, the biomass values were more evenly distributed, ranging from 472.9 to 572.5 g m^{-2}. Although slightly greater than the cold-season values, differences among sequences were less pronounced. In contrast, the hot season revealed substantial divergence among rotation sequences. Several sequences, such as RTFL, ROFL, and RWFL, recorded markedly elevated weed biomass, exceeding 600 g m^{-2}, whereas most other sequences remained within the moderate range of 473–500 g m^{-2}. The RWS and ROG in the rainy season significantly recorded higher biomass than RWFL, ROC, RTW, RTF, RTC, ROR and ROFL did in the season.

Weed density

For both cowpea, maize, and rice-based rotation sequences, the number of weeds per square meter varied with season and rotation sequence. In cowpea-based systems, cowpea-tomato-rice (CTR) had the most weeds, with 13.4% more weeds than did CWR and 10.4% more weeds than did COR (Figure 5). In the maize-based rotation sequences, the MOC had the fewest weeds per square meter, whereas the maize-tomato-groundnut (MTG) had the highest. The numbers of weeds m^{-2} were statistically comparable for the MOFL, MTC, MTFL, MTS, and MWC. In rice-based systems, rice–wheat-maize (RWM) presented the highest number of weeds m^{-2} in comparison with the other sequences. The rice–wheat–cowpea (RWC) rotation sequence

240 registered the lowest number of weeds, which was statistically similar to that of the rice–wheat–
241 groundnut (RWG), rice–tomato–rice (RTR), rice–tomato–forage (RTF), rice–onion–rice (ROR),
242 rice–onion–groundnut (ROG), rice–onion–forage (ROF) and rice–onion–cowpea (ROC) rotation
243 sequences.

244 The season had a significant effect on the number of weeds m^{-2} in the cowpea-, maize-
245 and rice-based rotation sequences (Figure 6). In all three seasons, the wet season had more weed
246 species than did the other two seasons. The rainy season had 60.2% more weeds than did the hot
247 dry season and 55.6% more weeds than did the cold dry season in the cowpea-based rotation
248 sequence. However, in the maize-based sequence, the wet season had 46.6% more weeds than
249 did the hot dry season and 37.78% more weeds than did the cold dry season. For the rice-based
250 sequence, the rainy season had 68% more weeds than did the hot dry season and 55% more
251 weeds than did the cold dry season.

252 The interaction effects of rotation sequence and season on weed density in cowpea-based
253 rotation systems are displayed in Table 6. The three rotation sequences resulted in statistically
254 similar weed densities in the hot dry season. A similar trend was observed in the rainy season.
255 However, CWR resulted in a significantly greater number of weeds in the cold season than did
256 COR and CTR, which presented the lowest number of weeds in the season. Compared with all
257 the other treatment combinations, the CTR resulted in the highest weed density in the rainy
258 season, while the same sequence did; however, fewer weeds were reported in the colder climates.

259 A significant interaction effect between rotation sequence and season was observed for
260 weed density m^{-2} in the maize-based rotation sequence (Fig. 7). The effect of rotation sequence
261 on weed number varied across seasons, demonstrating a pronounced sequence × season
262 interaction. During the cold season, weed density ranged from 170.5 to 206.1 weeds m^{-2} across

rotation sequences. Most sequences exhibited moderate densities (~170–190 weeds m^{-2}), with a gradual increase observed in the MWFL, MWS, MTG, and MOS. In the hot season, weed densities were generally lower than those in the cold season for most sequences (161–200 weeds m^{-2}), except for MWFL and MTG, which presented moderately elevated densities (~195–200 weeds m^{-2}). The rainy season presented the highest weed density and the greatest variation among sequences, ranging from 190.7 to 250.3 weeds m^{-2}. The MWFL presented the highest weed density (250 weeds/m^2), whereas the MTC, MTG, and MOG presented elevated weed density (232–237 weeds/m^2). The MWC supported more weeds during the rainy season than during the hot and dry seasons. Similar trends were observed for MWFL, MTG and MTC. In all the rotation sequences, weeds were generally more prevalent during the wet season than during the hot and dry seasons.

The effect of rotation sequence on weed density varied across seasons, demonstrating a strong sequence × season interaction in rice-based systems (Figure 8). During the cold season, weed densities were relatively uniform across sequences, ranging from 244.7 to 291.3 weeds m^{-2}. Most sequences presented moderate densities (245–255 weeds m^{-2}), with the RWM sequence showing the highest density (291.3 weeds m^{-2}). In the hot season, weed densities were generally lower and less variable for most sequences (241–258 weeds m^{-2}), with the exceptions of RTFL, ROFL and RWM, which presented slightly elevated densities (258–271 weeds m^{-2}). The rainy season presented the highest densities and the greatest variation among sequences, ranging from 276.2 to 328.8 weeds m^{-2}. The MWFL, RWM, and RWP sequences presented the highest densities (>320 weeds m^{-2}), whereas several other sequences remained in the 305–310 range. In general, ROC (in the cold season), ROG (in the hot dry season) and ROC (in the rainy season) presented the lowest weed density compared with the other rotation sequences. More

286 weeds were supported by the rice–wheat–soybean (RWS) rotation sequence in the rainy season
287 than in the hot and cold seasons. Similar trends were observed for RTF, RWP, RWF, RWM,
288 RWWM, RTS and RTG.

289 **Importance Value Index (IVI)**

290 In the cowpea-based system, all of the rotation sequences had higher IVIs during the hot
291 dry season than during the cold and rainy seasons (Figure 9). Compared with the other seasons,
292 the COR rotation sequence had the highest IVI during the hot, dry season. The sequence also
293 supported higher broadleaf species in all seasons, with sedges and grasses having lower IVIs in
294 the rainy season. The sedge species were completely absent during the cold dry season in the
295 COR rotation sequence, whereas broadleaf plants consistently presented greater IVIs in both
296 seasons in the sequence. During both seasons, grasses had higher IVIs in the CTR and CWR
297 sequences, whereas the IVIs of these species were lower in the COR sequence in both seasons.
298 Sedges had higher IVIs in the CWR rotation sequence during the rainy season than in the COR
299 sequence during the wet and hot dry seasons but completely absent during the cold season.

300 The effects of rotation sequence and season on the importance value indices of weed
301 species in maize-based systems are presented in Figure 10. Compared with the cold and hot dry
302 seasons, the rotation sequences presented greater IVIs for both weed groups during the rainy
303 season. In the cold season, the MOC and MWC sequences had the lowest IVIs, whereas the
304 MTG and MTS rotation sequences had the highest IVIs during the rainy season. In the MTFL
305 sequences during hot dry seasons, and in the MOC and MOS rotation sequences during the cold
306 dry season, the IVI of sedge species was 0%. In contrast to other morphological groupings of
307 weeds during the cold season, the IVI of this species was greater in the MTC sequence. During

the wet season, sedges had the highest IVI among the rotation series, with the exception of the MTG and MWS rotation sequences, where grasses outperformed the two morphological groups of weed. Sedge species had the lowest IVI in all the rotation sequences during the hot dry season except in the MMG, where grass had a lower IVI than sedges did.

