



RESEARCH ARTICLE

# Effect of non-chemical weed management on nutrient uptake, microbial population and grain nutritional parameters in transplanted rice (*Oryza sativa* L.)

Lizabeni M Kithan<sup>1</sup>, E Somasundaram<sup>2\*</sup>, P Murali Arthanari<sup>1</sup>, R Kannan<sup>3</sup>, P Janaki<sup>4</sup>, R Sunitha<sup>5</sup> & Surya K<sup>1</sup>

<sup>1</sup>Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

<sup>2</sup>Directorate of Agribusiness Development (ABD), Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

<sup>3</sup>Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

<sup>4</sup>Department of Nammazhvar Organic Farming Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

<sup>5</sup>Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

\*Correspondence email - [somasundaram.e@tnau.ac.in](mailto:somasundaram.e@tnau.ac.in)

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## Abstract

Non-chemical weed management strategies in transplanted rice (*Oryza sativa* L.) were evaluated for their effect on nutrient uptake, soil microbial population and grain nutritional parameters during *rabi* 2022 and *kharif* 2024 at Tamil Nadu Agricultural University, Coimbatore. The experiment setup consisted of twelve treatments laid out in a randomized block design (RBD) with three replications. Hand weeding (HW) twice at 20 and 40 DAT (T<sub>11</sub>) recorded the least NPK uptake by weed in both *rabi* 2022 (N:10.85, 12.48, 12.89, 12.51 kg ha<sup>-1</sup>, P: 5.31, 6.67, 7.97, 9.39 kg ha<sup>-1</sup>, K: 15.92, 22.69, 26.91, 28.48 kg ha<sup>-1</sup>) and *kharif* 2024 (N: 10.74, 12.62, 12.78, 12.76 kg ha<sup>-1</sup>, P: 5.44, 6.81, 8.19, 9.6 kg ha<sup>-1</sup>, K: 16.19, 23.08, 27.39, 28.81 kg ha<sup>-1</sup>) at 30, 45, 60, 80 DAT respectively. Butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as pre-emergence (PE) + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as post-emergence (POE) (T<sub>9</sub>) recorded the highest NPK uptake by plant in both *rabi* 2022 (NPK: 51.5, 7.58, 79.1 kg ha<sup>-1</sup>) which was at par with T<sub>11</sub> and during *kharif* 2024, T<sub>11</sub> recorded the highest NPK uptake by plants (NPK: 51.0, 7.83, 76.2 kg ha<sup>-1</sup>) which was at par with T<sub>9</sub>. Mycoherbicide foliar spray treatments (T<sub>2</sub> and T<sub>10</sub>) at 25 DAT + HW at 40 DAT increased soil available nutrients and microbial populations with the highest NPK available in soil recorded in T<sub>10</sub> (NPK: 219.3, 20.80, 734.0 kg ha<sup>-1</sup>) in *rabi* 2022 and (NPK: 220.9, 21.42, 723.0 kg ha<sup>-1</sup>) in *kharif* 2024 which was on par with T<sub>2</sub> and the highest microbial population recorded in T<sub>10</sub> (Bacteria: 9.78 × 10<sup>7</sup> CFU g<sup>-1</sup>, Fungi: 5.14 × 10<sup>3</sup> CFU g<sup>-1</sup>, Actinomycetes: 6.45 × 10<sup>4</sup> CFU g<sup>-1</sup>) in *rabi* 2022 and (Bacteria: 9.87 × 10<sup>7</sup> CFU g<sup>-1</sup>) in *kharif* 2024 which was on par with T<sub>2</sub> and T<sub>2</sub> recording the highest fungi population of 5.06 × 10<sup>3</sup> CFU g<sup>-1</sup> and actinomycetes population of 6.42 × 10<sup>4</sup> CFU g<sup>-1</sup> which was on par with T<sub>10</sub> in *kharif* 2024. Grain nutritional parameters (protein, crude fibre, fat, carbohydrates) showed no significant variation across treatments (p > 0.05). Bibliometric analysis revealed a research gap in non-chemical weed control with only 11 publications compared to 1783 on general weed management in rice (1990-2025). These findings highlight the potential of non-chemical weed management strategies to improve nutrient efficiency and soil health and therefore, strengthening and validating the pressing need for sustainable rice production.

**Keywords:** mycoherbicide; non-chemical weed management; nutrient uptake

## Introduction

Rice (*Oryza sativa* L.) is a major staple food crop that supports the livelihood and food security of over half the world population. But its growth faces significant challenges from weed competition which can reduce yields by 15-66 % depending on weed species, weed density and weed management practices (1). In transplanted rice system, weed competition poses a significant threat to crop growth, nutrient availability and yield (2). Traditionally, chemical herbicides have been widely used for effective weed suppression. However, their long-term use has raised environmental and ecological concerns including herbicide resistance, soil degradation and residue accumulation. These negative impacts on non-target soil biota have intensified the search for sustainable non-chemical alternatives (3). Non-chemical weed management in transplanted

rice is gaining attention as a sustainable alternative to chemical herbicides with potential benefits for nutrient uptake and soil microbial populations (4). Non-chemical weed management methods such as mulching and green manuring can enhance soil health and nutrient availability while reducing environmental risks associated with chemical inputs. These methods aim to suppress weed growth without the adverse environmental effects associated with herbicides, while potentially enhancing soil microbial activity and nutrient availability (5, 6). Soil microorganisms play a critical role in organic matter decomposition, nitrogen mineralization, phosphorus solubilization and the mobilization of micronutrients, thereby directly affecting nutrient uptake and plant health. Non-chemical weed management practices are hypothesized to create a more favourable environment for these microbial communities by

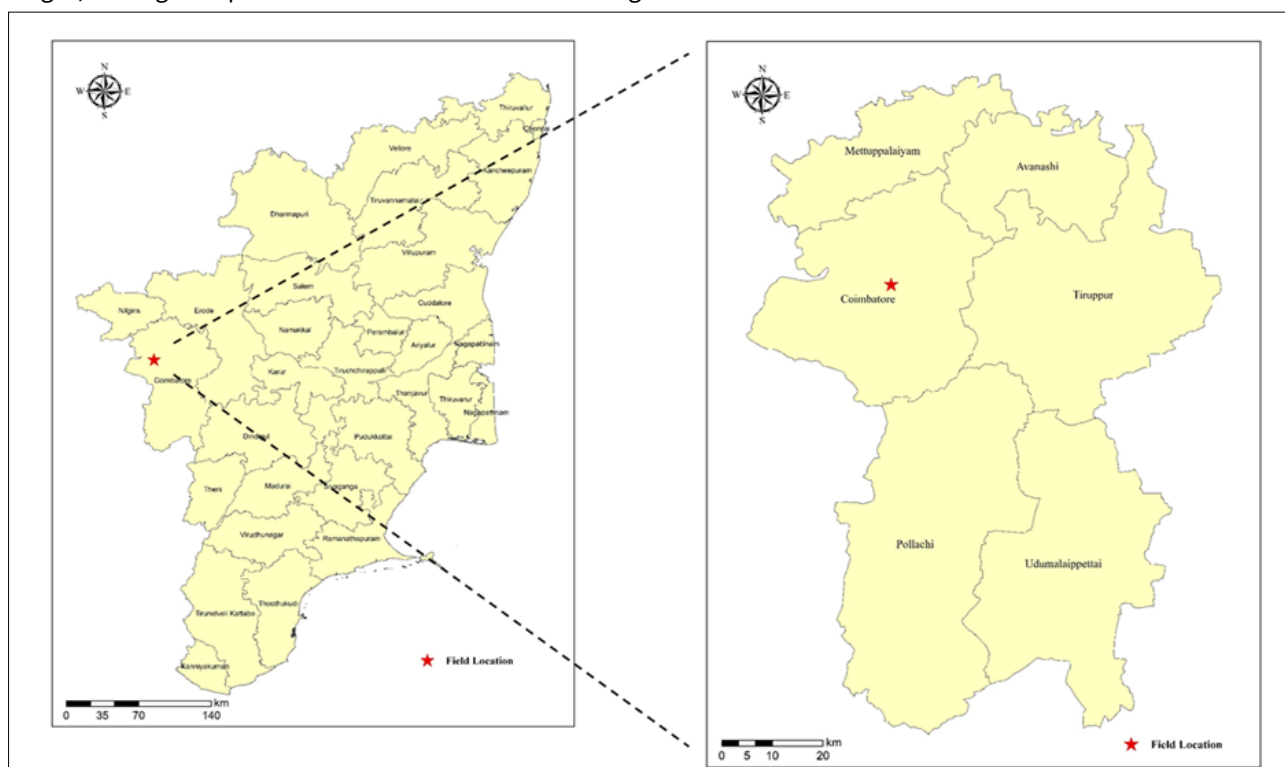
avoiding the toxic effects of herbicides which can disrupt microbial diversity and functions (7). By reducing weed competition through non-chemical strategies, rice plants exhibit improved access to soil nutrients like nitrogen (N), phosphorus (P) and potassium (K), leading to enhanced growth and yield (8). Non-chemical and integrated weed management practices, especially those combining organic amendments (like biofertilizers, organic mulches or green manures) with manual weeding, have been shown to improve nutrient uptake in rice. These methods can increase the availability and absorption of key nutrients such as nitrogen, phosphorus and potassium by the rice crop, often surpassing chemical approaches (9, 10). Non-chemical weed management, particularly when combined with organic inputs, supports higher soil microbial biomass and activity by creating favourable conditions for beneficial soil microbes, which play a crucial role in nutrient cycling and plant health. Chemical herbicides can temporarily suppress microbial populations and enzymatic activities (11). While several studies highlight the benefits of integrated and non-chemical weed management on nutrient uptake and microbial health, most research focuses on chemical or combined approaches. There is a lack of comprehensive studies isolating the effects of purely non-chemical weed management in transplanted rice systems. Few studies detail the specific changes in microbial community structure and function under non-chemical weed management, especially over multiple seasons or in different agro-ecological zones. Conducting dedicated experiments comparing non-chemical weed management methods with chemical and integrated approaches in transplanted rice will help determine their specific impacts on nutrient uptake and soil microbial populations. Despite the potential benefits, the effect of non-chemical weed management on nutrient uptake and soil microbial populations in transplanted rice systems are not fully understood. Variations in soil type, climate and management practices can influence the outcome of these strategies, making site-specific research essential. Understanding

how non-chemical weed control practices influence nutrient uptake and soil microbial dynamics is essential for developing sustainable weed management systems in rice cultivation which can enhance nutrient use efficiency and support the ecological balance of soil systems, thereby contributing to long-term agricultural sustainability. This study aims to evaluate the impact of different non-chemical weed management practices on nutrient uptake and soil microbial population dynamics in transplanted rice, with the following objectives of assessing the impact of non-chemical weed management strategies on nutrient uptake by crop and weed in transplanted rice, evaluation of microbial dynamics and grain nutritional parameters for various weed control practices and evaluation and assessment of scientometric analysis for identifying the research gap and scientific impact of non-chemical weed control in rice.

