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Adikant Pradhan

adi19agro@gmail.com

Indira Gandhi Krishi Vishwavidyalaya

V. Paramesha

ICAR-Central Coastal Agricultural Research Institute

K. S. Keram

Indira Gandhi Krishi Vishwavidyalaya

Abhinav Sao

Indira Gandhi Krishi Vishwavidyalaya

S. K. Nag

Indira Gandhi Krishi Vishwavidyalaya

A. Kerketta

Indira Gandhi Krishi Vishwavidyalaya

S. Malaiya

Indira Gandhi Krishi Vishwavidyalaya

Amar Nath

Indira Gandhi Krishi Vishwavidyalaya

Sweekruta Mohapatra

Indira Gandhi Krishi Vishwavidyalaya

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***Echinochloa* ecotypes and its impact on yield loss of different rice cropping under irrigated agro-ecology**

Adikant Pradhan^{1*}, V. Paramesha^{2*}, K. S. Keram³, Abhinav Sao⁴, S. K. Nag⁵, A. Kerketta⁶, S. Malaiya⁷, Amar Nath⁸ and Sweekruta Mohapatra⁹

^{1,8,9}Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur (India)

² ICAR-Central Coastal Agricultural Research Institute, Old Goa, Goa, India

^{3,6} KVK, Indira Gandhi Krishi Vishwavidyalaya, Kanker (India)

⁴ Department of Genetics and Plant Breeding, Indira Gandhi Krishi Vishwavidyalaya, Raipur (India)

⁵ KVK, Indira Gandhi Krishi Vishwavidyalaya, Jagdalpur (India)

***Email of the corresponding author: adi19agro@gmail.com**

Abstract

A field investigation was conducted during the kharif and summer seasons of 2024 in rice-growing areas surrounding Dudhawa Dam to examine the influence of *Echinochloa* ecotypes on rice yield under different crop establishment methods. The rice variety MTU 1001 was used at all experimental sites. A soil seed bank assessment was carried out to quantify yield losses associated with both active and dormant seeds of *Echinochloa* species. For this purpose, 1 m × 1 m quadrats were randomly placed at three locations within each treatment site and observations were recorded with three replications. The density of *Echinochloa colona* was significantly greater under wet-seeded conditions (Lehi), which was statistically comparable to dry direct-seeded rice (DSR). At 25 days after sowing, higher populations of *Echinochloa crus-galli* were recorded under transplanted rice, followed by *Echinochloa oryzicola*, with densities similar to those observed in wet-seeded and dry-seeded systems. Yield reduction was most pronounced due to *E. colona* infestation in broadcasting methods, followed by dry direct seeding. Broadcasting resulted in the highest yield loss (8.27 q ha⁻¹), primarily because the soil conditions favored germination from the soil seed bank. In contrast, puddled transplanting reduced infestation levels due to disturbance of the seed bank during tillage operations. Among the studied species, *E. crus-galli* tended to emerge later during the cropping cycle in transplanted rice systems. Herbicide application and hand weeding were found to be equally effective in minimizing seed deposition of *Echinochloa* species. Burning of crop residues also reduced weed seed persistence and was widely adopted by farmers because of its operational simplicity. Principal Component Analysis indicated that the first component (PC1) explained 85.12% of total variation, whereas the second component (PC2) explained 10.93%, together accounting for 96.06% of cumulative variance. The strong loading of infestation parameters on PC1 suggests that weed intensity was the major factor differentiating treatments and determining management effectiveness.

Key words: *Echinochloa* weed species, growth behaviour, rice weed, rice yield, establishment methods

Introduction

Rice is a staple food for a large proportion of the global population. According to the Food and Agriculture Organization (FAO, 2009), rice is cultivated on approximately 143 million hectares worldwide, producing about 612 million tonnes, with nearly 90% of production concentrated in Asia. It contributes 30–75% of the daily caloric intake for more than three billion people in the region (Kush, 2004). With the global population projected to rise, an additional 114 million tonnes of milled rice will be required by 2035, representing a 26% increase in production despite limited scope for horizontal expansion. Consequently, future demand must be met through enhanced productivity and improved resource-use efficiency.

In India, and particularly in Chhattisgarh, rice-based cropping systems dominate agricultural production. The state has experienced a significant expansion in irrigation infrastructure over recent decades, especially through canal irrigation systems, which has facilitated increased summer rice cultivation. Chhattisgarh has a population of approximately 25.5 million, with nearly 70% dependent on agriculture and allied sectors across about 3.75 million farm households. The total geographical area of the state is about 13.8 million hectares, of which 4.65 million hectares constitute the net sown area (Annual Report, 2023). Currently, around 1.48 million hectares are irrigated, representing approximately 32% of the net sown area. The state lies between 17°46'–24°50' N latitude and 80°15'–84°20' E longitude and receives an average annual rainfall of approximately 1200 mm. The expansions of irrigation and favorable minimum support prices have encouraged intensive and continuous rice cultivation throughout the year. However, continuous rice cultivation involving repeated puddling, intensive input use, and reduced fallow periods has significantly altered weed dynamics. Such systems create favorable conditions for the proliferation of *Echinochloa* species, which have emerged as dominant and highly competitive weeds in rice ecosystems (Gibson and Fischer, 2001). These species are well adapted to diverse agro-ecological conditions and exhibit traits such as high fecundity, prolonged seed dormancy, rapid growth, and strong phenotypic plasticity, enabling them to thrive under both flooded and aerobic conditions (Maun and Barrett, 1986; Lopez-Martinez et al., 1999). The genus *Echinochloa* comprises approximately 50 species distributed predominantly in tropical and subtropical regions (Michael, 1983).

Among them, *Echinochloa crus-galli*, *Echinochloa colona*, and *Echinochloa oryzicola* are particularly problematic in rice-growing regions worldwide. *E. crus-galli* and *E. colona* are ranked among the world's most troublesome weeds due to their widespread distribution and high competitive ability (Holm et al., 1991). Yield losses caused by *E. colona* can exceed 75% at high

densities (Mercado and Talatala, 1977), while *E. crus-galli* can reduce yields by more than 50% even at low plant densities (Maun and Barrett, 1986). *E. oryzicola*, commonly associated with flooded rice systems, exhibits crop mimicry during early growth stages, making it difficult to distinguish from rice and thereby complicating management (Yamasue, 2001). The morphological and physiological similarities between rice and *Echinochloa* species facilitate their coexistence under similar environmental conditions, enhancing their persistence in rice fields. Although cultural practices such as narrow row spacing, increased seeding rates, and the use of competitive cultivars can suppress weed growth (Chauhan, 2012; Chauhan and Johnson, 2011a), the high biomass accumulation and rapid growth of *Echinochloa* species often result in severe crop–weed competition, particularly during critical growth stages (Forcella *et al.*, 1993).