Figure 11 presents the effects of the season and rotation sequence on IVI of grasses, broadleaves and sedges in the rice-based rotation sequence. Sedges typically exhibited greater IVIs during colder seasons than during hot, dry seasons. In every season, the RWM rotation sequence had a higher IVI than any other rotation sequence. Additionally, during the rainy season, the sequence had a greater number of grass and broadleaf species than did any other sequence during both seasons. During the hot dry season, sedge species were not supported by the RWG rotation sequence. In the rainy season, the ROFL sequences included fewer broadleaf species, but in the cold season, the ROS supported fewer grass species.

Discussion

Effects of rotation sequence on weed dynamics

Compared with maize- and cowpea-based rotation sequences, all categories of weed species were more prevalent in rice-based rotation sequences. This might be explained by the fact that rice is inherently weak for competing with weeds and is cultivated in environments that are more conducive to weed growth than other crops are. Additionally, many weed species resemble rice, which makes it easy for them to evade control and survive in rice fields. Das [8] reported that several grasses were able to evade numerous weed control tactics since they looked like cereals. Cardina et al. [9] reported that crop type and the timing of weed management measures increased the variety of weed types. Compared with cowpea-based systems, which are based on maize and rice, the degree of weed infestation is often lower, suggesting that new,

enhanced rotation systems that incorporate legumes aid in weed control. This implies that improved crop rotation systems (with legumes) are effective approaches for weed management, as reported by Shahzad et al. [10]. Cowpea grows faster and provides ground cover to suppress weed growth.

These findings demonstrated that although certain weed species are site-, crop-, and season specific, others flourish in a variety of environmental settings. Tillage techniques, cropping schemes, weed management, and other habitat modifications can cause weed movement and density in continuously farmed land [11]. It is believed that crop rotation increases species diversity and decreases weed density [5]. The lowest weed density observed in the COR sequence (in the cowpea-based rotation system) could be attributed to complete ground cover by cowpea in the rainy season and frequent hoe weeding of the onion during the cold dry season. The lowest weed densities were detected in the ROS and ROG in rice, and the MOS, MOG, and MOC in the maize-based systems suggested that they could be employed to limit the establishment and development of weeds. This finding corroborated the findings of Wozniak [12], who reported that the number and air dry weight of weeds were greater in cereal monocultures than in crop rotations. In cereals, crop rotation with crops such as soybeans can also be used to eliminate troublesome weeds such as *Striga hermonthica*. This is because involving soybean in rotation has been shown to promote the suicidal germination of Striga parasites [13]. This suggested that adding soybean to a rice-based rotation sequence could be a useful strategy for eliminating *Striga asiatiaca*, a parasitic weed of rice that is prevalent in the study area.

Owing to their impact on weed density, the cowpea-wheat–rice (CWR) sequence supported the largest weed biomass in cowpea-based crops, as opposed to cowpea-onion-tomato

(COT). The lower weed density observed on MTF than on MTFL implied that including forage crops in rotation suppressed weed growth better than allowing the field to fallow. This could be attributed to the fact that forage crops are aggressive at suppressing weeds because of their quick canopies and allelopathic effects, as reported by Mohler [14]. The lowest weed biomass observed under MWC and RTF implies that the inclusion of legumes and forage crops in the rotation sequence reduces the level of weed infestation due to their ability to provide quick and complete canopy cover. This corroborated with the findings of Shahzad et al. [10], who reported that fallow–wheat crop rotation encourages weed growth and biomass. Improved rotation systems with legumes, forage, and pasture reduce weed infestations because legumes, forage, and pasture cover the entire ground in the corresponding season. This was demonstrated by the lower weed biomass observed at the MWC, MWS (in the maize-based system) and ROC, ROF, ROP, and RTF in the rice-based system. In addition to increasing soil fertility, adding legumes, pasture, and forage crops in rotation sequences could help supply animal feed during shortages. Additionally, this will lessen the recurring disputes between farmers and cattle rearers that often arise in the study area due to the scarcity of animal feed. The higher weed density observed at RMW implied that this rotation sequence involving crops in the same family encouraged weed growth and should be avoided. This finding corroborated the findings of Shahzad et al. [10], who reported that, compared with other rotation sequences, the rice–wheat rotation sequence had a greater weed density.

Effect of Season

The ideal weather conditions for weed growth and development during the rainy season, as opposed to the hot and cold dry seasons, may be the reason for the higher weed density observed in the rainy season across the cropping sequence and rotation systems. According to

377 Olabode et al. [15], the rainy season creates an environment that is conducive to weed seeds
378 breaking dormancy and germination. Owing to the early start of the 2021 rainy season, which
379 began prior to crop harvest, a considerable number of weeds were also aided by the hot dry
380 season. However, according to Das [8], the cold dry season results in the lowest weed density
381 because of the adverse effects of cold weather on weed seed germination, growth and
382 development. Seasonal variations were observed in the number of weeds m^{-2} across all rotation
383 sequences. During the wet and hot dry seasons, a greater number of weed species were observed
384 in all rotation sequences, suggesting that temperature significantly affects infestation. Olabode et
385 al.[15] reported higher weed density and dry weight during the rainy season than during the dry
386 season. For the maize-based sequences, the cold dry season had the lowest weed biomass,
387 whereas the hot dry season had the highest biomass across all rotation sequences. In contrast to
388 the cold dry season, when the temperature is low and weed growth is slow, the hot dry season
389 offered a warm temperature and additional moisture from the early onset of rain in 2021,
390 allowing luxuriant weed growth to flourish in all rotation sequences [8].

391 **Interaction effects of season and cropping sequence on weed dynamics**

392 According to our research, the impact of fallowing on weed control changes with season.
393 In contrast to allowing the fallow period to occur during the hot dry season, which produces an
394 environment that is favorable for breaking weed seed dormancy and enhancing weed seed
395 germination, allowing it to occur during the wet or dry season may have improved weed control.
396 The gradual increase in weed density observed in MWFL, MWS, MTG, and MOS during the
397 cold season in the maize base rotation sequence indicates that these sequences slightly favored
398 greater weed establishment even under cooler conditions. In these systems, rotation sequences
399 consisting of cereal–cereal-fallow mixtures with sufficient soil moisture and optimal

400 temperatures during the rainy and hot seasons promote greater weed growth than those during
401 the cold dry season, as indicated by the greater weed biomass in the RWFL rotation sequence in
402 the hot season. This could be explained by the fact that weeds may have been able to overcome
403 some physiological hibernation during the hot, dry season by taking advantage of the fallow
404 period. This finding corroborates the findings of Ramesh et al.[16], who reported that weed
405 problems could be aggravated by high temperature and, most significantly, by water stress.
406 Compared with COR (cowpea-based systems), the CWR rotation resulted in greater weed
407 biomass regardless of the season. These findings indicate that the cereal–cereal rotation pattern
408 promoted weed growth and should be discouraged. The low dry weight of COR in all seasons
409 further supported the claim that weed growth prevents crop diversification in any cropping
410 system.