## Materials and Methods

### Study location and weather condition

A field experiments were carried out at the wetland farm, Tamil Nadu Agricultural University (TNAU), Coimbatore, across two cropping seasons such as *rabi* 2022 and *kharif* 2024. The site is in the Western Agro-climatic Zone of Tamil Nadu at 11°01' 8" N latitude and 76°54'17" E longitude, with an elevation of 426.7 m above mean sea level (Fig. 1). The region has a tropical climate, receiving an average annual rainfall of about 846 mm. During the *rabi* 2022 season, the average maximum and minimum temperatures were 30.11 °C and 21.92 °C respectively. Morning (07:22 hr) and afternoon (14:22 hr) relative humidity values averaged 82.91 % and 56.48 %. The average wind speed was 2.55 km hr<sup>-1</sup>, with a daily average of 4.62 sunshine hours, 5.41 mm of evaporation and solar radiation of 292.01 cal cm<sup>-2</sup> day<sup>-1</sup>. In contrast, the *kharif* 2024 season experienced slightly higher temperatures and humidity levels. The average maximum and



**Fig. 1.** Research field location. The experimental location lies in the Western Agro-climatic Zone of Tamil Nadu, situated at 11°01' 8" N latitude and 76°54'17" E longitude, with an altitude of 426.7 m above mean sea level. The experimental site experiences a tropical climate with an average annual rainfall of approximately 846 mm.

minimum temperatures were 31.9 °C and 23.7 °C, respectively. Relative humidity averaged 85.0 % in the morning and 58.8 % in the afternoon. The wind velocity increased to 8.0 km/hr, while daily sunshine duration averaged 5.6 hr. The season recorded an average evaporation rate of 5.6 mm day<sup>-1</sup> and solar radiation of 324.7 cal cm<sup>-2</sup> day<sup>-1</sup>.

### Treatment details

The experiment followed a randomized block design (RBD) with three replications and included twelve weed management treatments. The treatments included: T<sub>1</sub> - Foliar spray (FS) of ITK-based farmers' practices (cow urine + lime solution + khadi soap + common salt) at 25 days after transplanting (DAT) followed by hand weeding (HW) at 40 DAT; T<sub>2</sub> - Foliar spray (FS) of Mycoherbicide-1 at 25 DAT + hand weeding at 40 DAT; T<sub>3</sub> - Application of rice bran @ 5 t ha<sup>-1</sup> as a basal dose at transplanting + hand weeding at 40 DAT; T<sub>4</sub> - Intercropping daincha with rice in a 3:1 ratio + incorporation at 40 DAT; T<sub>5</sub> - Azolla as a dual crop @ 1 t ha<sup>-1</sup> + incorporation at 40 DAT; T<sub>6</sub> - Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT; T<sub>7</sub> - Double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + 25 DAT; T<sub>8</sub> - Cono-weeding four times at 10, 20, 30 and 40 DAT; T<sub>9</sub> - Application of Butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as pre-emergence (PE) + Bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as post-emergence (POE); T<sub>10</sub> - Foliar spray of Mycoherbicide-2 at 25 DAT + hand weeding at 40 DAT; T<sub>11</sub> - Hand weeding twice at 20 and 40 DAT; T<sub>12</sub> - Unweeded check.

### Experimental design, varietal characters and agronomic practices

The field experiment was laid out in a randomized block design with twelve treatments and three replications across two seasons such as *rabi* 2022 and *kharif* 2024. The gross and net plot sizes were 5.0 × 4.0 m and 4.5 × 3.5 m respectively, with four sample rows per plot. A 60 cm buffer channel separated adjacent plots and 1.0 m irrigation channels were provided between replications. The rice variety CO 51, released in 2013 through the cross ADT 43 / RR 272-1745, was used in both the seasons. It is a semi-dwarf, medium-duration variety (105-110 days), flowering in 75-80 days and is suitable for multiple seasons. It produces 250-300 grains per panicle, has medium slender white grains with a 1000-grain weight of 16 g, yields about 6623 kg ha<sup>-1</sup> and contains 7.5 % protein with moderate resistance to major pests and diseases. Field preparation involved two tractor ploughings, rotavator and puddling using a cage wheel tractor. Seeds were sown at 60 kg ha<sup>-1</sup>, soaked in water for 24 hr and the sprouted seeds were broadcasted in the nursery. 14 days old seedlings were transplanted at 20 × 20 cm spacing. Irrigation was maintained at 2.5 cm until panicle initiation and 5 cm thereafter. Fertilizers were applied at 150:50:50 NPK kg ha<sup>-1</sup>, with full dose of basal phosphorus and potassium and N was given in split application. All agronomic practices were uniformly followed across both seasons.

### Observations recorded

#### Weed uptake NPK

The uptake of nitrogen (N), phosphorus (P) and potassium (K) by weeds was assessed by sampling weed biomass from each experimental plot during the peak vegetative growth stage. These samples were initially shade-dried, followed by oven drying at 65 °C until a constant weight was achieved. The dried samples were then grounded to a fine powder using a Willey mill. Total nitrogen content was determined using the Kjeldahl method, phosphorus was estimated by the vanado-molybdate yellow colorimetric method

and potassium content was measured through flame photometry.

Nutrient uptake was computed using the formula:

$$\text{Nutrient uptake} = \frac{\text{nutrient content (\%)}}{\text{dry biomass (kg ha}^{-1}\text{)}} \times 100 \quad (\text{Eqn. 01})$$

This approach enabled quantification of the nutrients extracted by weeds, providing insight into their competitive impact on nutrient availability for the main crop.

### Plant analysis

Plant samples were randomly collected from each plot, followed by shade drying and subsequent oven drying. The dried samples were then finely ground using a Willey mill to prepare them for nutrient analysis. The concentrations of total nitrogen (N), phosphorus (P) and potassium (K) were determined and nutrient uptake was calculated using the appropriate formula (Table 1).

Nutrient uptake =

$$\frac{\text{Percentage of nutrient in plant} \times \text{Total DMP} \left(\frac{\text{kg}}{\text{ha}}\right)}{100} \quad (\text{Eqn. 02})$$

**Table 1.** Standard methods followed for the plant analysis

| S. No. | Method  | Parameters       | Reference |
|--------|---|------------------|-----------|
| 1.     | Diacid extract - Micro kjeldhal digestion and distillation method               | Total nitrogen   | (12)      |
| 2.     | Triacid extract - Vanadomolybdate colorimetric method                           | Total phosphorus | (13)      |
| 3.     | Triacid extract - Neutralised with ammonia and estimated using flame photometer | Total potassium  | (13)      |

### Soil analysis

Soil samples were obtained from each plot at two critical stages: pre-sowing and post-harvest. Sampling was conducted at a depth of 0-15 cm from five randomly selected points within each plot. The collected samples were shade-dried, finely ground and passed through a 2 mm nylon mesh sieve for uniformity. The initial (pre-sowing) soil samples were analyzed for their physical and chemical properties, including texture, bulk density, particle density, porosity, pH, electrical conductivity (EC), organic carbon and available nitrogen (N), phosphorus (P) and potassium (K). The final (post-harvest) samples were analyzed specifically to assess the available levels of N, P and K in the soil.

### Soil microbial load (CFU)

Microbial analysis was conducted using the serial dilution method to evaluate population dynamics at various crop growth stages, specifically before sowing, following the application of treatments and at harvest. For the initial dilution (10<sup>-1</sup>), 1 g of soil was added to a test tube containing 10 mL of sterile distilled water and thoroughly shaken. Subsequently, a 10<sup>-2</sup> dilution was prepared by transferring 1 mL of the 10<sup>-1</sup> suspension into 9 mL of sterile distilled water using a sterile pipette. Microbial population estimates were obtained at appropriate dilution levels: 10<sup>7</sup> for bacteria, 10<sup>3</sup> for fungi and 10<sup>4</sup> for actinomycetes, depending on the specific microbial group (Table 2).

**Table 2.** Soil microbial analysis

| Microbes   | Media                  | Dilution factor  | Incubation Period |
|--|------------------------|------------------|-------------------|
| Bacterial population (10 <sup>7</sup> CFU/g)     | Nutrient Agar medium   | 10 <sup>-7</sup> | 2 days            |
| Fungal population (10 <sup>3</sup> CFU/g)        | Rose Bengal medium     | 10 <sup>-3</sup> | 4 days            |
| Actinomycetes population (10 <sup>4</sup> CFU/g) | Ken knight Agar medium | 10 <sup>-4</sup> | 7 days            |

### Nutritional parameters of rice

Assessing the nutritional parameters of crops like rice is vital for evaluating their quality and nutritional contribution to human diets. These parameters usually encompass essential components such as protein, carbohydrates, fats and fibre, which are crucial for determining the crop's overall nutritional value. The nutritional content of rice has been examined to better understand its role in human nutrition. Evaluating these factors provides valuable insights into the crop's nutritional profile, aids in optimizing agricultural practices to enhance yield and quality and supports food security for communities relying on these staple crops.

### Protein content

The protein content of rice was determined using the Kjeldahl method formulated by Lowery *et al.* (1951) (14). A known amount of the dried sample was subjected to digestion with concentrated sulfuric acid, which decomposes organic matter and transforms nitrogen into ammonium sulfate. After digestion, the solution was neutralized with sodium hydroxide and the ammonia was distilled and absorbed in a boric acid solution. The ammonia was then measured through titration with a standard acid solution. To calculate the protein percentage, the nitrogen content was multiplied by a conversion factor of 6.25. This method offers an accurate assessment of protein content, which is crucial for determining the nutritional quality of the crop.

$$\% \text{Crude protein} = \% \text{N} \times F \text{ (general factor of 6.25)} \quad (\text{Eqn.03})$$

### Crude fibre

The crude fibre content in rice was determined using the acid and alkali digestion method which given by Holst (1982) (15). A known weight of the dried sample was initially treated with an acidic solution (such as sulfuric acid) to eliminate soluble materials. The sample was then exposed to an alkaline solution (such as sodium hydroxide) to remove any remaining soluble substances, leaving only the fibrous residue. After treatment, the residue was filtered, washed and dried at a constant temperature. The dried residue was weighed and the crude fibre content was calculated as a percentage of the initial sample weight. Crude fibre is a key dietary component that aids digestion and promotes overall health.