Puddling, a common practice in lowland rice cultivation, is employed to reduce percolation losses, improve water retention, suppress weeds, and facilitate transplanting (Sanchez, 1973). However, repeated puddling degrades soil physical properties by reducing permeability, destroying soil structure, and forming a compacted plough pan (Aggarwal *et al.*, 1995; Sharma and De Datta, 1985). These changes not only affect the performance of succeeding crops (Hobbs and Gupta, 2000; Tripathi *et al.*, 2005) but also influence weed emergence patterns and seed bank dynamics. Chemical weed control remains a widely adopted strategy in rice cultivation, with herbicides such as pyrazosulfuron-ethyl, bispyribac-sodium, 2,4-D, butachlor, anilofos, fenoxaprop-p-ethyl, ethoxysulfuron, and metsulfuron-methyl commonly used. However, continuous reliance on herbicides, particularly those with similar modes of action, has led to shifts in weed flora and the evolution of herbicide-resistant biotypes (Chauhan, 2012; Chauhan *et al.*, 2012). Resistance in *Echinochloa* species, especially *E. colona* and *E. crus-galli*, has been reported against multiple herbicides including bispyribac-sodium, cyhalofop-butyl, fenoxaprop-P-ethyl, glyphosate, and quinclorac (Heap, 2015; Liu, 2018), posing a serious threat to sustainable rice production.

Given these challenges, a comprehensive understanding of *Echinochloa* behavior under continuous rice cultivation is essential. Therefore, the present study was undertaken to evaluate the dynamics of *Echinochloa* species in rice-based systems, with a focus on seed bank behavior, sources of infestation, and the development of effective and sustainable weed management strategies to minimize yield losses.

Materials and Methods

2.1 Study area and site description

A field experiment was conducted during the kharif and summer seasons of 2024 at Dudhawa village, Narharpur block, Kanker district, Chhattisgarh, India. The experimental site is geographically located at 19°06'48" N latitude and 81°51'58" E longitude, with an elevation of 554 m above mean sea level. The study area represents a typical rice-based farming system comprising bunded upland, midland, and lowland ecologies, exhibiting a wide variation in the density and distribution of *Echinochloa* species, which are known to cause substantial yield reduction in rice (Fig 8).

The region falls under a tropical monsoon climate, with an average annual rainfall of 1402 mm. During the kharif season (June–September), the total rainfall received was 1118.6 mm. The occurrence of extreme weather events, particularly high-intensity rainfall during July–August, coincided with the critical period of weed emergence and growth (Cousens and Moss, 1990). Subsequently, relatively dry conditions during October promoted aerobic soil conditions, favoring weed maturation and seed production.

The soils of the study area were sandy loam in texture and classified under Inceptisols. Soil properties varied across toposequences (bunded upland, midland, and lowland). The soils were low in organic carbon (0.43%, 0.39%, and 0.31%), available nitrogen (178, 146, and 131 kg ha⁻¹), and available phosphorus (21.4, 19.92, and 16.23 kg ha⁻¹), while medium in available potassium (179, 167, and 145 kg ha⁻¹), respectively. Soil reaction was acidic, with pH values of 6.8, 6.2, and 5.9 for upland, midland, and lowland conditions, respectively.

2.2 Soil sampling and analysis

To ensure uniformity of soil type, only Inceptisol soils were selected for the study. Soil samples were collected from the plough layer (0–15 cm depth) of paddy fields under each treatment. The collected samples were air-dried, ground, and passed through a 2-mm sieve prior to analysis.

Bulk density of the soil was determined using the core method as described by Blake and Hartge (1986), and was found to be 0.89 g cm⁻³. Soil pH was measured in a soil–water suspension (1:2.5 w/v) following the procedure outlined by Thomas (1996). Total nitrogen content was determined using the Kjeldahl method (Bremner, 1996). Available phosphorus was estimated using the sodium bicarbonate extraction method (Olsen, 1954), while available potassium was determined using the sodium acetate extraction method (Hosseinpur and Samavati, 2008).

2.3 Experimental details and field layout

A multi-location field experiment was conducted during the kharif and summer seasons of 2024 across 41 locations in villages surrounding the Dudhawa dam region (Table 1). The selected

villages were geo-referenced and mapped (Fig. 1), with an average elevation of 553 m above mean sea level. The sites were purposively selected based on continuous rice cultivation during both kharif and summer seasons and the presence of significant *Echinochloa* infestation. Each treatment was replicated three times across locations to ensure reliability of observations.

Rice variety MTU 1001, developed by Acharya N.G. Ranga Agricultural University, Andhra Pradesh, was used as the test cultivar across all sites. At each location, a representative plot measuring 10 m × 10 m was demarcated in the central portion of the field. Plot harvesting was carried out in both treated and unweeded (control) plots. The harvested crop was bundled, threshed, and grain yield was recorded. Yield data were converted to quintals per hectare (q ha⁻¹) for analysis.

2.4 Assessment of fallen seeds and seed rain

Fallen (shattered) seeds of *Echinochloa* species on the soil surface were quantified using quadrat sampling. A quadrat of 1 m × 1 m was placed randomly at three locations within each treatment plot. Seed counts were recorded at multiple stages, including 20 days prior to harvest during kharif, fallow, and summer seasons, without disturbing the soil surface.

To prevent seed movement and ensure accurate counting, each quadrat area was enclosed using a nylon net. Additionally, germinated seedlings were counted at 20 days after sowing or transplanting to assess the emergence potential of fallen seeds.

2.5 Seed bank dynamics: active and dormant seeds

Soil seed bank studies were conducted following standard procedures at 35 days after sowing or transplanting. Fields with a high density of *Echinochloa* species (>30% relative abundance) were selected for detailed analysis. Species composition was recorded under different crop establishment methods, including wet direct seeding, dry direct seeding, transplanting, and broadcasting.

Within each quadrat, the total number of fallen seeds was recorded. Germinated seedlings within the demarcated area were classified as **active seeds**, whereas seeds that failed to germinate were considered **dormant or non-viable seeds**. Species-wise seed counts were recorded and expressed per square meter.

2.6 Identification of seed sources

The source of *Echinochloa* infestation was categorized based on seed origin. Seeds were classified as originating either from outside the village (external sources) or from within the field or village (internal sources) as suggested by Rutkowski (2007). Additional sources of infestation, such as

contaminated seed material, farm machinery, continuous rice cultivation, and soil seed bank persistence, were also considered during observations (Fig 4 a-d).