411 Weed biomass varied with season in all rotation sequences in the rice-based systems.
412 Compared with the other sequences during the rainy season, the RWFL rotation sequence had
413 the lowest weed biomass. However, higher weed biomass was achieved when the fallow period
414 fell during either the hot or cold dry season. These findings suggest that the season affects the
415 ability of the fallow period to suppress weeds. The dynamics of weed populations in cropping
416 systems are influenced by a wide range of elements, and the changing climate has made matters
417 more complex. According to Anderson [17], the arrangement of crops in a series of two cool-
418 season crops followed by two warm-season crops can disturb weed dynamics and cause changes
419 in weed flora during the growing season.

420 **Effect of rotation sequence and season on the IVI of weeds**

The relatively warm temperatures during the dry season created an environment that promoted weed seed germination and increased the density and frequency of all weed species, leading to a relatively high IVI. The increased IVI of broadleaf weed species throughout the season demonstrated that this rotation promoted the growth of this weed group throughout the year. During onion cultivation in the COR rotation sequence, frequent manual hoe weeding may have encouraged the sprouting of this group of weed species, increasing their density and frequency and thus their IVI. Because the crop itself and the management practices associated with it can produce various habitats for weeds, this unequivocally demonstrated that crop rotation can aid in weed control [18, 1, 2]. Our results support those of Yusuf and Lado [19], who reported that during the wet season, broadleaf weed had a higher IVI (in cereal) than did grass and sedges. The combination of cold weather during the cold season and frequent tillage throughout the onion growing season may have contributed to the unfavorable conditions for sedge growth and development in the COR rotation sequence during the cold season.

It is possible to infer from this study that all weed types were more prevalent during the rainy season than during the cold and dry seasons, demonstrating how weather affects weed occurrence throughout all rotation seasons. With the exception of MTC (cold season) and MTS (hot dry season), grasses dominated all rotation sequences (in maize-based systems). The inclusion of soybean (MTS) and cowpea (MTC) in the rotation may have provided a full canopy cover, lowering the frequency and density of grass and, consequently, IVI. The cereal–legume rotation sequence generated more biomass, which aided in weed management, according to Gerasimova and Motiva [1]. Cowpea and soybean may have an allelopathic effect on sedges, which may be more noticeable in colder climates, which explains why sedges were absent in the MOC and MOS during the cold season. These may have given grasses a chance to spread, hence

increasing IVI. These findings support those of Yakubu et al.[20], who reported that in the Nigerian savannah of northern Guinea, grasses had the greatest IVI among irrigated carrots.

In the RWM, the IVI of grass increased every season. This may be because maize, wheat, and rice are members of the Poaceae family, which is a family of grasses. The degree of weed infestation may increase if the same crop type is continuously grown. Butkeviciene et al. [3] reported that rye monocultures in the spring produced an average of 2.7 times more weed seedlings than did rye crops in other crop rotations. In contrast, RTC and RTF experienced complete crop type changes throughout the year, which reduced the amount of weed infestation and ultimately resulted in the total eradication of sedge species during the cold season. Additionally, this offered solid evidence that the shift in the cropping season contributed to a decrease in weed dominance and occurrence, as reported by Ņečajeva et al. [21]. Similarly, Waznoik [5] reported wide variations in weed species composition between cereal monocultures and crop rotations at Lubin, southern Poland.

Conclusion.

The nonparallel trends across seasons in the interaction plot confirm the presence of a significant interaction effect. Overall, the results suggest that the influence of rotation sequences on weed density is highly season dependent, with certain sequences exhibiting strong sensitivity to rainfall and others remaining relatively stable across seasons. Crop rotation is an effective alternative method for weed management, especially in organic agriculture. The continuous cultivation of crops belonging to the same morphological group increases the density of weed species. The improved rotation sequences with legumes and forage crops reduced weed density and dry weight in the rice, maize and cowpea rotation sequences. This provides alternative

methods of weed management other than chemical pesticides and provides an environmentally healthy environment. The rainy season provides a conducive environment for weed infestations in both rotation sequences in the study area.

Abbreviations:

HVIP Hadejia Valley Irrigation Project

KRIP Kano River Irrigation Project

RWR Rice- Wheat- Rice

RTR Rice-Tomato-Rice

ROR Rice- Onion-Rice

RWC Rice-Wheat-Cowpea

RTC Rice-Tomato-Cowpea

ROC Rice-Onion-Cowpea

RWG Rice-Wheat- Groundnut

RTG Rice-Tomato- Groundnut

ROG Rice-Onion- Groundnut

RWS Rice-Wheat-Soybean

RTS Rice-Tomato- Soybean

ROS Rice-Onion- Soybean

RWP Rice-Wheat-Pasture

RTP Rice-Tomato-Pasture

ROP Rice-Onion-Pasture

RWF Rice-Wheat-Forage

RTF Rice-Tomato-Forage

ROF Rice-Onion-Forage

RWFL Rice-Wheat-Fallow

RTFL Rice-Tomato-Fallow

ROFL Rice-Onion-Fallow

RWM Rice-Wheat- Maize

RWWM Rice-Wheat- Watermelon

MWC Maize- Wheat-Cowpea

MTC Maize-Tomato-Cowpea

MOC Maize-Onion-Cowpea

MWG Maize-Wheat-Groundnut

MTG Maize-Tomato-Groundnut

MOG Maize-Onion-Groundnut

MWS Maize-Wheat-Soybean

MTS Maize-Tomato-Soybean

MOS Maize-Onion-Soybean

MWFL Maize-Wheat-Fallow

MTFL Maize-Wheat-Fallow

CWR Cowpea-Wheat-Rice

CTR Cowpea-Tomato-Rice

COR Cowpea-Onion-Rice

IVI Important Value Index

Declarations:

Consent for publication: Not applicable

Availability of data and materials: All weed samples collected were from our experimental plots and no permission is required as per the instructional policy

Competing Interests: Not applicable

Authors' contributions: A.L. conceptualization, original draft, review and editing; M.A.H. supervision, resources, funding acquisition; A.A. conceptualization, data collection; I.I.G. formal

analysis; A.A.A. writing, review and editing. B.L.A. project administration, A.Y.K. investigation, writing, F.Z.B. review and editing, N.B.S. conceptualization, prepared figures, M.D.A. project administration. All the authors reviewed the manuscript.