Crude (%) =

$$\frac{\text{Weight of crucible + dried residue} - (\text{weight of crucible} + \text{ash})}{\text{Weight of sample}} \times 100 \quad (\text{Eqn. 04})$$

### Fat

The fat content in rice was measured using the Soxhlet extraction method. A known weight of the dried sample was placed in a Soxhlet extractor, where petroleum ether was used as the solvent for fat extraction. The sample was heated, allowing the solvent to pass

through the plant material repeatedly, extracting the fat. After the extraction, the solvent was evaporated using a rotary evaporator leaving the extracted fat behind. The fat was then weighed and the fat content was calculated as a percentage of the total sample weight. This method is commonly used due to its effectiveness in accurately determining fat content in plant samples. Fat is a vital nutrient, providing a significant energy source and essential fatty acids in the diet.

Fat (%) =

$$\frac{\text{final weight of the flask with extracted fat (W2)} - \text{initial weight of the empty flask (w1)}}{\text{Weight of the original sample (S)}} \times 100 \quad (\text{Eqn. 05})$$

### Carbohydrate

The carbohydrate content of rice was measured using the Anthrone method, a widely used technique for estimating carbohydrates in plant samples (16). In this method, a known weight of dried plant material is first hydrolyzed with dilute acid, followed by the addition of Anthrone reagent. The mixture is then heated and cooled and the intensity of the green color formed is measured using a spectrophotometer. The absorbance is compared to a standard glucose curve to determine the carbohydrate concentration. This method is accurate and commonly used for quantifying total carbohydrates in plant tissues. Carbohydrates are a vital energy source in the human diet and assessing their content is important for evaluating the energy value of crops.

% carbohydrate =

$$\frac{\text{Conc. Of unknown sample (C unknown)} \times \text{Volume of the sample extract (V sample)}}{1000 \times \text{initial weight of the sample (W sample)}} \times 100 \quad (\text{Eqn.06})$$

### Scientometric analysis

A comprehensive bibliometric analysis was conducted to assess research trends, identify gaps and evaluate the scientific impact of non-chemical weed control in rice production systems. Two distinct search queries were used in the Scopus database to retrieve relevant literature: one for the broader topic of "weed management in rice" and another specifically targeting "non-chemical weed control in rice". The comparative assessment aimed to analyze global research output, country-wise contributions and the evolution of scientific focus on non-chemical strategies relative to conventional weed control practices in rice. Scopus, chosen as the primary data source, offers extensive coverage with more than 23000 indexed journals across all scientific disciplines, surpassing Web of Science in scope. The time frame selected for this analysis was 35 years (1990-2025), allowing for the exploration of long-term research trends and emerging themes in weed management. To ensure relevance and quality, the subject area was restricted to Agricultural and Biological Sciences. One of the key challenges encountered during data acquisition was optimizing the search strategy to retrieve a high volume of pertinent documents while minimizing irrelevant records. This required refining search terms and applying exclusion criteria to eliminate inappropriate results. From the Scopus database, 1783 documents were retrieved under the title "weed management in rice", while only 11 publications were identified with the more specific title "Non-chemical weed control in rice", highlighting a notable gap in focused research on non-chemical approaches. The retrieved data were exported in CSV format and analyzed using R

software version 4.4.0. The bibliometrix R-package and its web-based interface, Biblioshiny, were employed for data processing and visualization.

### Statistical analysis

The analysis of variance (ANOVA) for all measured traits was conducted using R software (version 4.2.1) through R Studio for Windows (R Core Team, 2020). Mean comparisons were made using Fisher's Least Significant Difference (LSD) test at a 5 % significance level and non-significant results were indicated as "NS" (17).

## Results

### Weed uptake NPK

#### Weed uptake nitrogen

The nitrogen uptake by weeds was significantly affected by various non-chemical weed management practices at different stages of crop growth, as shown in Table 3. In both the *rabi* 2022 and *kharif* 2024 seasons, the unweeded check (T<sub>12</sub>) consistently recorded the highest nitrogen uptake by weeds at all observation intervals, indicating high weed pressure in the absence of control measures. The peak nitrogen uptake by weeds occurred at 60 DAT in both the season (19.11 kg ha<sup>-1</sup> in *rabi* 2022 and 18.83 kg ha<sup>-1</sup> in *kharif* 2024), followed by a slight decrease at 80 DAT due to weed senescence and crop canopy closure. Among the treatments, the combination of FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) resulted in the highest nitrogen uptake by weeds with values of 13.81, 17.34, 17.78 and 17.42 kg ha<sup>-1</sup> in *rabi* 2022 and 13.67, 17.51, 17.61 and 17.67 kg ha<sup>-1</sup> in *kharif* 2024 at 30, 45, 60 and 80 DAT respectively. The lowest weed nitrogen uptake was consistently observed in HW at 20 and 40 DAT (T<sub>11</sub>) with recorded values of 10.85, 12.48, 12.89 and 12.51 kg ha<sup>-1</sup> in *rabi* 2022 and 10.74, 12.62, 12.78 and 12.76 kg ha<sup>-1</sup> in *kharif* 2024 at 30, 45, 60 and 80 DAT respectively.

#### Weed uptake phosphorous

The phosphorus (P) uptake by weeds, as shown in Table 4 was measured at 30, 45, 60 and 80 DAT during *rabi* 2022 and *kharif* 2024 to assess the effect of various non-chemical weed management practices. In both the season, unweeded check (T<sub>12</sub>) recorded the

highest P uptake by weeds indicating significant nutrient depletion due to uncontrolled weed growth with recorded values of 8.14, 9.32, 10.53 and 12.51 kg ha<sup>-1</sup> during *rabi* 2022 and 8.27, 9.48, 10.72 and 12.74 kg ha<sup>-1</sup> during *kharif* 2024 at 30, 45, 60 and 80 DAT respectively.

The lowest weed P uptake was recorded in HW at 20 and 40 DAT (T<sub>11</sub>) with 5.31, 6.67, 7.97 and 9.39 kg ha<sup>-1</sup> during *rabi* 2022 and 5.44, 6.81, 8.19 and 9.60 kg ha<sup>-1</sup> at 30, 45, 60 and 80 DAT respectively. Among the non-chemical treatments, FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT (T<sub>1</sub>) and azolla as a dual crop @ 1 t ha<sup>-1</sup> + incorporation at 40 DAT (T<sub>5</sub>) also exhibited relatively lower P uptake by weeds with T<sub>1</sub> recording values of 5.73, 6.97, 8.23 and 9.78 kg ha<sup>-1</sup> during *rabi* 2022 and 5.84, 7.06, 8.41 and 9.92 kg ha<sup>-1</sup> during *kharif* 2024 and T<sub>5</sub> recording values of 5.92, 7.11, 8.37 and 9.96 kg ha<sup>-1</sup> during *rabi* 2022 and 6.04, 7.25, 8.61 and 10.19 kg ha<sup>-1</sup> during *kharif* 2024 at 30, 45, 60 and 80 DAT respectively.

#### Weed uptake potassium

The potassium (K) uptake by weeds, shown in Table 5 was measured at 30, 45, 60 and 80 DAT during both *rabi* 2022 and *kharif* 2024. The unweeded check (T<sub>12</sub>) consistently recorded the highest K uptake by weeds in both *rabi* 2022 and *kharif* 2024 indicating significant nutrient depletion due to uncontrolled weed growth with K uptake of 23.68, 32.96, 38.21 and 39.67 kg ha<sup>-1</sup> in *rabi* 2022 and 23.81, 33.25, 38.59 and 39.93 kg ha<sup>-1</sup> at 30, 45, 60 and 80 DAT, respectively.

Among the treatments, HW at 20 and 40 DAT (T<sub>11</sub>) showed the lowest K uptake by weeds with values of 15.92, 22.69, 26.91 and 28.48 kg ha<sup>-1</sup> during *rabi* 2022 and 16.19, 23.08, 27.39 and 28.81 kg ha<sup>-1</sup> during *kharif* 2024 at 30, 45, 60 and 80 DAT. Among the non-chemical treatments, relatively lower K uptake was recorded in FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT (T<sub>1</sub>) and azolla as a dual crop @ 1 t ha<sup>-1</sup> + incorporation at 40 DAT (T<sub>5</sub>) with T<sub>1</sub> recording the weed K uptake of 16.51, 23.11, 28.04 and 29.46 kg ha<sup>-1</sup> during *rabi* 2022 and 16.76, 23.47, 28.38 and 29.67 kg ha<sup>-1</sup> during *kharif* 2024 and T<sub>5</sub> recording uptake of 17.11, 23.61, 28.65 and 30.15 kg ha<sup>-1</sup> during *rabi* 2022 and 17.37, 23.94, 29.05 and 30.57 kg ha<sup>-1</sup> during *kharif* 2024 at the 30, 45, 60 and 80 DAT respectively.