2.7 Crop establishment methods

Different crop establishment methods commonly practiced by farmers were evaluated:

- **Dry Direct-Seeded Rice (D-DSR):** Fields were prepared with one summer ploughing followed by two cultivator passes and planking. Rice was sown using a seed drill before the onset of monsoon.
- **Wet Direct-Seeded Rice (W-DSR):** Fields were prepared under moist conditions with two ploughings followed by leveling. Pre-germinated seeds were broadcast uniformly.
- **Transplanting (TP):** Fields were puddled under standing water, allowed to settle for one day, and 25-day-old seedlings were transplanted manually at a spacing of 20×10 cm.
- **Broadcasting:** Seeds were directly broadcast in prepared fields after summer ploughing under rainfed conditions.
- **Alternate DSR–TP:** Alternating crop establishment methods (DSR and transplanting) in successive years to improve sustainability and manage weed infestation.
- **Biasi operation:** A traditional intercultural practice performed at 30 days after sowing, involving the use of a country plough without a share to disturb soil and uproot weeds in standing crop conditions.

2.8 Weed management practices

Farmers' management practices were considered as treatments, including:

- Summer ploughing followed by two tillage operations and planking
- Herbicide application (bispyribac-sodium @ 80 g ha^{-1}) at 20 days after sowing/transplanting
- One hand weeding at 25 DAS
- Stubble burning at 30 days after harvest
- Unweeded control (no weed management)

All selected fields followed similar mechanized operations for land preparation and harvesting to maintain uniformity.

2.9 Weed density and biomass accumulation

Weed density of *Echinochloa* species was recorded as the number of plants per square meter using quadrat sampling at three randomly selected locations within each plot. Similarly, species-wise observations were recorded under different crop establishment methods (Tokarska-Guzik et al., 2012). For biomass estimation, all *Echinochloa* plants within the quadrat were uprooted and cut at

the root–shoot junction. Samples were initially sun-dried and subsequently oven-dried at $65 \pm 2^\circ\text{C}$ until constant weight was achieved. Dry weight was recorded and expressed as g m^{-2} .

2.10 Statistical and multivariate analysis

2.10.1 Statistical analysis

All data were analyzed using SPSS software (version 14.0). A two-way factorial analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$ to evaluate the effects of seed source, management practices, *Echinochloa* species, and seasonal variation. Yield loss and seed bank parameters were analyzed separately.

2.10.2 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was conducted using R statistical software to evaluate multivariate relationships among treatments based on infestation and reproductive parameters. Prior to analysis, all variables were standardized to zero mean and unit variance. PCA was performed using the correlation matrix approach, and eigenvalues were used to determine the significance of principal components. The first two principal components explaining the majority of total variance were retained for interpretation. A biplot was generated to visualize treatment distribution and variable contributions (Fig. 11).

2.10.3 Artificial Neural Network (ANN) modeling

An artificial neural network (ANN) model was developed using a backpropagation algorithm with gradient descent optimization. A linear output function (`linear.output = TRUE`) was used for regression analysis. The model was trained to minimize the sum of squared error (SSE) between predicted and observed values. Convergence was achieved after 94 iterations, with a final error value of 0.009977, indicating good model performance.

Results and discussion

3.1 Effect of crop establishment methods

Crop establishment methods exerted a significant influence on the density and dry matter accumulation of *Echinochloa* species. *Echinochloa colona* recorded significantly higher density under wet seeding (Lehi), which was statistically comparable to transplanting. In contrast, *Echinochloa crus-galli* exhibited maximum density under transplanting and remained at par with wet seeding. The density of *Echinochloa oryzicola* was also higher under transplanting, confirming its ecological preference for puddled and flooded conditions.

Dry direct-seeded rice (DSR) and broadcasting did not show significant differences in the density of *E. colona* and *E. oryzicola*, indicating that these species respond similarly under aerobic

soil conditions. However, *E. crus-galli* exhibited a relatively higher density under DSR, which was statistically comparable to transplanting (23.61 plants m⁻²). Under wet seeding and broadcasting, *E. crus-galli* showed similar density patterns. A similar trend was observed in the dry matter accumulation of *Echinochloa* species across different crop establishment methods (Table 2).

Crop–weed competition is a natural and inevitable phenomenon in agro-ecosystems, driven by competition for light, nutrients, moisture, and space (Renton and Chauhan, 2017). The genus *Echinochloa* is widely distributed across tropical and temperate regions and is highly responsive to agronomic manipulations such as crop establishment methods (Bajwa et al., 2015). *E. colona*, being a C₄ annual grass native to India, exhibited strong persistence across multiple cropping systems due to its rapid growth and adaptive capacity (Masood et al., 2016).

Early emergence of *Echinochloa* species from an active soil seed bank resulted in intense competition with rice plants. Both *E. colona* and *E. crus-galli* can emerge from 15 days after rice establishment and persist until maturity, causing yield losses of up to 80% under severe infestation (Smith, 1983). Continuous rice cultivation involving repeated tillage operations enhances seed dormancy and facilitates seed survival under mechanized systems (Table 3). Notably, *E. crus-galli* var. *oryzicola* can produce up to 40,000 seeds per plant and closely resembles rice seedlings, leading to unintentional transplantation and secondary infestation (Holm et al., 1977).

Environmental conditions such as high temperature further enhance the competitive ability of barnyard grass. Under elevated temperatures, *Echinochloa* species grow more vigorously than rice, particularly under monoculture systems (Oh-e et al., 2007; Aminpanah et al., 2016). These findings indicate that crop establishment methods, in combination with climatic factors, play a critical role in determining weed dynamics and competition intensity.

3.2 Effect of dormancy

Seed dormancy played a crucial role in regulating the persistence and seasonal dynamics of *Echinochloa* species. Primary dormancy allowed seeds to survive unfavorable environmental conditions and germinate during the subsequent cropping season, particularly between August and October. During the kharif season, the combination of moderate temperature (20–30°C) and adequate soil moisture under flooded conditions created a favorable environment for rapid germination (Table 5). Flooded soil conditions, which are common in rice cultivation, reduced oxygen availability and, when combined with high temperatures (30–40°C), accelerated the breakdown of dormancy. Seed shattering was identified as a key ecological trait contributing to the persistence of *Echinochloa* species in rice ecosystems. *E. crus-galli* exhibited higher seed shattering

(30%) compared to *E. colona* (20%), and dormancy levels were recorded at 85% and 83%, respectively (Fig. 9; Estorninos et al., 2002). Seed dormancy acts as a bet-hedging mechanism, enabling seeds to spread germination over time and increasing the likelihood of survival under fluctuating environmental conditions (Baskin and Baskin, 2004). This adaptive strategy contributes significantly to the persistence and resilience of *Echinochloa* species in intensively cultivated rice systems.