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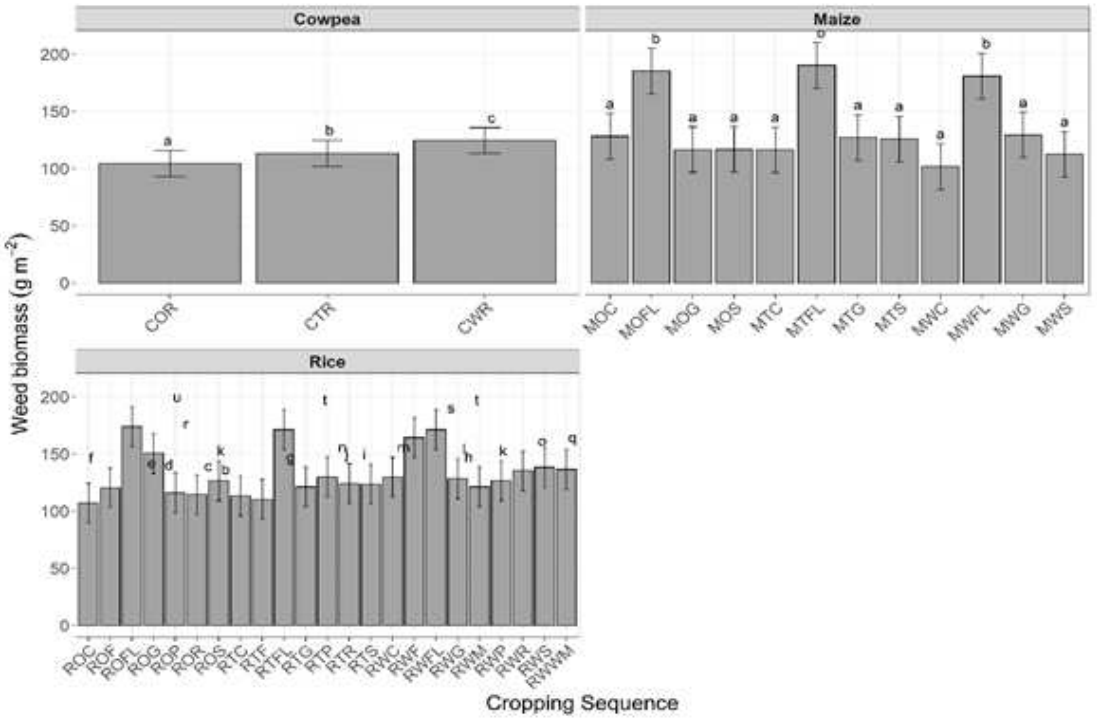


Figure1. Weed biomass of cowpea, maize and rice as influenced by cropping sequence.

The error bars represent the standard error (±) of the mean for each group. Within each panel, different letters indicate significant differences between means as determined by Tukey's HSD test at the 5% significance level ($p < 0.05$).

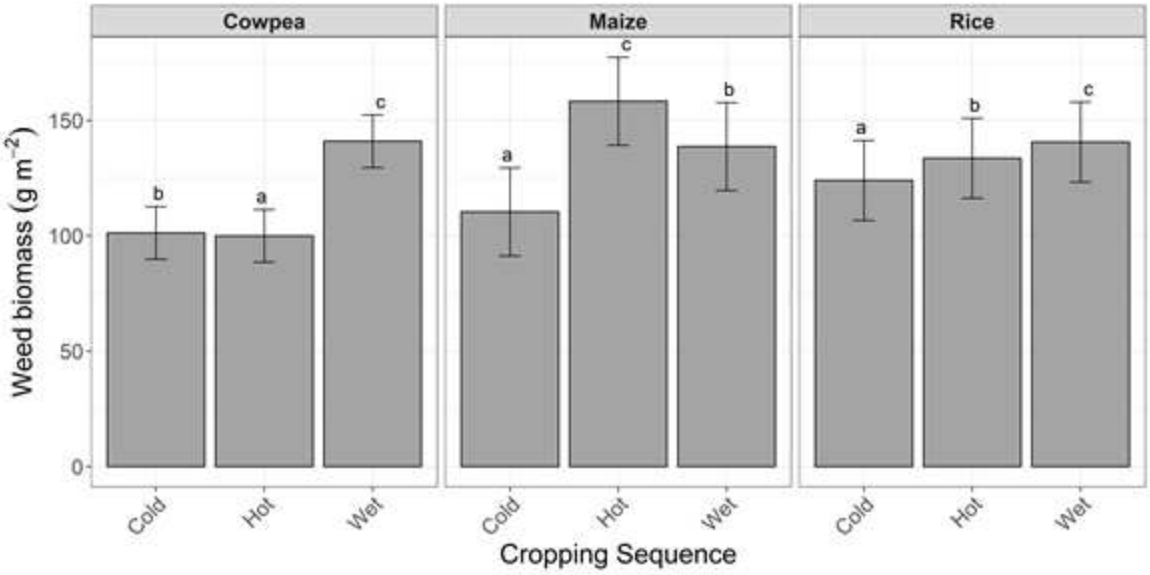


Figure 2. Weed biomass g/m² of cowpea, maize and rice as influenced by cropping season.

The error bars represent the standard error (±) of the mean for the group. Within each panel, different letters indicate significant differences between means as determined by Tukey's HSD test at the 5% significance level ($p < 0.05$).

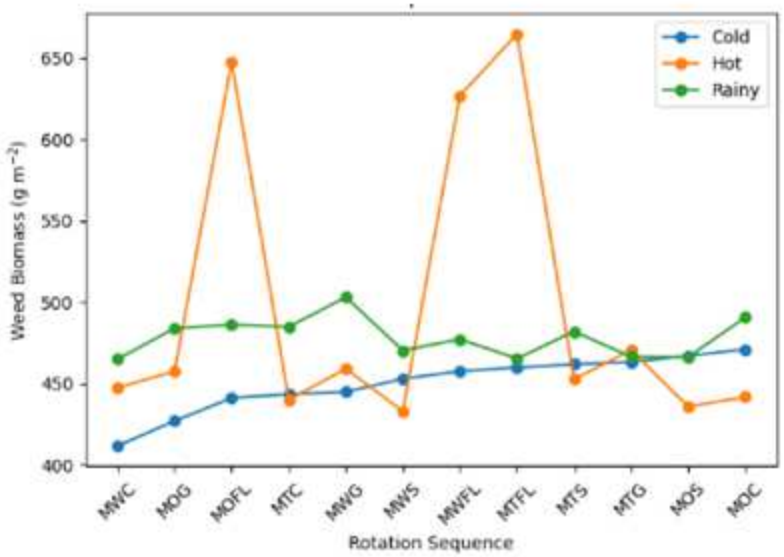


Figure 3. Interaction effect of rotation sequence and season on weed biomass in maize-based rotation sequences.