**Table 3.** Effect of non- chemical weed management practices on weed uptake N (kg ha<sup>-1</sup>) at 30, 45, 60 and 80 DAT in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No               | Treatments   | <i>rabi</i> 2022 |             |             |             | <i>kharif</i> 2024 |             |             |             |
|--------------------|--|------------------|-------------|-------------|-------------|--------------------|-------------|-------------|-------------|
|                    |  | 30 DAT           | 45 DAT      | 60 DAT      | 80 DAT      | 30 DAT             | 45 DAT      | 60 DAT      | 80 DAT      |
| T <sub>1</sub>     | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 11.32            | 13.66       | 13.91       | 13.38       | 11.17              | 13.78       | 13.83       | 13.62       |
| T <sub>2</sub>     | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 13.64            | 17.11       | 17.58       | 17.11       | 13.41              | 17.24       | 17.47       | 17.43       |
| T <sub>3</sub>     | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 12.09            | 15.44       | 15.83       | 15.32       | 11.95              | 15.59       | 15.71       | 15.67       |
| T <sub>4</sub>     | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 12.73            | 15.61       | 15.95       | 14.44       | 12.64              | 15.73       | 15.82       | 14.76       |
| T <sub>5</sub>     | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 11.54            | 13.82       | 14.22       | 13.86       | 11.46              | 13.95       | 14.04       | 14.11       |
| T <sub>6</sub>     | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 12.94            | 15.68       | 16.07       | 15.61       | 12.83              | 15.8        | 15.95       | 15.92       |
| T <sub>7</sub>     | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 12.38            | 15.52       | 15.93       | 15.52       | 12.27              | 15.66       | 15.8        | 15.82       |
| T <sub>8</sub>     | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 11.42            | 13.73       | 14.12       | 13.75       | 11.31              | 13.87       | 14.05       | 13.98       |
| T <sub>9</sub>     | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 11.06            | 13.21       | 13.66       | 13.24       | 10.89              | 13.34       | 13.52       | 13.57       |
| T <sub>10</sub>    | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 13.81            | 17.34       | 17.78       | 17.42       | 13.67              | 17.51       | 17.61       | 17.67       |
| T <sub>11</sub>    | Hand weeding twice at 20 and 40 DAT  | 10.85            | 12.48       | 12.89       | 12.51       | 10.74              | 12.62       | 12.78       | 12.76       |
| T <sub>12</sub>    | Unweeded check   | 14.97            | 18.63       | 19.11       | 18.66       | 14.88              | 18.78       | 18.83       | 18.89       |
| <b>S.Ed</b>        |  | <b>0.82</b>      | <b>0.76</b> | <b>0.9</b>  | <b>0.9</b>  | <b>0.68</b>        | <b>0.43</b> | <b>0.9</b>  | <b>0.86</b> |
| <b>CD (P=0.05)</b> |  | <b>1.71</b>      | <b>1.59</b> | <b>1.87</b> | <b>1.87</b> | <b>1.42</b>        | <b>0.9</b>  | <b>2.04</b> | <b>1.8</b>  |

**Table 4.** Effect of non- chemical weed management practices on weed uptake P (kg ha<sup>-1</sup>) at 30, 45, 60 and 80 DAT in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No            | Treatments   | <i>rabi</i> 2022 |             |             |             | <i>kharif</i> 2024 |             |             |             |
|-----------------|--|------------------|-------------|-------------|-------------|--------------------|-------------|-------------|-------------|
|                 |  | 30 DAT           | 45 DAT      | 60 DAT      | 80 DAT      | 30 DAT             | 45 DAT      | 60 DAT      | 80 DAT      |
| T <sub>1</sub>  | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 5.73             | 6.97        | 8.23        | 9.78        | 5.84               | 7.06        | 8.41        | 9.92        |
| T <sub>2</sub>  | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 7.27             | 8.48        | 9.74        | 11.26       | 7.38               | 8.57        | 9.92        | 11.41       |
| T <sub>3</sub>  | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 6.49             | 7.73        | 8.98        | 10.48       | 6.61               | 7.89        | 9.17        | 10.67       |
| T <sub>4</sub>  | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 6.77             | 7.92        | 9.15        | 10.75       | 6.85               | 8.07        | 9.38        | 10.93       |
| T <sub>5</sub>  | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 5.92             | 7.11        | 8.37        | 9.96        | 6.04               | 7.25        | 8.61        | 10.19       |
| T <sub>6</sub>  | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 6.85             | 8.06        | 9.33        | 10.83       | 6.94               | 8.19        | 9.57        | 11.07       |
| T <sub>7</sub>  | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 6.65             | 7.83        | 8.91        | 10.46       | 6.76               | 7.98        | 9.18        | 10.64       |
| T <sub>8</sub>  | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 5.82             | 6.94        | 8.18        | 9.75        | 5.86               | 7.11        | 8.39        | 9.98        |
| T <sub>9</sub>  | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 5.54             | 6.76        | 8.05        | 9.59        | 5.68               | 6.92        | 8.27        | 9.81        |
| T <sub>10</sub> | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 7.36             | 8.53        | 9.76        | 11.38       | 7.48               | 8.69        | 9.98        | 11.56       |
| T <sub>11</sub> | Hand weeding twice at 20 and 40 DAT  | 5.31             | 6.67        | 7.97        | 9.39        | 5.44               | 6.81        | 8.19        | 9.6         |
| T <sub>12</sub> | Unweeded check   | 8.14             | 9.32        | 10.53       | 12.51       | 8.27               | 9.48        | 10.72       | 12.74       |
|                 | <b>S.Ed</b>  | <b>0.38</b>      | <b>0.48</b> | <b>0.45</b> | <b>0.52</b> | <b>0.42</b>        | <b>0.58</b> | <b>0.48</b> | <b>0.72</b> |
|                 | <b>CD (P=0.05)</b>   | <b>0.78</b>      | <b>1.01</b> | <b>0.94</b> | <b>1.09</b> | <b>0.89</b>        | <b>1.21</b> | <b>1.01</b> | <b>1.49</b> |

**Table 5.** Effect of non- chemical weed management practices on weed uptake K (kg ha<sup>-1</sup>) at 30, 45, 60 and 80 DAT in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No            | Treatments   | <i>rabi</i> 2022 |             |             |             | <i>kharif</i> 2024 |             |             |             |
|-----------------|--|------------------|-------------|-------------|-------------|--------------------|-------------|-------------|-------------|
|                 |  | 30 DAT           | 45 DAT      | 60 DAT      | 80 DAT      | 30 DAT             | 45 DAT      | 60 DAT      | 80 DAT      |
| T <sub>1</sub>  | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 16.51            | 23.11       | 28.04       | 29.46       | 16.76              | 23.47       | 28.38       | 29.67       |
| T <sub>2</sub>  | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 20.78            | 28.81       | 34.82       | 36.39       | 20.92              | 29.11       | 35.21       | 36.83       |
| T <sub>3</sub>  | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 18.25            | 25.74       | 31.54       | 33.11       | 18.49              | 25.97       | 31.97       | 33.56       |
| T <sub>4</sub>  | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 18.93            | 26.33       | 31.93       | 33.48       | 19.13              | 26.68       | 32.36       | 33.87       |
| T <sub>5</sub>  | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 17.11            | 23.61       | 28.65       | 30.15       | 17.37              | 23.94       | 29.05       | 30.57       |
| T <sub>6</sub>  | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 19.14            | 26.58       | 32.12       | 32.71       | 19.38              | 26.87       | 32.58       | 33.09       |
| T <sub>7</sub>  | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 18.82            | 26.12       | 31.76       | 33.28       | 19.03              | 26.49       | 32.11       | 33.69       |
| T <sub>8</sub>  | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 16.87            | 23.42       | 28.21       | 29.79       | 17.05              | 23.76       | 28.62       | 30.11       |
| T <sub>9</sub>  | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 16.11            | 22.89       | 27.63       | 29.15       | 16.37              | 23.21       | 28.09       | 29.58       |
| T <sub>10</sub> | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 21.37            | 29.14       | 35.11       | 36.71       | 21.62              | 30.17       | 35.52       | 37.08       |
| T <sub>11</sub> | Hand weeding twice at 20 and 40 DAT  | 15.92            | 22.69       | 26.91       | 28.48       | 16.19              | 23.08       | 27.39       | 28.81       |
| T <sub>12</sub> | Unweeded check   | 23.68            | 32.96       | 38.21       | 39.67       | 23.81              | 33.25       | 38.59       | 39.93       |
|                 | <b>S.Ed</b>  | <b>1.14</b>      | <b>1.57</b> | <b>2</b>    | <b>1.81</b> | <b>1.01</b>        | <b>1.49</b> | <b>2.11</b> | <b>1.66</b> |
|                 | <b>CD (P=0.05)</b>   | <b>2.36</b>      | <b>3.25</b> | <b>4.15</b> | <b>3.75</b> | <b>2.11</b>        | <b>3.1</b>  | <b>4.39</b> | <b>3.45</b> |

### Plant uptake NPK in rice

The uptake of plant nutrients (N, P and K) at harvest varied significantly among the non-chemical weed management treatments during both *rabi* 2022 and *kharif* 2024 seasons, as shown in Table 6.

The highest N uptake was recorded in the chemical control treatment butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) with uptake of 51.5 kg ha<sup>-1</sup> during *rabi* 2022 and 49.2 kg ha<sup>-1</sup> during *kharif* 2024. Among the non-chemical treatments, azolla as a dual crop @ 1 t ha<sup>-1</sup> + incorporation at 40 DAT (T<sub>5</sub>) and FS of ITK-based farmers' practices on 25 DAT + HW

at 40 DAT (T<sub>1</sub>) with T<sub>5</sub> recording 49.7 kg ha<sup>-1</sup> during *rabi* 2022 and 51.9 kg ha<sup>-1</sup> during *kharif* 2024 and T<sub>1</sub> recording 49.5 kg ha<sup>-1</sup> during *rabi* 2022 and 49.6 kg ha<sup>-1</sup> during *kharif* 2024 resulted in good performance suggesting that azolla incorporation and ITK practices can positively influence nutrient dynamics. The lowest N uptake was recorded in the unweeded check (T<sub>12</sub>) with 28.9 kg ha<sup>-1</sup> during *rabi* 2022 and 29.9 kg ha<sup>-1</sup> during *kharif* 2024 indicating effective weed suppression that enhanced nutrient absorption.

The highest P uptake was recorded in butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) with values of 7.58 kg ha<sup>-1</sup> during *rabi* 2022 and 7.65 kg ha<sup>-1</sup> during *kharif*.