3.3 Effect on yield loss

Yield loss due to *Echinochloa* infestation was significantly influenced by both species and crop establishment methods. Broadcasting resulted in the highest yield reduction due to *E. colona*, followed by wet seeding (5.08 q ha⁻¹) and DSR (7.05 q ha⁻¹). Transplanting recorded the lowest yield reduction for *E. colona* (Table 2; Fig. 2), likely due to initial crop advantage and water management conditions. In contrast, *E. crus-galli* caused maximum yield reduction under transplanting (5.04 q ha⁻¹), with similar trends observed under DSR. Broadcasting and wet seeding resulted in comparatively lower yield losses due to this species. *E. oryzicola* exhibited relatively lower yield loss compared to the other two species, possibly due to its ecological specialization under flooded conditions.

The extended flowering window of *Echinochloa* species allows cross-pollination among different biotypes, thereby enhancing genetic variability and adaptability under continuous rice cultivation. This may contribute to sustained infestation levels in both kharif and summer seasons. Transplanting and wet seeding showed comparable yield reductions under *E. oryzicola* infestation (Fig. 3), indicating similar ecological suitability. Above-ground competition, particularly during reproductive stages, was identified as the primary factor responsible for yield reduction. Barnyard grass significantly reduced dry matter accumulation and grain formation in rice (Chauhan, 2003; Clements et al., 2013). A strong negative correlation between weed biomass and crop yield further supports this observation (McDonald and Gill, 2009).

3.4 Effect of seed bank dynamics

Seed bank dynamics were significantly influenced by cropping systems, seasonal variation, and sources of infestation. Seed fall of *Echinochloa* species was highest during summer rice cultivation compared to kharif and fallow periods (Table 5). This increase was associated with high temperatures, irrigation-induced flooding, and mechanized harvesting operations. Mechanization, particularly during harvesting, caused disturbance to mature plants, leading to increased seed shattering due to loosely attached spikelets (Patterson, 1995). Soil seed banks further contributed to

the accumulation of seeds in the field (Figs. 5 and 6) (Sekutowski and Smagacz, 2011). Similar findings have been reported where mechanical operations increased seed production compared to chemical weed control (Perron and Légère, 2000).

Seed production of *E. crus-galli* can exceed 326,000 seeds m^{-2} under mechanical disturbance (McDonald and Gill, 2009), highlighting the importance of management practices in regulating seed bank dynamics. Germination patterns varied across seasons, with kharif conditions favoring higher emergence due to optimal moisture and temperature. Mechanization and seed source were identified as major contributors to seed dispersal and germination (Turra, 2023), while fallow conditions reduced early seed density. Tillage operations influenced seed distribution both vertically and horizontally, affecting dormancy and emergence patterns (Yenish et al., 1992; Wolfe et al., 2008).

3.5 Effect of management practices

Management practices significantly influenced the density, seed fall, and germination of *Echinochloa* species. The unweeded control recorded the highest number of fallen and germinated seeds, whereas hand weeding at 25 DAS resulted in the lowest seed accumulation. Herbicide application (bispiribac-sodium @ 80 g ha^{-1}) and hand weeding were equally effective in reducing seed fall and germination (Sekutowski and Smagacz, 2014). Burning was moderately effective and widely adopted due to its operational simplicity and cost-effectiveness.

Rice-fallow systems showed higher seed deposition initially but reduced seed viability over time due to exposure to high temperatures and desiccation stress. In contrast, summer rice cultivation significantly increased seed production (Fig. 7). Mechanization promoted germination by disturbing soil layers and exposing seeds to favorable conditions. Overall, integrated weed management practices combining mechanical, chemical, and cultural approaches were more effective in reducing *Echinochloa* infestation and limiting seed bank build-up (Zhang et al., 2017).

3.6 Active and dormant seed bank

Active seed bank density was significantly influenced by both species and crop establishment methods. *E. colona* recorded the highest active seed density under transplanting (1502 seeds m^{-2}), followed by *E. crus-galli* (680 seeds m^{-2}). Broadcasting and DSR recorded lower active seed densities due to aerobic conditions limiting germination. Dormant seed banks were also significantly affected by crop establishment methods. Transplanting preserved higher dormant seeds due to puddling and prolonged soil moisture conditions. In contrast, DSR reduced dormancy due to enhanced aeration and early germination (Table 4).

Soil tillage influenced seed distribution and depth, thereby affecting dormancy dynamics (Dyer, 1995). Surface soil layers were more favorable for germination (Benech-Arnold et al., 2000; Mayor and Maillard, 1995). Reduced tillage systems often resulted in higher weed abundance due to seed accumulation near the soil surface (Cardina et al., 1991; Armengot et al., 2016). *E. oryzicola* exhibited lower dormant seed density compared to *E. colona* and *E. crus-galli*, irrespective of crop establishment method. The dominance of *Echinochloa* species over rice can be attributed to their higher photosynthetic efficiency, with *E. crus-galli* exhibiting rates up to $33.5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ compared to $21.5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in rice.

3.7 Artificial Neural Network (ANN)

The artificial neural network (ANN) model effectively captured nonlinear relationships among infestation-related variables and the response variable (S1). The network architecture (6–3–1) converged after 94 iterations with a low sum of squared error (0.009977), indicating a strong fit to the observed data. However, the limited sample size ($n = 9$) poses a significant limitation, as neural networks generally require larger datasets for robust generalization (Fig 10). The model likely exhibits overfitting, capturing specific patterns in the training dataset rather than generalizable relationships. Therefore, while ANN demonstrates methodological applicability, results should be interpreted cautiously.

3.8 Principal Component Analysis (PCA)

Principal Component Analysis explained 96.06% of the total variance, with PC1 accounting for 85.12% and PC2 for 10.93%. PC1 represented infestation intensity, with strong loadings from all variables, indicating that treatment differences were primarily driven by weed pressure. *n*managed treatments (no weeding, seed source, mechanization) were associated with high infestation levels, whereas herbicide application, hand weeding, and burning were associated with reduced infestation. PC2 differentiated reproductive traits from density-related parameters, although its contribution was relatively minor. Strong clustering of variables confirmed positive correlations among infestation parameters. Overall, PCA results clearly demonstrated the effectiveness of management practices in reducing weed infestation and highlighted infestation intensity as the primary factor influencing treatment variation.