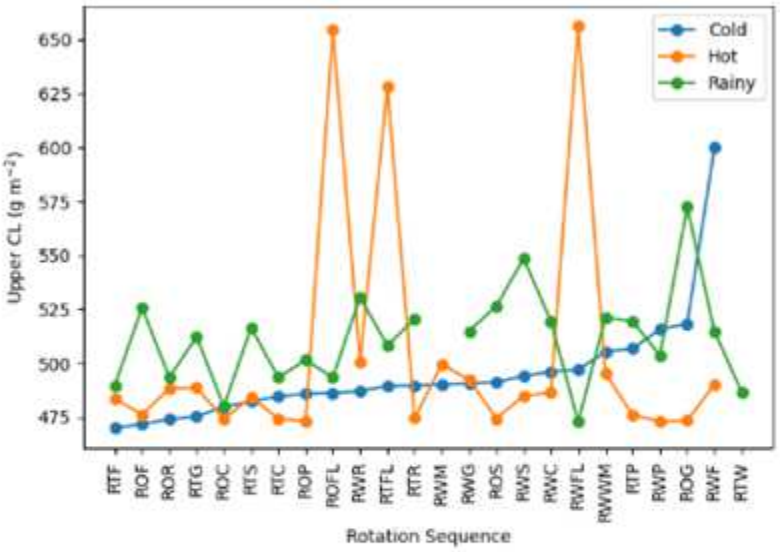


Figure 4: Interaction effects of rotation sequence and season on weed biomass in rice-based rotation sequences

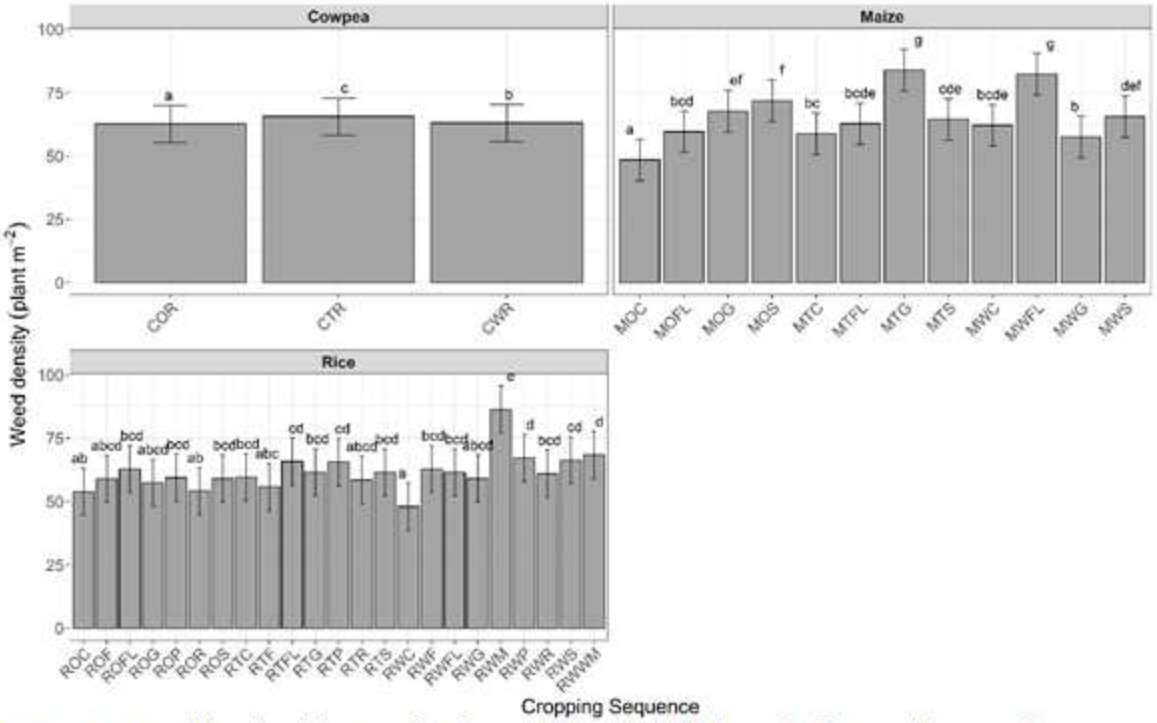


Figure 5. Weed density (plants m^{-2}) of cowpea, maize and rice as influenced by cropping sequence.

The error bars represent the standard error (±) of the mean for each group. Within each panel, different letters indicate significant differences between means as determined by Tukey's HSD test at the 5% significance level ($p < 0.05$).

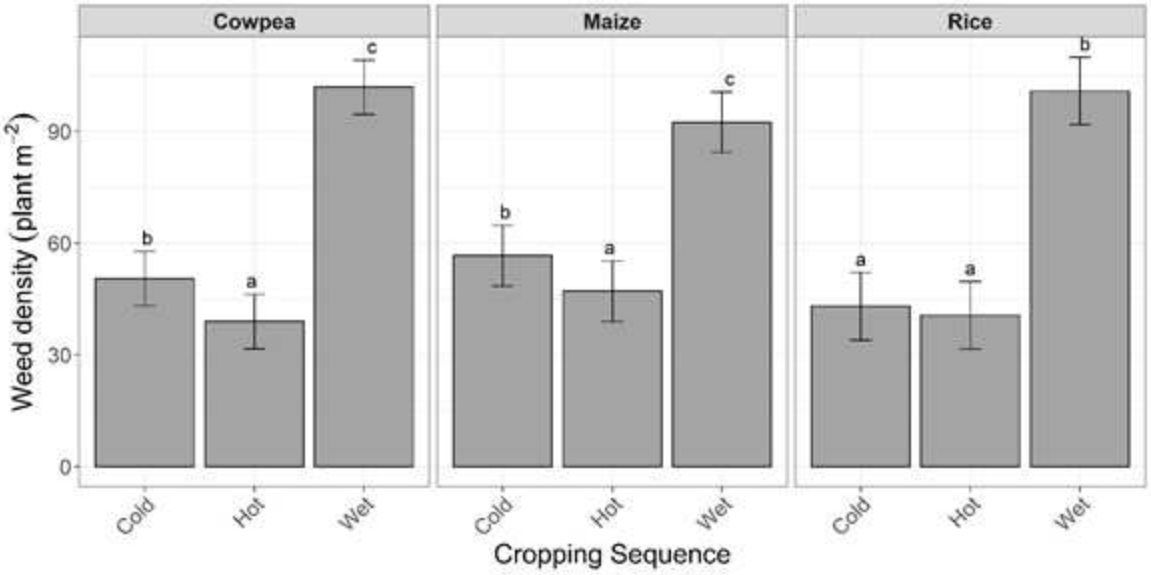


Fig. 6. Weed density (plants m^{-2}) of cowpea, maize and rice as influenced by cropping season.

The error bars represent the standard error (±) of the mean for each group. Within each panel, different letters indicate significant differences between means as determined by Tukey's HSD test at the 5% significance level ($p < 0.05$).