**Table 6.** Effect of non- chemical weed management practices on plant uptake NPK (kg ha<sup>-1</sup>) at harvest stage in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No               | Treatments   | <i>rabi</i> 2022 |             |             | <i>kharif</i> 2024 |             |             |
|--------------------|--|------------------|-------------|-------------|--------------------|-------------|-------------|
|                    |  | N                | P           | K           | N                  | P           | K           |
| T <sub>1</sub>     | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 49.5             | 7.38        | 73.7        | 49.6               | 7.32        | 72.6        |
| T <sub>2</sub>     | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 40.6             | 6.27        | 55.8        | 39.1               | 6.02        | 57.5        |
| T <sub>3</sub>     | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 46.6             | 6.83        | 65.2        | 48.0               | 7.08        | 65.7        |
| T <sub>4</sub>     | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 47.3             | 6.69        | 63.1        | 47.1               | 6.55        | 61.7        |
| T <sub>5</sub>     | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 49.7             | 7.21        | 71.3        | 51.9               | 7.00        | 72.0        |
| T <sub>6</sub>     | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 46.2             | 6.62        | 61.7        | 46.8               | 6.93        | 61.1        |
| T <sub>7</sub>     | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 47.1             | 6.78        | 64.5        | 45.9               | 6.85        | 66.8        |
| T <sub>8</sub>     | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 50.3             | 7.28        | 72.5        | 50.5               | 7.30        | 73.7        |
| T <sub>9</sub>     | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 51.5             | 7.58        | 79.1        | 49.2               | 7.56        | 80.3        |
| T <sub>10</sub>    | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 38.6             | 6.15        | 53.2        | 38.4               | 6.13        | 51.2        |
| T <sub>11</sub>    | Hand weeding twice at 20 and 40 DAT  | 51.1             | 7.46        | 76.3        | 51.0               | 7.83        | 76.2        |
| T <sub>12</sub>    | Unweeded check   | 28.9             | 4.31        | 45.3        | 29.9               | 4.17        | 45.5        |
| <b>S.Ed</b>        |  | <b>2.74</b>      | <b>0.34</b> | <b>2.85</b> | <b>1.76</b>        | <b>0.45</b> | <b>2.92</b> |
| <b>CD (P=0.05)</b> |  | <b>5.69</b>      | <b>0.71</b> | <b>5.92</b> | <b>3.66</b>        | <b>0.94</b> | <b>6.06</b> |

Among the non-chemical treatments, FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT (T<sub>1</sub>) and azolla as a dual crop @ 1 t ha<sup>-1</sup> + incorporation at 40 DAT (T<sub>5</sub>) were comparable to the chemical control, highlighting their effectiveness in maintaining phosphorus availability with T<sub>1</sub> recording uptake of 7.38 kg ha<sup>-1</sup> and 7.32 kg ha<sup>-1</sup> and T<sub>5</sub> recording uptake of 7.21 kg ha<sup>-1</sup> and 7.00 kg ha<sup>-1</sup> during *rabi* 2022 and *kharif* 2024 respectively.

The highest potassium uptake was recorded in butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) with values of 79.1 kg ha<sup>-1</sup> during *rabi* 2022 and 80.3 kg ha<sup>-1</sup> during *kharif* 2024. HW at 20 and 40 DAT (T<sub>11</sub>) and FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT (T<sub>1</sub>) recorded higher uptake with T<sub>11</sub> values of 76.3 kg ha<sup>-1</sup> and 76.2 kg ha<sup>-1</sup> and T<sub>1</sub> values of 73.7 kg ha<sup>-1</sup> and 72.6 kg ha<sup>-1</sup> during *rabi* 2022 and *kharif* 2024 respectively.

#### Soil available NPK

Soil nutrient availability at harvest, including nitrogen, phosphorus and potassium was significantly affected by the non-chemical weed management practices during both *rabi* 2022 and *kharif* 2024 seasons (Table 7).

The highest available N availability was recorded in FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) with uptake of 219.3 kg ha<sup>-1</sup> during *rabi* 2022 and 220.9 kg ha<sup>-1</sup> during *kharif* 2024. This was followed closely by FS Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) with recorded values of 214.8 kg ha<sup>-1</sup> for both *rabi* 2022 and *kharif* 2024 and intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT (T<sub>4</sub>) values of 209.7 kg ha<sup>-1</sup> during *rabi* 2022 indicating the positive impact of mycoherbicide application and daincha intercropping on nitrogen retention in the soil and rice hull solution (50 % FS) at 15 DAT + HW at 40 DAT (T<sub>6</sub>) values of 201.7 during *kharif* 2024. The unweeded control (T<sub>12</sub>) recorded the lowest available N at 168.6 kg ha<sup>-1</sup> indicating significant depletion due to weed competition and lack of soil-enriching practices.

FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) recorded the highest P availability with 20.80 kg ha<sup>-1</sup> and 21.42 kg ha<sup>-1</sup> followed by FS of Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) with 19.70 kg ha<sup>-1</sup> and 19.90 kg ha<sup>-1</sup> and intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT (T<sub>4</sub>) with 19.30 kg ha<sup>-1</sup> and 19.23 kg

ha<sup>-1</sup> during *rabi* 2022 and *kharif* 2024 respectively emphasizing the phosphorus-conserving effects of microbial and green manuring practices.

FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) recorded the highest K availability with 734.0 kg ha<sup>-1</sup> and 723.0 kg ha<sup>-1</sup> followed by FS of Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) with 728.0 kg ha<sup>-1</sup> and 715.0 kg ha<sup>-1</sup> and intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT (T<sub>4</sub>) with 709.0 kg ha<sup>-1</sup> and 699.0 kg ha<sup>-1</sup> during *rabi* 2022 and *kharif* 2024.

#### Soil microbial dynamics in rice

Soil microbial populations, including bacterial, fungal and actinomycetes colonies, were significantly affected by the non-chemical weed management practices implemented during both the *rabi* 2022 and *kharif* 2024 seasons in transplanted rice (Table 8).

Both in *rabi* 2022 and *kharif* 2024, FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) recorded the highest bacterial population with  $9.78 \times 10^7$  CFU g<sup>-1</sup> and  $9.87 \times 10^7$  CFU g<sup>-1</sup> followed by FS of Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) with  $9.73 \times 10^7$  CFU g<sup>-1</sup> and  $9.82 \times 10^7$  CFU g<sup>-1</sup> respectively, indicating that microbial-based herbicide applications and organic inputs effectively boosted bacterial abundance in the soil. The lowest bacterial count was observed in butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) which recorded only  $8.62 \times 10^7$  CFU g<sup>-1</sup> during *rabi* 2022 and  $8.59 \times 10^7$  CFU g<sup>-1</sup> during *kharif* 2024 suggesting that synthetic herbicides have a suppressive effect on beneficial soil microbes.

For fungal populations, intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT (T<sub>4</sub>) recorded the highest count at  $5.65 \times 10^3$  CFU g<sup>-1</sup> during *rabi* 2022 and  $5.61 \times 10^3$  CFU g<sup>-1</sup> during *kharif* 2024. This was followed by FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) ( $5.14 \times 10^3$  CFU g<sup>-1</sup>) and FS Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) ( $5.12 \times 10^3$  CFU g<sup>-1</sup>) during *rabi* 2022 and FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) ( $5.14 \times 10^3$  CFU g<sup>-1</sup>) (T<sub>2</sub>) recording ( $5.06 \times 10^3$  CFU g<sup>-1</sup>) during *kharif* 2024 indicating the beneficial impact of legume intercropping and mycoherbicides on fungal growth.

**Table 7.** Effect of non-chemical weed management practices on soil available NPK (kg ha<sup>-1</sup>) at harvest stage in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No            | Treatments   | <i>rabi</i> 2022 |             |              | <i>kharif</i> 2024 |             |              |
|-----------------|--|------------------|-------------|--------------|--------------------|-------------|--------------|
|                 |  | N                | P           | K            | N                  | P           | K            |
| T <sub>1</sub>  | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 188.4            | 17.20       | 657.0        | 197.0              | 17.32       | 644.0        |
| T <sub>2</sub>  | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 214.8            | 19.70       | 728.0        | 214.8              | 19.90       | 715.0        |
| T <sub>3</sub>  | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 201.7            | 18.40       | 689.0        | 205.1              | 18.34       | 677.0        |
| T <sub>4</sub>  | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 209.7            | 19.30       | 709.0        | 208.8              | 19.23       | 699.0        |
| T <sub>5</sub>  | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 193.8            | 17.60       | 672.0        | 198.6              | 17.68       | 662.0        |
| T <sub>6</sub>  | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 205.4            | 18.90       | 701.0        | 210.7              | 18.25       | 691.0        |
| T <sub>7</sub>  | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 203.4            | 18.50       | 696.0        | 201.2              | 18.56       | 683.0        |
| T <sub>8</sub>  | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 190.6            | 17.40       | 665.0        | 198.2              | 17.61       | 652.0        |
| T <sub>9</sub>  | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 180.4            | 16.80       | 645.0        | 186.7              | 16.50       | 634.0        |
| T <sub>10</sub> | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 219.3            | 20.80       | 734.0        | 220.9              | 21.42       | 723.0        |
| T <sub>11</sub> | Hand weeding twice at 20 and 40 DAT  | 185.7            | 17.10       | 651.0        | 188.5              | 17.52       | 640.0        |
| T <sub>12</sub> | Unweeded check   | 168.6            | 15.60       | 576.0        | 167.8              | 16.17       | 565.0        |
| <b>S.Ed</b>     |  | <b>2.92</b>      | <b>1.02</b> | <b>31.10</b> | <b>2.92</b>        | <b>0.92</b> | <b>36.10</b> |

**Table 8.** Effect of non-chemical weed management practices on bacterial (10<sup>7</sup>), fungal (10<sup>3</sup>) and actinomycetes (10<sup>4</sup>) population (CFU g<sup>-1</sup> of soil) at harvest stage in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No               | Treatments   | <i>rabi</i> 2022 |             |               | <i>kharif</i> 2024 |             |               |
|--------------------|--|------------------|-------------|---------------|--------------------|-------------|---------------|
|                    |  | Bacteria         | Fungus      | Actinomycetes | Bacteria           | Fungus      | Actinomycetes |
| T <sub>1</sub>     | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 8.87             | 4.75        | 6.03          | 8.94               | 4.72        | 5.98          |
| T <sub>2</sub>     | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 9.73             | 5.12        | 6.44          | 9.82               | 5.06        | 6.42          |
| T <sub>3</sub>     | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 8.90             | 4.72        | 5.98          | 9.04               | 4.68        | 5.88          |
| T <sub>4</sub>     | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 8.73             | 5.65        | 5.74          | 8.86               | 5.61        | 5.71          |
| T <sub>5</sub>     | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 8.98             | 4.76        | 5.83          | 9.12               | 4.71        | 5.78          |
| T <sub>6</sub>     | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 9.54             | 5.02        | 6.14          | 9.63               | 4.96        | 6.11          |
| T <sub>7</sub>     | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 9.52             | 5.05        | 6.23          | 9.66               | 4.99        | 6.19          |
| T <sub>8</sub>     | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 8.89             | 4.74        | 5.94          | 9.02               | 4.71        | 5.92          |
| T <sub>9</sub>     | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 8.62             | 4.60        | 5.40          | 8.59               | 4.82        | 5.38          |
| T <sub>10</sub>    | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 9.78             | 5.14        | 6.45          | 9.87               | 4.56        | 6.41          |
| T <sub>11</sub>    | Hand weeding twice at 20 and 40 DAT  | 9.57             | 4.98        | 6.12          | 9.68               | 4.93        | 6.09          |
| T <sub>12</sub>    | Unweeded check   | 9.55             | 5.04        | 6.25          | 9.63               | 5.03        | 6.21          |
| <b>S.Ed</b>        |  | <b>0.21</b>      | <b>0.10</b> | <b>0.09</b>   | <b>0.21</b>        | <b>0.08</b> | <b>0.12</b>   |
| <b>CD (P=0.05)</b> |  | <b>0.43</b>      | <b>0.21</b> | <b>0.19</b>   | <b>0.45</b>        | <b>0.16</b> | <b>0.25</b>   |