Declarations

Ethics Approval and Consent to Participate

The study did not involve human participants, human data, or animals requiring ethical approval. Therefore, ethics approval and consent to participate are not applicable.

Consent for Publication

All authors have read and approved the final manuscript for publication.

Competing Interests

The authors declare that they have no competing interests.

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This research was not funded by any external agency and was carried out as part of institutional research activities. The funding body had no role in study design, data collection, analysis, interpretation, or manuscript preparation.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

A.P. conceptualized the study, conducted field investigations, and prepared the manuscript. V.P. supervised the research work and contributed to manuscript editing. K.S.K., A.S., S.K.N., A.K., S.M., A.N., and S.M. assisted in data collection, analysis, and interpretation. All authors read and approved the final manuscript.

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Funding Declaration:

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Field Permission Statement

The field surveys conducted in the Dudhawa Dam region was carried out after obtaining the necessary permissions from the relevant local authorities and landowners. Prior to data collection, official consent was secured to access the study sites, ensuring compliance with local regulations and ethical research standards. All field activities were conducted with due respect to environmental guidelines and community norms.

Table 1 Selected sites of study area in Dhudhawa dam

S. No.	Village	Lat	Long	Season	Landform
1	Devkhut	20.285	81.824	Summer	Lowland
2	Anchhidongri	20.293	81.778	Kharif	Midland
3	Kormud	20.270	81.747	Kharif	Bunded upland
4	Dudhawa	20.296	81.752	Kharif	Midland
5	Dhanora	20.302	81.743	Kharif	Midland
6	Dudhawa	20.303	81.723	Summer	Lowland
7	Dudhawa	20.295	81.729	Summer	Lowland
8	Musurputa	20.303	81.748	Kharif	Bunded upland
9	Bhursidongri	20.267	81.770	Kharif	Lowland
10	Banoramal	20.268	81.794	Kharif	Lowland
11	Sonpur	20.292	81.796	Summer	Lowland
12	Aamgaon	20.284	81.787	Kharif	Bunded upland
13	Musurputa	20.262	81.794	Kharif	Midland
14	Musurputa	20.265	81.782	Summer	Midland
15	Ghodabad	20.256	81.771	Summer	Lowland
16	Musurputa	20.245	81.775	Kharif	Midland
18	Bihawa	20.250	81.757	Kharif	Bunded upland
19	Nawagaon	20.255	81.744	Kharif	Midland
20	Dompadar	20.272	81.756	Kharif	Midland
21	Dompadar	20.258	81.830	Kharif	Bunded upland
22	Banora Ryt	20.272	81.828	Kharif	Bunded upland
23	Bhumkamal	20.268	81.819	Kharif	Bunded upland
24	Bhumkamal	20.283	81.805	Summer	Midland
25	Birgudi	20.303	81.831	Kharif	Midland
26	Birgudi	20.308	81.833	Summer	Lowland
27	Birgudi	20.311	81.851	Kharif	Bunded upland
28	Goddangari	20.315	81.840	Kharif	Midland
29	Hirridh	20.306	81.858	Summer	Lowland
30	Nawagaon	20.280	81.854	Summer	Lowland
31	Ghodabad	20.284	81.845	Summer	Midland
32	Basanwahi	20.249	81.839	Kharif	Bunded upland
33	Basanwahi	20.237	81.772	Summer	Midland
34	Maddabhari	20.226	81.761	Summer	Lowland
35	Borbadha	20.209	81.748	Kharif	Bunded upland
36	Nawagaom	20.231	81.740	Kharif	Bunded upland
37	Kasipur	20.242	81.820	Kharif	Midland
38	Belagaon	20.248	81.820	Kharif	Midland
39	Sihawa	20.246	81.851	Summer	Bunded upland
40	Bem Ryt	20.273	81.838	Summer	Bunded upland
41	Banora Ryt	20.302	81.888	Summer	Bunded upland

Table 2 Effect of crop establishment methods on *Echinochloa species*

Crop Establishment	Density (No./m ⁻²) at 25 DAS			Dry wt. (No./m ⁻²) at 25 DAS		
	<i>E. colona</i>	<i>E. crusgallii</i>	<i>E. oryzoides</i>	<i>E. colona</i>	<i>E. crusgallii</i>	<i>E. oryzoides</i>
Wet seeding (Lehi)	31.51	19.84	23.08	13.84	6.90	7.64
Dry seeding(DSR)	22.59	26.74	21.06	10.05	8.17	6.39
Transplanting	26.35	23.61	28.49	11.87	10.38	12.99
Broadcasting	19.84	16.75	15.90	8.72	7.70	7.37
CD (p=0.05)	5.86	3.76	5.68	3.01	2.33	2.85

Table 3 Effect of tillage operations on *Echinochloa species*

<i>Sanwa species</i>	Density (No. m ⁻²) at 25 DAS				Dry wt. (g m ⁻²) at 25 DAS			
	Ploughing	Puddling	Hoeing	Hand Weeding	Ploughing	Puddling	Hoeing	Hand Weeding
<i>Echinochloa colona</i>	5.71 (32.15)	3.64 (12.74)	4.21 (17.25)	4.12 (16.49)	2.59 (6.20)	1.43 (1.54)	1.55 (1.89)	1.54 (1.86)
<i>Echinochloa crusgallii</i>	4.13 (16.52)	4.86 (23.15)	3.85 (14.36)	3.65 (12.80)	1.94 (3.27)	1.63 (2.16)	1.35 (1.32)	1.24 (1.04)
<i>Echinochloa oryzicola</i>	4.79 (22.48)	4.31 (18.05)	5.17 (26.27)	3.47 (11.53)	2.25 (4.56)	2.00 (3.49)	2.44 (5.46)	1.68 (2.32)
CD (p=0.05)	0.93	0.56	0.97	NS	0.35	0.38	0.91	NS

Table 4 Effect of source of infestation and management practices on *Echinochloa species*

Treatment	Seeds m ⁻² at harvest			Germinated seeds m ⁻² at 25DAS		
	Kharif rice	Rice-fallow	Summer rice	Kharif rice	Rice-fallow	Summer rice
Source of infestation (SI)						
Seed	1429	942	2169	1075	247	742
Mechanization	1556	559	2362	1171	146	808
Regular rice cultivation	1230	564	1866	925	148	638
Soil seed bank	1339	695	2032	1007	182	695
CD (p=0.05)	138	88	332	166	46	67
Management practices (MP)						
1 ploughing + 1 rotavator	918	407	2073	608	151	671
Herbicide (Bispyribac-Na @ 80g/ha)	641	497	1229	482	111	333
Hand weeding (25 DAS)	625	484	1197	470	108	324
No weeding	1633	1264	3129	1228	282	848
Burning at 30 DAH	837	648	1604	629	145	434
CD (p=0.05)	315	NS	387	167	64	153
Interaction SI x MP CD (p=0.05)	456	NS	867	298	NS	NS