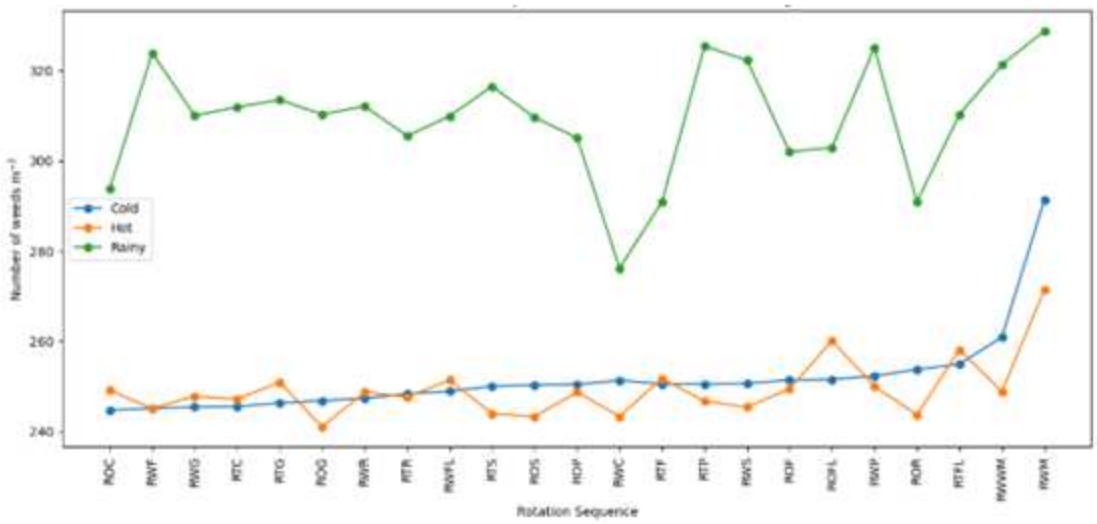


Figure 7. Interaction between rotation sequence and season on the number of weeds m^{-2} in the rice-based rotation sequence

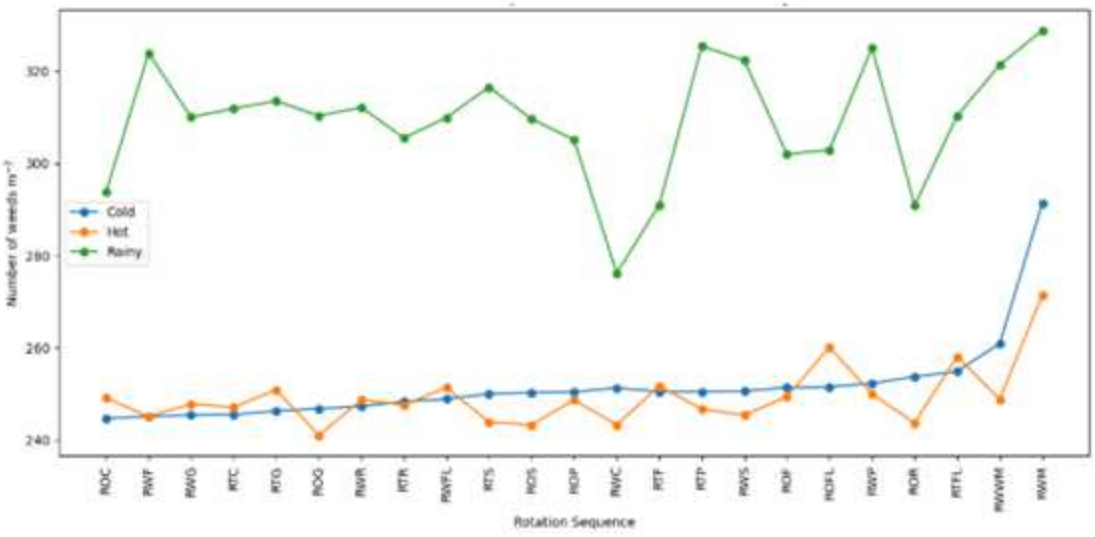


Figure 8. Interaction between rotation sequence and season on the number of weeds m^{-2} in the rice-based rotation sequence

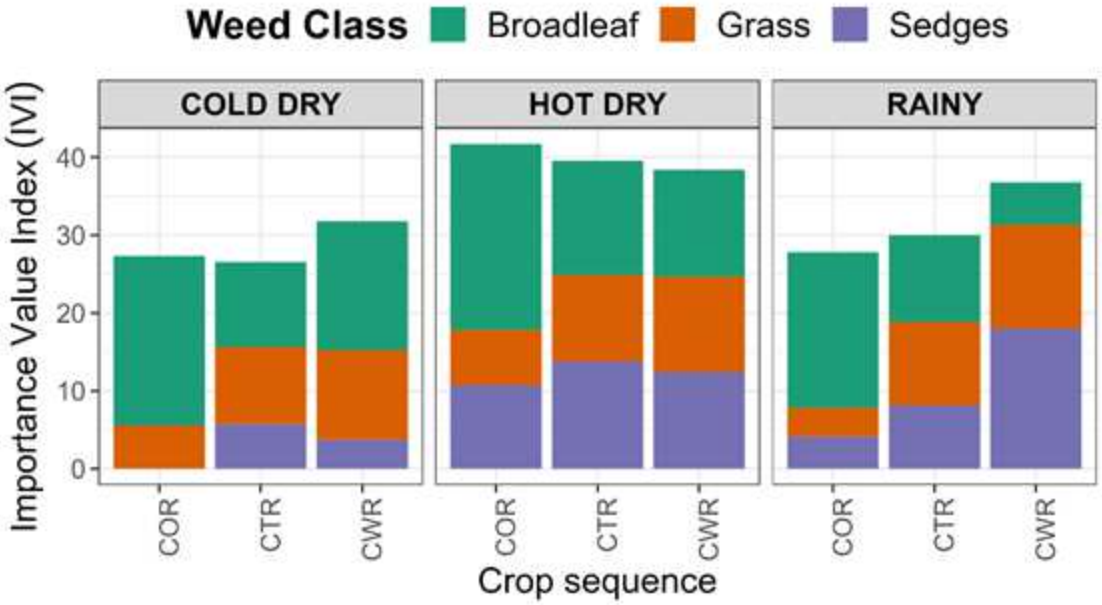


Figure 9. Effects of rotation sequence and season on the weed importance value index (IVI) in cowpea-based rotation sequences

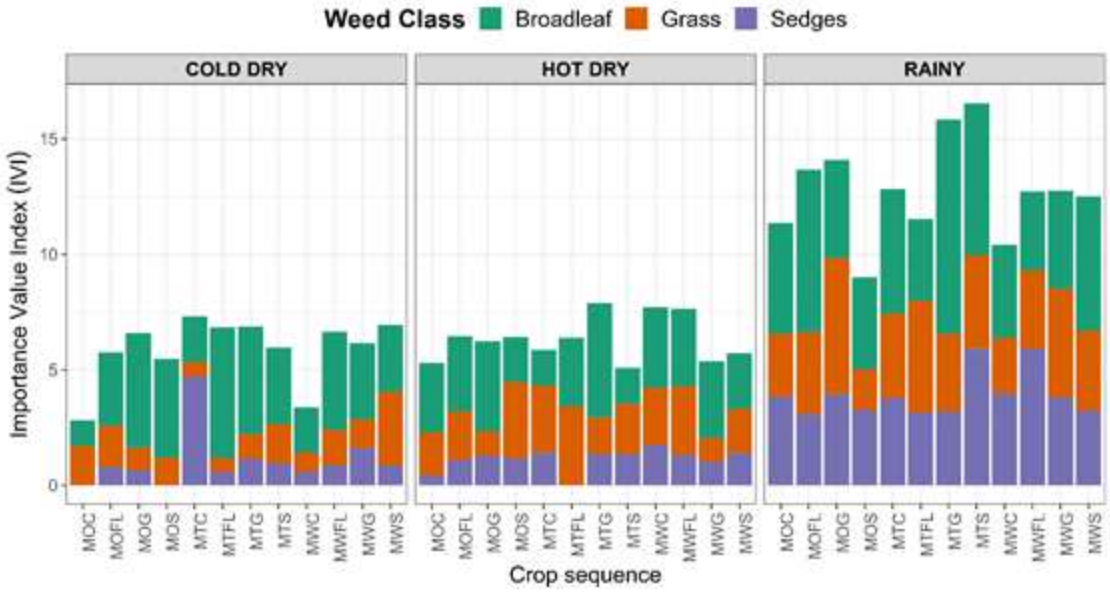


Figure 10. Effects of rotation sequence and season on the weed importance value index in maize base rotation sequences