For actinomycetes, the highest population was observed in FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) with count of 6.45 × 10<sup>4</sup> CFU g<sup>-1</sup> and 6.41 × 10<sup>4</sup> CFU g<sup>-1</sup> followed by FS of Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) with count of 6.44 × 10<sup>4</sup> CFU g<sup>-1</sup> and 6.42 × 10<sup>4</sup> CFU g<sup>-1</sup> and double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + at 25 DAT (T<sub>7</sub>) with count of 6.23 × 10<sup>4</sup> CFU g<sup>-1</sup> and 6.19 × 10<sup>4</sup> CFU g<sup>-1</sup> during *rabi* 2022 and *kharif* 2024 respectively.

### Grain nutritional parameters on rice

The effect of non-chemical weed management practices on the grain nutritional quality of transplanted rice during the *rabi* 2022 and *kharif* 2024 seasons exhibited only slight variations in parameters such as protein, crude fibre, fat and carbohydrate content across treatments (Table 9). However, statistical analysis indicated that none of these differences were significant at the 5 % level, suggesting that the treatments did not markedly alter the nutritional composition of the rice grain in either season.

Protein content was recorded the highest value in double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + at 25 DAT (T<sub>7</sub>) with content

of 2.72 g/100g during *rabi* 2022. During *kharif* 2024, double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + at 25 DAT (T<sub>7</sub>) and butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) recorded the highest with 2.72 g/100 g each.

Crude fibre content remained relatively uniform with a marginally higher value of 0.33 g/100 g observed in rice bran @ 5 t ha<sup>-1</sup> as basal at transplanting + HW at 40 DAT (T<sub>3</sub>) and unweeded check (T<sub>12</sub>) during *rabi* 2022. While the crude fibre content peaked at 0.33 g/100 g in double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + at 25 DAT (T<sub>7</sub>) during *kharif* 2024.

Fat content showed minimal fluctuation between 0.37 and 0.38 g/100 g in all the treatments while carbohydrate levels ranged from 27.97 g/100 g in cono-weeding at 10, 20, 30 and 40 DAT (T<sub>8</sub>) and unweeded check (T<sub>12</sub>) to a slightly higher 28.20 g/100 g in butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) during *rabi* 2022. During *kharif* 2024, the fat content varied slightly between 0.37 and 0.39 g/100 g with the highest observed in rice hull solution (50 % FS) at 15 DAT + HW at 40 DAT (T<sub>6</sub>).

**Table 9.** Effect of non-chemical weed management practices on grain nutritional parameters (g/100g) in transplanted rice (*rabi* 2022 and *kharif* 2024)

| T.No               | Treatments   | <i>rabi</i> 2022 |              |              |               | <i>kharif</i> 2024 |              |              |               |
|--------------------|--|------------------|--------------|--------------|---------------|--------------------|--------------|--------------|---------------|
|                    |  | Protein          | Crude fibre  | Fat          | Carbo hydrate | Protein            | Crude fibre  | Fat          | Carbo hydrate |
| T <sub>1</sub>     | Foliar spray of ITK-based farmers' practices (cow urine+ lime solution+ khadi soap + common salt) at 25 DAT + hand weeding at 40 DAT | 2.70             | 0.31         | 0.38         | 28.17         | 2.70               | 0.31         | 0.38         | 28.13         |
| T <sub>2</sub>     | Foliar spray Mycoherbicide (1) at 25 DAT + hand weeding at 40 DAT  | 2.71             | 0.31         | 0.37         | 28.10         | 2.70               | 0.31         | 0.37         | 28.03         |
| T <sub>3</sub>     | Rice bran @ 5 t ha <sup>-1</sup> as basal at transplanting + hand weeding at 40 DAT  | 2.71             | 0.33         | 0.38         | 28.10         | 2.71               | 0.31         | 0.38         | 28.17         |
| T <sub>4</sub>     | Intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT  | 2.70             | 0.32         | 0.38         | 28.13         | 2.71               | 0.32         | 0.37         | 27.90         |
| T <sub>5</sub>     | Azolla as dual crop @ 1 t ha <sup>-1</sup> + incorporation at 40 DAT   | 2.69             | 0.32         | 0.38         | 28.13         | 2.70               | 0.32         | 0.38         | 28.13         |
| T <sub>6</sub>     | Rice hull solution (50 % foliar spray) at 15 DAT + hand weeding at 40 DAT  | 2.71             | 0.32         | 0.37         | 28.13         | 2.70               | 0.31         | 0.39         | 28.07         |
| T <sub>7</sub>     | Double green manuring @ 6.25 t ha <sup>-1</sup> at transplanting + at 25 DAT   | 2.72             | 0.31         | 0.37         | 28.13         | 2.72               | 0.33         | 0.38         | 28.00         |
| T <sub>8</sub>     | Cono-weeding 4 times on 10, 20, 30 and 40 DAT  | 2.71             | 0.31         | 0.38         | 27.97         | 2.69               | 0.31         | 0.37         | 28.30         |
| T <sub>9</sub>     | Butachlor @ 1 kg ha <sup>-1</sup> at 3 DAT as PE + Bispyribac sodium @ 25 g ha <sup>-1</sup> at 25 DAT as POE                        | 2.70             | 0.30         | 0.38         | 28.20         | 2.72               | 0.31         | 0.38         | 28.03         |
| T <sub>10</sub>    | Foliar spray of Mycoherbicide (2) at 25 DAT + hand weeding at 40 DAT   | 2.70             | 0.32         | 0.38         | 28.10         | 2.70               | 0.31         | 0.38         | 28.13         |
| T <sub>11</sub>    | Hand weeding twice at 20 and 40 DAT  | 2.70             | 0.31         | 0.38         | 28.00         | 2.69               | 0.32         | 0.38         | 28.13         |
| T <sub>12</sub>    | Unweeded check   | 2.70             | 0.33         | 0.38         | 27.97         | 2.71               | 0.31         | 0.38         | 28.00         |
| <b>S.Ed</b>        |  | <b>0.015</b>     | <b>0.012</b> | <b>0.013</b> | <b>0.187</b>  | <b>0.014</b>       | <b>0.014</b> | <b>0.012</b> | <b>0.157</b>  |
| <b>CD (P=0.05)</b> |  | <b>NS</b>        | <b>NS</b>    | <b>NS</b>    | <b>NS</b>     | <b>NS</b>          | <b>NS</b>    | <b>NS</b>    | <b>NS</b>     |

Carbohydrate content remained stable across all treatments ranging from 27.90 g/100 g in intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT (T<sub>4</sub>) to a maximum of 28.30 g/100 g in cono-weeding at 10, 20, 30 and 40 DAT (T<sub>8</sub>).

### Scientometric analysis

The scientometric trends related to weed management in rice with specific attention to both general and non-chemical approaches (Fig. 2). The global distribution of scientific output for the broader query “weed management in rice” (Fig. 2A) indicates that countries such as the United States, China, India, Brazil and Australia have contributed significantly to research in this area, reflecting the widespread concern over weed control in rice production systems. The associated keyword co-occurrence word cloud (Fig. 2B) highlights dominant research themes with keywords such as *weed control*, *herbicide*, *pesticide resistance* and *integrated pest management* prominently featured, suggesting a continued focus on chemical and integrated approaches. In contrast, Fig. 2C, which focuses specifically on “non-chemical weed control in rice”, reveals a shift in research concentration with India emerging as the leading contributor in this specialized domain, followed by the United States, China and Australia. The corresponding word cloud for non-chemical weed control (Fig. 2D) displays a higher frequency of terms like *Oryza sativa*, *crop yield*, *Echinochloa* and *biological control*, indicating growing research interest in eco-friendly and sustainable strategies.