*DAH= days after harvesting

Table 5. Effect of *Echinochloa species* and crop establishments on seed bank

Sanwa + Crop establishment	Seed bank		
	Yield loss (q/ha)	Active seed bank (No. m ⁻²)	Dormant seed bank (No. m ⁻²)
<i>Ec</i> +Wet seeding (<i>Lehi</i>)	2.36 (5.08)	34.72 (1205)	17.48 (305.12)

<i>Ec</i> +Dry seeding (DSR)	2.75 (7.05)	31.41 (986)	15.77 (248.25)
<i>Ec</i> +Transplanting	1.89 (3.07)	38.76 (1502)	19.48 (378.95)
<i>Ec</i> +Broadcasting	2.96 (8.27)	32.01 (1024)	16.30 (265.08)
<i>Ecr</i> +Wet seeding (<i>Lehi</i>)	1.60 (2.05)	23.36 (545)	11.78 (138.26)
<i>Ecr</i> +Dry seeding (DSR)	1.88 (3.02)	21.13 (446)	11.30 (127.25)
<i>Ecr</i> +Transplanting	2.35 (5.04)	26.09 (680)	13.22 (174.24)
<i>Ecr</i> +Broadcasting	1.57 (1.95)	21.53 (463)	10.95 (119.32)
<i>Eo</i> +Wet seeding (<i>Lehi</i>)	1.20 (0.95)	21.58 (465)	10.86 (117.42)
<i>Eo</i> +Dry seeding (DSR)	1.13 (0.78)	19.53 (381)	9.87 (96.82)
<i>Eo</i> +Transplanting	0.97 (0.45)	24.09 (580)	12.07 (145.27)
<i>Eo</i> +Broadcasting	1.16 (0.84)	19.89 (395)	9.95 (98.57)
<i>CD (p=0.05)</i>	0.72	4.04	3.18

**Ecr* = *Echinochloa crusgalli*, *Ec* = *Echinochloa colona*, *Eo* = *Echinochloa oryzicola*.

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Figure 1 a) Soil sampling from locations, b) DSR method of sowing, c) Broadcasting of rice d) Transplanted field of rice e) Bias system of rice f) Uprooting rice seedlings for transplanting

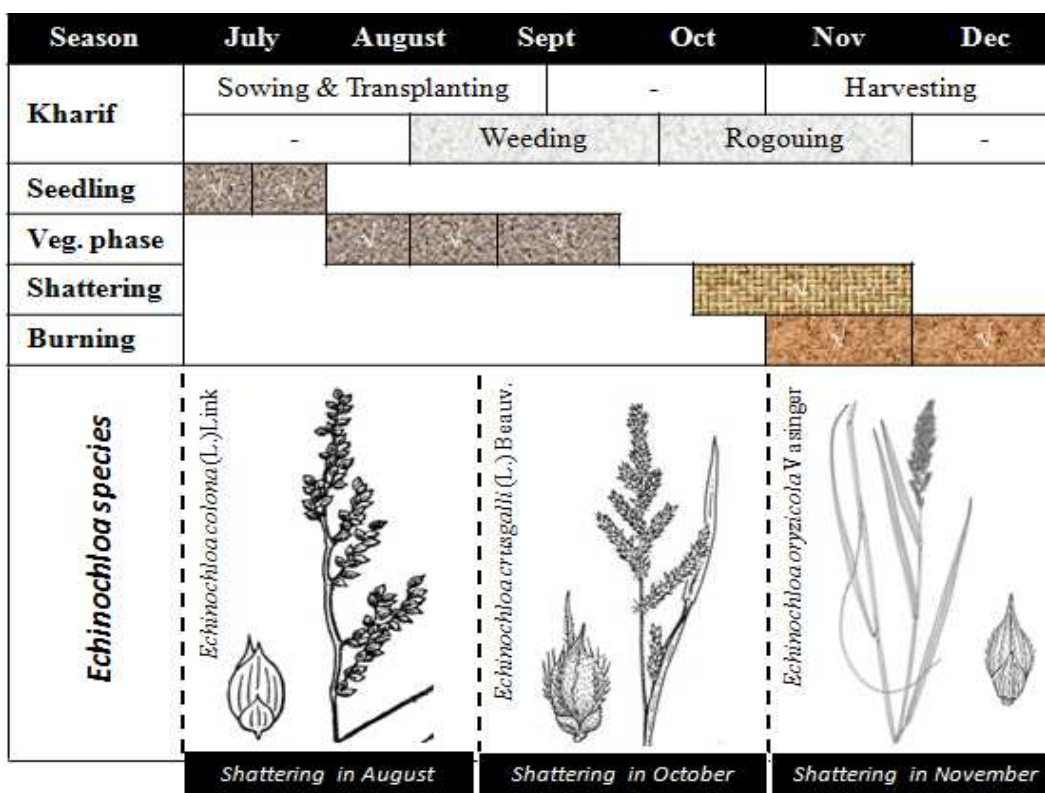


Fig 2. Month wise growth of *Echinochloa* species under different agronomical practices during kharif season.