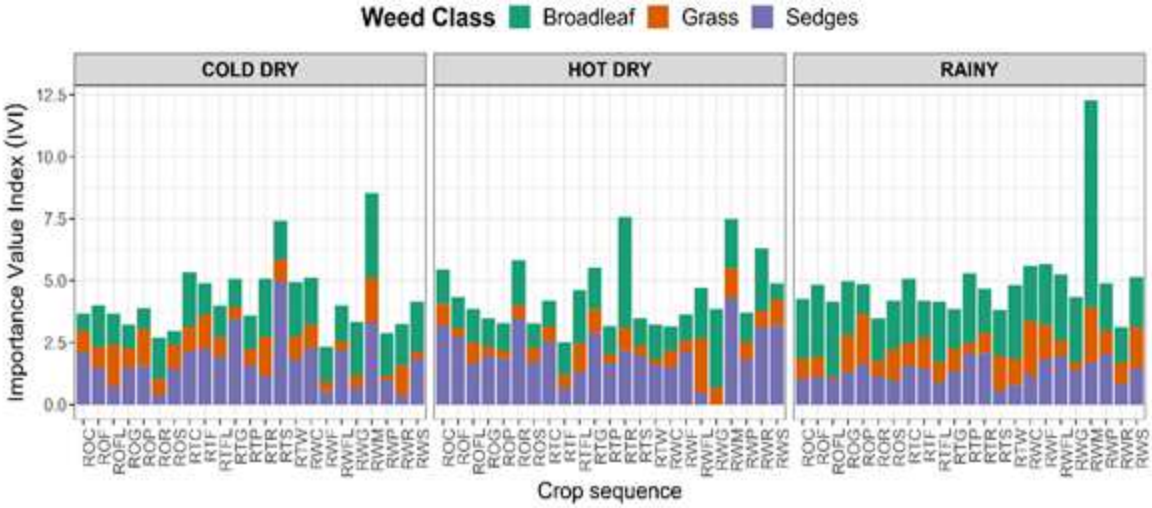


Figure 11. Effects of rotation sequence and season on the weed importance value index in rice-based systems

List Tables and Figures

Table 1: Monthly mean temperature and rainfall at the experimental site (averaged over 2020–2021)

Month	T_max (°C)	T_min (°C)	T_mean (°C)	Rainfall (mm)	T Range (°C)
Jan	30.25	12.35	21.30	0.0	17.89
Feb	31.52	13.94	22.73	0.0	17.58
Mar	36.92	19.83	28.38	0.0	17.09
Apr	38.06	22.27	30.17	6.2	15.79
May	37.82	23.68	30.75	49.2	14.15
Jun	34.74	23.41	29.08	87.5	11.33
Jul	29.69	21.64	25.67	290.3	8.05
Aug	28.67	21.24	24.95	314.1	7.43
Sep	29.60	21.21	25.41	187.1	8.39
Oct	31.11	19.40	25.26	11.1	11.71
Nov	29.23	15.37	22.30	0.0	13.86
Dec	27.78	11.94	19.86	0.0	15.83
Annual Mean	**32.12**	**18.86**	**25.49**	**945.6**	**13.26**

Table 2: List of rotation sequences

Cropping Sequence	Treatments	Season of a Year		
		Rainy Season	Cold Dry Season	Hot Dry Season
	RWR	Rice	Wheat	Rice
	RTR	Rice	Tomato	Rice
	ROR	Rice	Onion	Rice
	RWC	Rice	Wheat	Cowpea
	RTC	Rice	Tomato	Cowpea
	ROC	Rice	Onion	Cowpea
	RWG	Rice	Wheat	Groundnut

	RTG	Rice	*Tomato*	Groundnut
	ROG	Rice	Onion	Groundnut
	RWS	Rice	Wheat	Soybean
	RTS	Rice	Tomato	Soybean
	ROS	Rice	Onion	Soybean
	RWP	Rice	Wheat	Pasture grass
	RTP	Rice	Tomato	Pasture grass
Rice-based	ROP	Rice	Onion	Pasture grass
	RWF	Rice	Wheat	Forage Legume
	RTF	Rice	Tomato	Forage Legume
	ROF	Rice	Onion	Forage Legume
	RWFL	Rice	Wheat	Fallow
	RTFL	Rice	Tomato	Fallow
	ROFL	Rice	Onion	Fallow
	RWM	Rice	Wheat	Maize
	RWWM	Rice	Wheat	Watermelon
	MWC	Maize	Wheat	Cowpea
	MTC	Maize	Tomato	Cowpea
	MOC	Maize	Onion	Cowpea
	MWG	Maize	Wheat	Groundnut
	MTG	Maize	Tomato	Groundnut
	MOG	Maize	Onion	Groundnut
Maize-based	MWS	Maize	Wheat	Soybean
	MTS	Maize	Tomato	Soybean
	MOS	Maize	Onion	Soybean
	MWFL	Maize	Wheat	Fallow
	MTFL	Maize	Tomato	Fallow
	MOFL	Maize	Onion	Fallow
	CWR	Double cowpea	Wheat	Rice
Cowpea-based	CTR	Double cowpea	Tomato	Rice
	COR	Double cowpea	Onion	Rice

Table 3**.** Weed species composition and infestation levels in rice-, maize- and cowpea-based rotation sequences in the experimental site