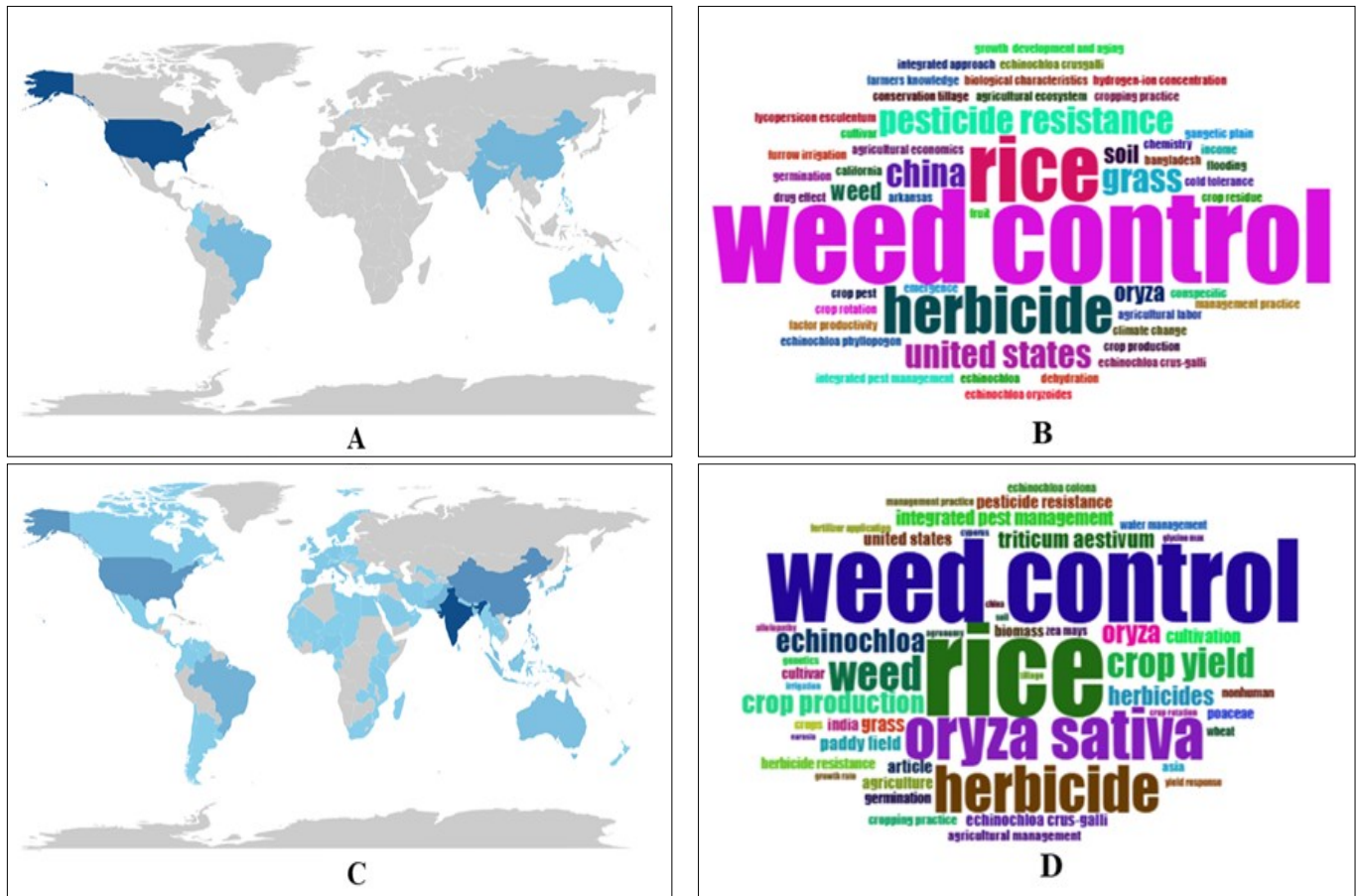
The bibliometric analysis of non-chemical weed control reveals a markedly lower volume of scientific output compared to general weed management signifying a substantial research gap in this crucial area. This limited focus emphasizes the urgent need to assess and promote non-chemical weed control practices, especially in the light of the global transition toward sustainable agriculture and environmentally safe food production systems. Furthermore, it highlights the increasing relevance of integrated weed management approaches that combine multiple control strategies beyond sole reliance on herbicides. On the other hand, the broader query “weed

management in rice” predominantly reflects research centred around chemical weed control, including studies on herbicide efficacy, degradation pathways in soil and the management of specific weed species using chemical inputs. This divergence indicates the prevailing emphasis on chemical solutions in traditional weed science literature and the comparatively nascent but growing interest in non-chemical alternatives.

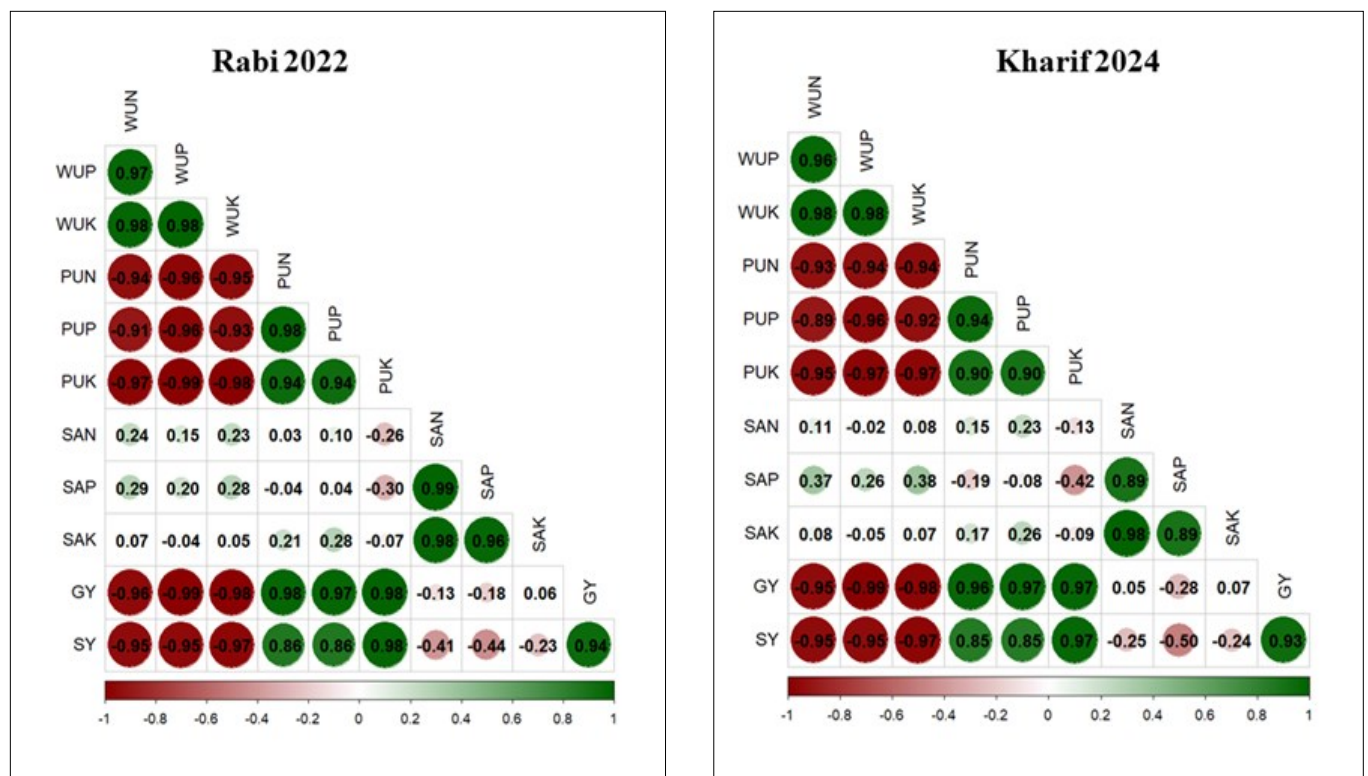
### Correlation analysis

The Pearson's correlation analysis revealed distinct interrelationships among nutrient uptake, soil fertility and yield parameters of rice under different non-chemical weed control treatments during *rabi* 2022 and *kharif* 2024 seasons (Fig. 3). Positive correlations are depicted in dark green and negative correlations in dark red providing a visual understanding of the associations among key traits related to nutrient dynamics and crop productivity.

In *rabi* 2022, strong and significant positive correlations were observed among weed nutrient uptake traits such as weed uptake nitrogen (WUN), phosphorus (WUP) and potassium (WUK), which were also positively correlated among themselves ( $r > 0.97$ ), indicating a parallel trend in nutrient absorption by weeds. However, these traits showed strong negative correlations with plant nutrient uptake parameters - PUN (plant uptake nitrogen), PUP (plant uptake phosphorous) and PUK (plant uptake potassium) suggesting a competitive interaction ( $r = -0.93$  to  $-0.98$ ) where increased weed nutrient absorption reduces nutrient availability for crop uptake. Grain yield (GY) and straw yield (SY) exhibited strong positive associations with plant nutrient uptake parameters, particularly PUN (0.98), PUP (0.97) and PUK (0.98), highlighting the importance of effective crop nutrient absorption in determining productivity. In contrast, GY and SY showed strong negative correlations with weed nutrient uptake traits ( $r = -0.96$  to  $-0.99$ ), indicating that greater nutrient acquisition by weeds can significantly reduce rice yield components. Soil available nutrients - SAN, SAP and SAK which are exhibited weak and inconsistent relationships with most parameters. Significantly, SAK was positively correlated with GY



**Fig. 2.** Represents the scientometric analysis results related to weed management in rice. A. Illustrates the country-wise scientific output for the query "weed management in rice". B. Displays the associated keyword co-occurrence visualized through a word cloud. C. Highlights the country-wise scientific output specifically for the query "non-chemical weed control in rice". D. Shows the corresponding word cloud representing the most frequent terms linked to non-chemical weed management practices in rice cultivation.



**Fig. 3.** Pearson's correlation coefficients were used to assess the associations among the weed and plant uptake NPK at harvest, post-harvest soil available NPK and yield parameters (grain and straw yield) of rice under different non-chemical weed control practices. Parameters included: Weed uptake nitrogen (WUN), weed uptake phosphorous (WUP), weed uptake potassium (WUK), plant uptake nitrogen (PUN), plant uptake phosphorous (PUP), plant uptake potassium (PUK), soil available nitrogen (SAN), soil available phosphorous (SAP), soil available potassium (SAK), grain yield (GY) and straw yield (SY). Positive correlations are indicated in dark green, while dark red denotes negative correlations.

(0.06) and SY (0.23), although the magnitude was low, suggesting marginal influence on yield. These trends highlight the central role of nutrient competition between crop and weed in shaping the productivity outcomes under non-chemical weed management systems.

During the *kharif* 2024 season, a similar competitive dynamic was evident. Weed nutrient uptake traits (WUN, WUP, WUK) were again strongly positively correlated with each other ( $r > 0.96$ ) and negatively associated with plant nutrient uptake ( $r = -0.92$  to  $-0.97$ ), confirming the antagonistic nutrient acquisition pattern between weeds and the rice crop. GY and SY maintained strong positive correlations with plant nutrient uptake such as PUN (0.96), PUP (0.97) and PUK (0.97) emphasizing that higher internal nutrient use efficiency in the crop leads to enhanced productivity. In contrast, GY and SY again showed significant negative associations with WUN, WUP and WUK ( $r = -0.95$  to  $-0.98$ ), emphasizing again the suppressive effect of weed nutrient uptake on crop performance. Among soil fertility parameters, SAP and SAK showed relatively stronger positive correlations with GY (0.05-0.07) and SY (0.07-0.08) than SAN, although the relationships remained modest. Interestingly, SAP was positively associated with PUN (0.38) and PUP (0.26), suggesting that phosphorus availability might support plant nutrient uptake during the *kharif* season. These results highlight that effective control of weed nutrient uptake is critical for maximizing plant nutrient absorption and optimizing yield. The competitive nutrient dynamics between crop and weed are central to yield outcomes in non-chemical weed management systems and monitoring these interactions can inform more sustainable nutrient and weed management strategies in rice production.