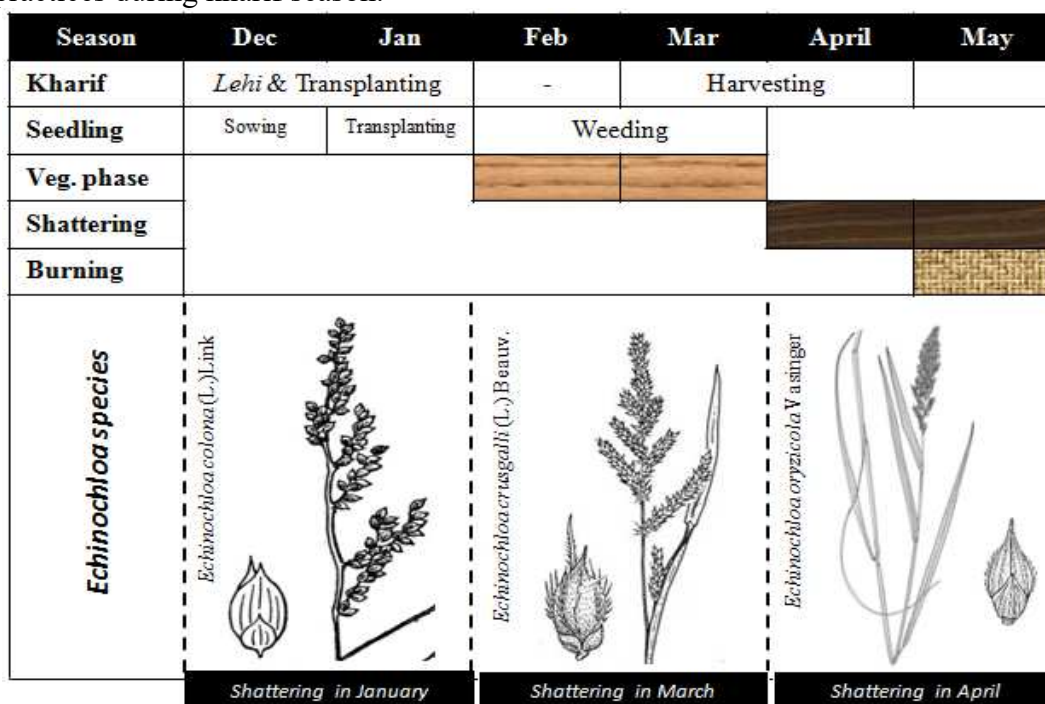


Fig 3. Month wise growth of *Echinochloa* species under different agronomical practices during rabi season.



Fig 4 a, b, c & d: Location of infested fields with *Echinochloa* species during kharif and summer season of rice cultivation; morphological differences of *E. species* in inset pictures



Fig 5 i) *Echinochloa crusgalli*, ii) *Echinochloa colona*, iii) *Echinochloa oryzoides*; a-m) species wise morphological variation *Echinochloa* in rice cultivation; iv) Bunch of *Echinochloa oryzoides*



Fig 6 a & b) stem morphology; c) Panicle of *Echinochloa oryzoides*; d) Leaf blade and sheath of *E. crusgalli*; Panicle and ligule differences of *Echinochloa* species



Fig 7 a) Burned stubbles, b) Unburned area; c) Grooves of seed hiding; d) Straw cover over fallen seeds of *Echinochloa* species