Weed Species	Maize Base rotation sequence			Rice Base rotation sequence			Cowpea Base rotation sequence		
	Rainy	Cold dry	Hot dry	Rainy	Cold dry	Hot dry	Rainy	Cold dry	Hot dry
GRASSES									
Axonopus compressus (Sw.) P.Beauv.	-	-	*	*	-	*	-	-	*
Chloris pilosa Schumach	-	*	*	*	**	*	-	-	*
Cynodon dactylon (Linn.) Pers	**	*	**	***	**	*	*	*	*
Dactyloctenium aegyptium (Linn)P. Beauv.	*	-	-	*	*	*	-	-	-
Digitaria ciliaris (Retz.) Koel.	-	-	*	*	*	**	-	*	*
Digitaria horizontalis Willd	**	*	*	*	**	*	*	*	-
Echinochloa obtusiflora Stapf	-	-	*	*	-	*	-	-	-
Eleusine indica (L) Gaertn	-	*	*	-	-	-	-	-	-
Elytrophorus spicatus (Willd.) A. Camus	*	-	-	-	-	-	-	-	-
Eragrostis ciliaris (Linn.) R. Br.	*	-	-	*	-	-	-	-	-
Imperata cylindricalls (Linn.)Raeuschel var. *Africana* (Anderss) C.E. Hubbard	-	-	*	-	-	-	**	*	**
Leptochloa filiformis (Lam.) P. Beauv	*	-	*	**	-	*	-	*	-
Oryza barthii A. Chev.	**	-	*	***	*	*	*	-	-
Oryza sativa Linn.	-	-	*	-	-	-	-	-	-
Paspalum scrobiculatum Linn. *(=P.poystachyum* R. Br.)	-	-	*	*	-	**	-	-	*
Pennisetum pedicellatum Trin.	-	*	*	-	*	*	-	*	*
Pennisetum polystachion (Linn.) Schult.	-	*	*	*	*	*	-	*	-
Saterea barbata (Lam.) Kunth	*	-	-	*	*	-	*	-	-
Sporobolus pyramidalis P. Beauv	-	*	*	-	-	-	-	-	-
Triticum aestivum Linn.	-	-	-	-	-	*	-	-	-
Zea mays Linn.	-	*	-	-	-	-	-	-	-
BROAD LEAVES									
Acanthospermum hispidum DC.	**	**	**	***	**	**	*	*	*
Ageratum conyzoides Linn.	*	*	*	*	**	*	-	*	-
Amaranthus hybridus Linn.	-	-	-	-	*	-	-	-	-
Amaranthus spinosus Linn.	-	*	*	*	*	**	-	*	-
Amaranthus viridus Linn.	-	-	-	-	*	-	-	*	-
Aspilia bussei O. Hoffm. &Muschl	-	-	*	-	-	-	-	-	-
Bidens pilosa Linn.	-	-	-	*	-	*	-	-	-
Celosia leptostachya Benth	*	*	*	*	*	*	-	-	*
Cyathula prostrate (L.) Blume	*	-	-	-	-	-	-	-	-

Commelina benghalensis L.	-	*	-	*	*	*	*	*	-
Commelina erecta L.	**	*	*	***	*	*	*	*	-
Corchorus olitorius L.	**	*	*	***	*	**	*	*	*
Crotelarea retusa Linn	*	*	*	*	*	-	-	-	*
Chamaecrista mimosoides (L.)Greene	*	-	*	*	-	*	-	-	-
Euphorbia heterophylla Linn.	-	*	*	**	*	**	-	-	-
Euphorbia hirta Linn.	*	-	*	-	-	-	-	-	-
Euphorbia hyssopifolia Linn.	-	-	*	-	-	-	-	-	-
Gomphrena celosioides Mart.	-	*	*	**	*	*	-	-	-
Indigofera spicata Forssk	*	*	-	*	**	-	-	*	-
Ipomea asarifolia (Desr.) Roem. &Schult	-	-	-	*	-	-	-	-	-
Ipomea eriocarpa R. Br.	-	-	-	-	-	*	-	-	-
Ipomea triloba Linn.	-	*	-	-	*	-	-	-	-
Ipomea repens Lam.	*	*	*	**	**	**	*	*	*
Laggera aurita (Linn.f.) Benth. Ex C.B.Cl.	-	-	*	-	-	-	-	-	-
Leucas martinicensis(Jacq.) Ait.f.	*	*	-	**	*	**	-	-	*
Mitracarpus villous (Sw.) DC.	**	-	*	***	*	*	-	-	*
Mimosa pudica Linn.	-	-	*	-	-	*	-	-	-
Nicortonia rustica	*	*	-	**	*	-	-	*	-
Portulaca quadrifica Linn.	-	*	*	-	**	**	-	-	-
Senna obtusifolia (L.) Irwin & Barneby	*	-	-	*	*	-	-	-	-
Senna occenditalis (L.)Link	-	*	-	-	*	*	-	-	-
Solanum lycopersicum L. Carl	-	-	*	-	-	-	-	-	-
Spermacoce verticillata Linn	*	*	*	-	-	-	-	-	-
Sphenoclea zeylanica Gaertn	-	-	-	-	-	*	-	-	*
Striga hermontheca (Del.) Benth	-	-	-	*	-	-	-	-	-
Synedrella nofiflora Gaertn.	-	-	*	*	-	*	-	-	-
Tephrosia linearis(Willd.) Pers.	-	-	-	*	-	-	-	-	-
Trianthema portulacastrum Linn.	*	*	-	*	-	*	-	-	-
Vernonia cinerea (Linn) Less	-	*	-	*	*	-	-	-	-
Vigna unguiculata (L.) Walf	-	-	-	-	-	-	-	*	-
SEDGES									
Cyperus difformis Linn.	**	*	-	****	****	***	-	-	-
Cyperus esculentus Linn.	***	*	**	**	***	****	*	*	*
Cyperus rotundus Linn.	*	*	*	*	****	***	-	-	-
Cyperus iria Linn.	-	-	-	-	-	*	-	-	-
Fuirena ciliaris (Linn.) Roxb	-	-	-	*	-	*	*	-	-
Kyllinga pumila Michx.	***	**	**	*	**	***	**	**	-
Kyllinga squamulata Thorn.ex Vahl	***	*	**	***	**	**	**	-	*

-= 0%; *=25%; **= 50%; ***=75%, ****=100

Table 4. Summary of mixed effect model analyses testing the effects of crop sequence (S), cropping season (C), and C × S interactions on weed density (plants m^{-2}) and weed biomass (g m^{-2}).

Cropping System	Weed density (plants m^{-2})			Weed biomass (g m^{-2})		
	Sequence	Season	S x C	Sequence	Season	S x C
Rice	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Cowpea	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Maize	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Table 5. Interactions between rotation sequence and season on weed biomass in cowpea-based rotation sequences.

Rotation Sequences	Seasons		
	Cold dry	Hot dry	Rainy
COR	165.43a	179.0ab	222.5c
CTR	199.6bc	179.1b	230.3c
CWR	200.0bc	203.0bc	231.4c
SE±	11.38		

Means followed by the same letter are not significantly different at the 5% level of probability according to Tukey's HSD test.

Table 6: Interaction between rotation sequence and season on the number of weeds m^{-2} in cowpea based rotation sequence

Rotation Sequences	Seasons		
	Cold dry	Hot dry	Rainy
COR	103.5ab	96.6a	155.7c
CTR	100.4ab	94.6a	169.4c
CWR	115.2ab	93.4a	148.1c
SE±	7.30		

Means followed by the same are not significantly different at the 5% level of probability according to Tukey's HSD test.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- WeedAccessionID.pdf