## Discussion

### Weed uptake NPK

Non-chemical weed management practices significantly influenced the uptake of NPK by weeds during both *rabi* 2022 and *kharif* 2024. The unweeded control ( $T_{12}$ ) consistently recorded the highest nutrient uptake, indicating intense competition with the crop due to unchecked weed growth. HW at 20 and 40 DAT ( $T_{11}$ ) resulted in the lowest nutrient uptake by weeds owing to timely and effective weed removal. Moderate nutrient uptake by weeds were seen in FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT ( $T_1$ ) and azolla as a dual crop @  $1 \text{ t ha}^{-1}$  + incorporation at 40 DAT ( $T_5$ ) which likely improved the soil health and showed some suppressive effect on weeds. These results align with earlier findings where unchecked weed growth facilitated maximum biomass accumulation and increases nutrient extraction from the soil (18). Timely physical removal of weeds in HW at 20 and 40 DAT ( $T_{11}$ ) drastically reduced weed biomass and their ability to uptake nutrients, thereby enhancing nutrient availability to the crop (19). FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT ( $T_1$ ) and azolla as a dual crop @  $1 \text{ t ha}^{-1}$  + incorporation at 40 DAT ( $T_5$ ) showed partial effectiveness through allelopathy, improved ground coverage and cultural suppression (20).

### Plant uptake NPK

Efficient weed management significantly improved nutrient uptake by the crop during both *rabi* 2022 and *kharif* 2024. Among the treatments, butachlor @  $1 \text{ kg ha}^{-1}$  at 3 DAT as PE + bispyribac sodium @  $25 \text{ g ha}^{-1}$  at 25 DAT as POE ( $T_9$ ) consistently recorded the highest absorption of NPK indicating the effectiveness in suppressing weed

competition and promoting nutrient availability for robust crop growth. Strategic herbicide application and timely manual weeding during critical periods of crop-weed competition contributed to enhanced nutrient absorption and minimized nutrient depletion by weeds. The nutrient uptake observed at different growth stages reflected the crop's improved biomass and nutrient status due to reduced weed interference. Butachlor @  $1 \text{ kg ha}^{-1}$  at 3 DAT as PE + bispyribac sodium @  $25 \text{ g ha}^{-1}$  at 25 DAT as POE ( $T_9$ ), HW at 20 and 40 DAT ( $T_{11}$ ) and cono-weeding at 10, 20, 30 and 40 DAT ( $T_8$ ) effectively recorded reduced weed biomass and nutrient extraction which consequently boosted soil nutrient availability for the crop (18). Among the non-chemical strategies, azolla as a dual crop @  $1 \text{ t ha}^{-1}$  + incorporation at 40 DAT ( $T_5$ ) and FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT ( $T_1$ ) recorded relatively high nutrient uptake, highlighting their potential as sustainable and environmentally friendly alternatives for weed and nutrient management. The unweeded control ( $T_{12}$ ) consistently showed the lowest nutrient uptake, highlighting the detrimental effects of unmanaged weed growth on soil fertility, crop performance and overall yield potential. The consistent results observed over both the season indicates the importance of integrated and timely weed control measures in maximizing nutrient use efficiency and ensuring resilient crop growth under diverse climatic scenarios (21, 22).

### Soil available NPK in rice

The results from *rabi* 2022 and *kharif* 2024 clearly highlights the positive influence of integrated and non-chemical weed management strategies on enhancing soil nutrient availability. FS Mycoherbicide (2) at 25 DAT + HW at 40 DAT ( $T_{10}$ ), FS Mycoherbicide (1) at 25 DAT + HW at 40 DAT ( $T_2$ ) and intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT ( $T_4$ ) consistently recorded increased levels of available NPK across both the season, showcasing the dual benefits of weed suppression and soil enrichment. These approaches, involving microbial and green manure-based treatments, likely improved nutrient retention and minimized leaching losses, thereby contributing to enhanced soil fertility (18). The higher nutrient status in these treatments indicates a synergistic effect between effective weed control and improved nutrient cycling. The unweeded control ( $T_{12}$ ) showed the lowest nutrient availability emphasizing the negative impact of unchecked weeds, which aggressively compete with crops for essential resources and significantly deplete soil nutrient reserves (23). Persistent nutrient loss under unweeded conditions can ultimately reduce soil productivity and crop yields. Overall, these findings confirm that integrated and sustainable non-chemical weed management practices, particularly those incorporating mycoherbicides and leguminous intercrops, not only suppresses weeds but also builds soil health. By reducing nutrient competition and enhancing nutrient availability, these strategies improved both crop uptake and long-term soil fertility. These results are consistent with earlier findings which highlights the importance of eco-friendly practices in sustaining soil quality and agricultural productivity (18).

### Soil microbial dynamics in rice

Soil microbial dynamics refers to the changes and interactions within microbial communities, influenced by environmental conditions and agricultural practices. These microbes are essential for nutrient cycling, organic matter decomposition and disease suppression but their balance can be disrupted by chemical inputs like herbicides (24). Observations from *rabi* 2022 and *kharif* 2024 clearly showed that FS Mycoherbicide (2) at 25 DAT + HW at 40 DAT

(T<sub>10</sub>) consistently recorded the highest bacterial and actinomycetes counts followed by FS Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) and rice hull solution (50 % FS) at 15 DAT + HW at 40 DAT (T<sub>6</sub>) indicating that microbial-based herbicides and organic strategies promotes a favourable environment for microbial proliferation. Butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) consistently showed the lowest microbial population confirming the negative impact of chemical herbicides (25). Fungal populations were significantly higher in intercropping daincha with rice (3:1 ratio) + incorporation at 40 DAT (T<sub>4</sub>) highlighting the role of legumes in enhancing soil fungal biomass through better organic inputs and root activity (26). While FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) and FS of Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) also boosted fungal counts during *rabi* 2022, a slight decline in T<sub>10</sub> during *kharif* 2024 suggest seasonal or microbial strain-specific variability. Similarly, actinomycetes populations were the highest in FS of Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>), FS of Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>) and double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + at 25 DAT (T<sub>7</sub>) justifying the compatibility of these treatments with beneficial soil microbes, crucial for decomposition and natural antibiotic production (27). The overall decline in microbial abundance in butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) across all microbial population is in accordance with the previous reports linking chemical herbicide use to reduced microbial biomass and enzyme activity (28, 29), reinforcing the value of sustainable, non-chemical management practices for maintaining soil biological health.

### Grain nutritional parameters on rice

The impact of non-chemical weed management practices on the nutritional quality of transplanted rice grains was minimal with only slight and statistically insignificant differences observed in protein, crude fibre, fat and carbohydrate content during both *rabi* 2022 and *kharif* 2024. Treatments such as double green manuring @ 6.25 t ha<sup>-1</sup> at transplanting + at 25 DAT (T<sub>7</sub>), FS Mycoherbicide (1) at 25 DAT + HW at 40 DAT (T<sub>2</sub>), rice bran @ 5 t ha<sup>-1</sup> as basal at transplanting + HW at 40 DAT (T<sub>3</sub>) and rice hull solution (50 % FS) at 15 DAT + HW at 40 DAT (T<sub>6</sub>) consistently recorded marginally higher protein and fibre contents, while butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) showed slightly improved carbohydrate levels. Fat content remained largely uniform in all the treatments. These suggest that non-chemical weed management does not significantly alter grain nutritional composition (18). However, improved yield attributes, physiological traits and grain quality were noted when 100 % NPK was applied in conjunction with daincha incorporation highlighting the benefit of integrated nutrient and weed management strategies (30).

### Conclusion

The study clearly demonstrated the significant impact of effective weed management practices on nutrient uptake, microbial populations and grain nutritional parameters in transplanted rice during both *rabi* 2022 and *kharif* 2024 seasons. Among the treatments, HW at 20 and 40 DAT (T<sub>11</sub>) and butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) consistently recorded the lowest NPK uptake by weeds, indicating superior weed suppression and reduced nutrient loss to weeds. In

terms of plant nutrient uptake, butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>) exhibited the highest nitrogen (51.5 kg ha<sup>-1</sup>), phosphorus (7.58 kg ha<sup>-1</sup>) and potassium (79.1 kg ha<sup>-1</sup>) uptake in *rabi* 2022 and also the highest potassium (80.3 kg ha<sup>-1</sup>) uptake with significant nitrogen and phosphorus absorption in *kharif* 2024. Non-chemical strategies, including FS of ITK-based farmers' practices on 25 DAT + HW at 40 DAT (T<sub>1</sub>), azolla as a dual crop @ 1 t ha<sup>-1</sup> + incorporation at 40 DAT (T<sub>5</sub>) and cono-weeding at 10, 20, 30 and 40 DAT (T<sub>8</sub>), also demonstrated substantial potential for enhancing plant nutrient uptake and minimizing weed nutrient uptake. These improved soil aeration, nutrient availability and provided critical weed suppression, promoting enhanced crop performance. In terms of microbial dynamics, FS Mycoherbicide (2) at 25 DAT + HW at 40 DAT (T<sub>10</sub>) consistently recorded the highest bacterial and actinomycetes populations, indicating a healthy soil microbial community. While grain nutritional parameters showed no significant differences, the overall findings emphasize the importance of effective weed control. Unweeded check (T<sub>11</sub>), however, recorded significantly lower growth, soil available NPK, plant nutrient uptake and higher weed nutrient uptake, highlighting the detrimental effects of uncontrolled weed competition. Lower microbial activity was observed in butachlor @ 1 kg ha<sup>-1</sup> at 3 DAT as PE + bispyribac sodium @ 25 g ha<sup>-1</sup> at 25 DAT as POE (T<sub>9</sub>). The study recommends the promotion of non-chemical weed management practices combining cultural and ecological methods over chemical management to ensure sustainable rice cultivation and improve soil and crop health.

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### Authors' contributions

LMK carried out the experiment, recording observations, analysis of data and preparation of the manuscript. ES guided the research by formulating the research concept and reviewed and approved the manuscript. PMA shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript. RK shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript. shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript. RS shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript. SK shared inputs for upscaling and facilitated analysis and helped in editing, summarizing and revising the manuscript. All authors read and approved the final manuscript.

### Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

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