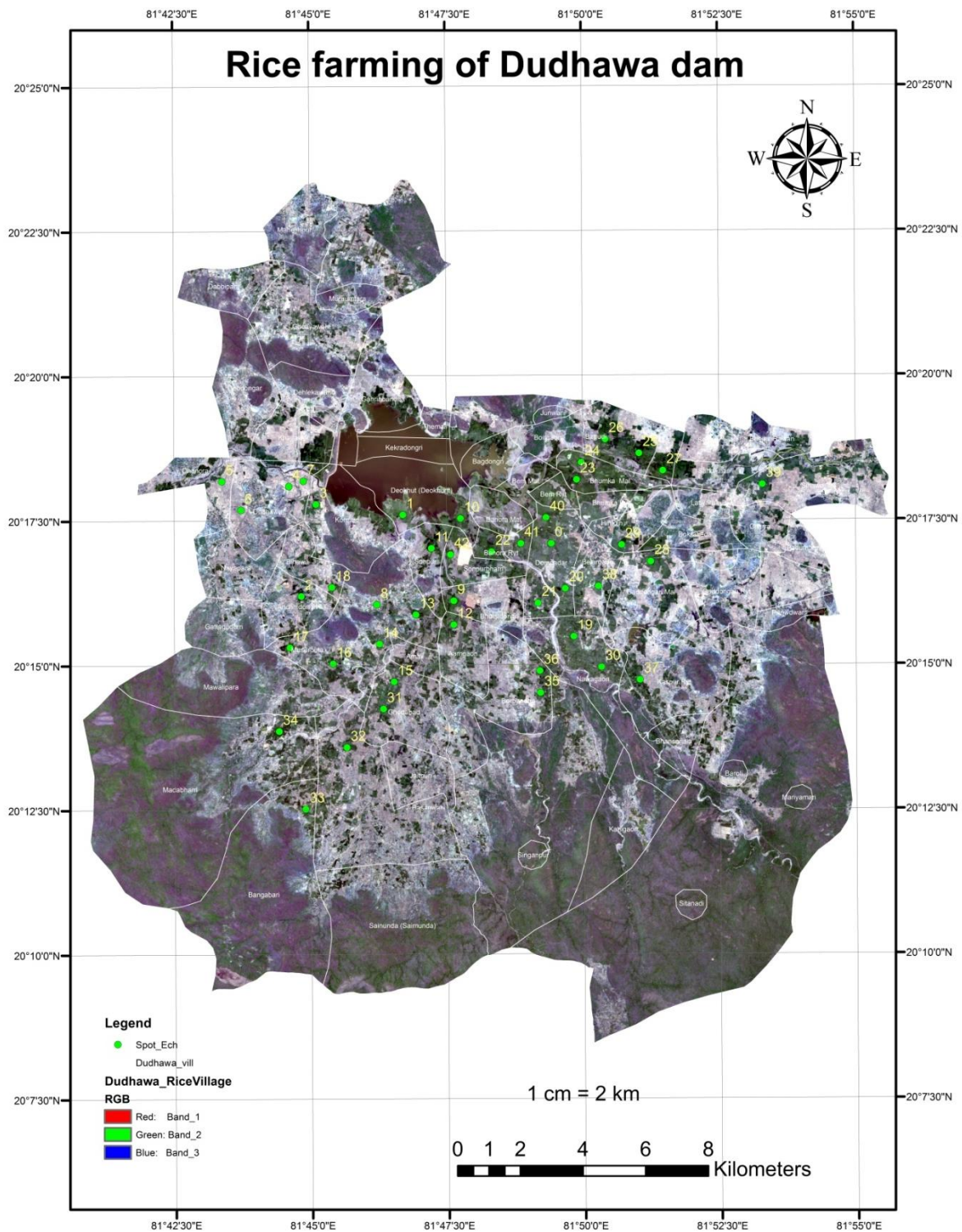


Fig 8 Satellite map of rice farming villages of *Dudhawa* dam under study

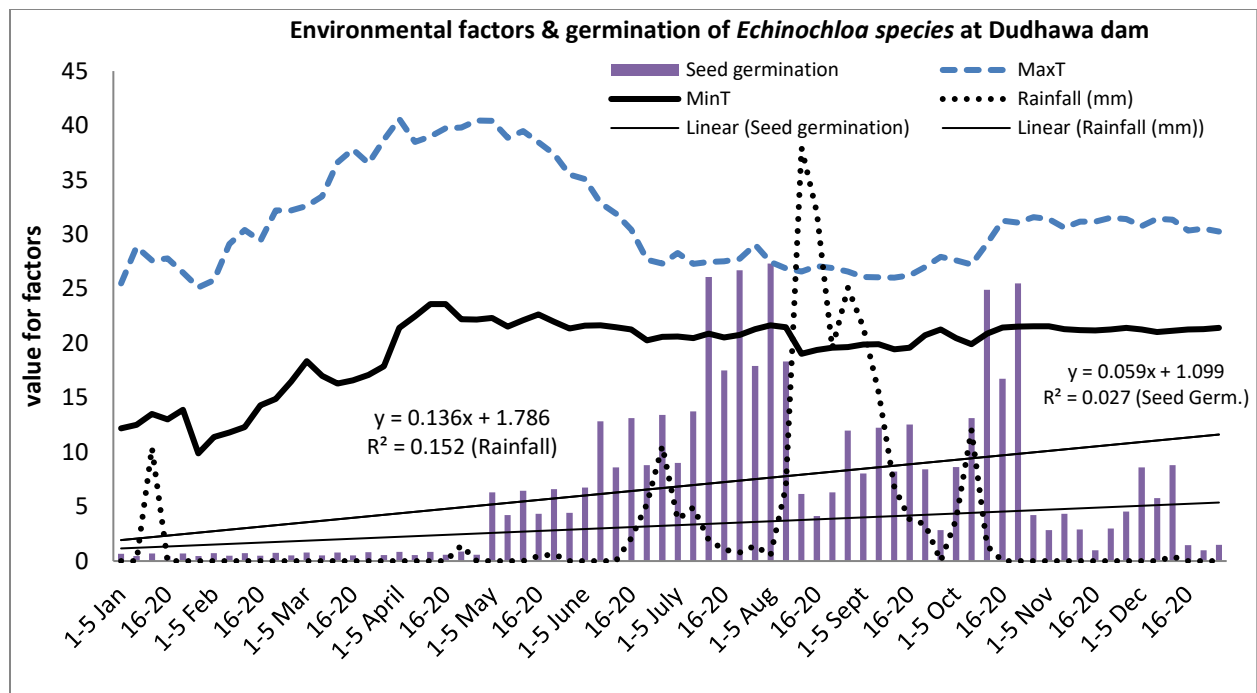


Fig 9 Climatic factors and seed germination of *Echinochloa* species

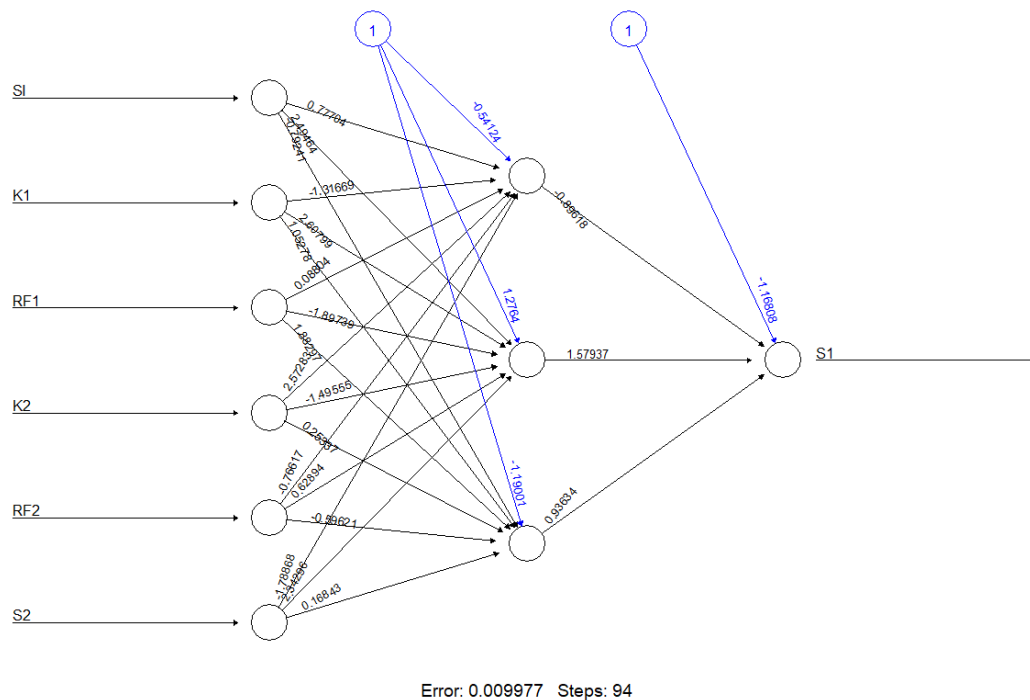


Fig 10 Graphical presentation of multilayer perceptron architecture with six input neurons (S1, K1, RF1, K2, RF2, and S2), one hidden layer containing three neurons, and one output neuron representing S1

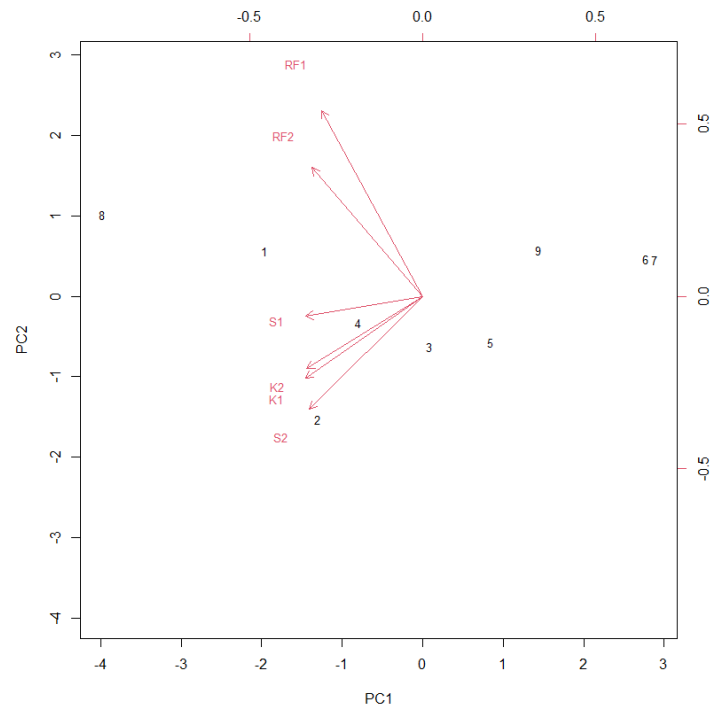


Fig 11 Principal Component Analysis (PCA) with clear structural pattern among treatments and infestation parameters