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Integrated Effects of NPK Fertilization and Vermicompost on Physiological traits, Nutrient Accumulation, and Grain Yield and Quality of Zea Mays L. (hybrid KSC703) under Full and Deficit Irrigation

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Research Article

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Abstract

Background

Zea mays L. (maize) is one of the world's most important cereal crops, serving as a staple food, livestock feed, and industrial raw material. It is cultivated across diverse agroecological regions because of its high yield potential, wide adaptability, and multiple ends uses. A two-year field experiment was conducted using a factorial arrangement within a randomized complete block design to evaluate the combined effects of irrigation regime, NPK fertilization, and vermicompost application on the physiological, biochemical, nutritional, and yield-related characteristics of maize (*Zea mays* L.). Treatments comprised two irrigation regimes (full irrigation at 100% field capacity and deficit irrigation at 70% field capacity), three NPK fertilizer levels (0, 50, and 100% of the recommended rate based on soil analysis), and four vermicompost rates (0, 2, 4, and 6 t ha^{-1}).

Results

Tukey's HSD test ($\alpha = 0.05$) revealed significant four-way interactions (Year × Irrigation × NPK × Vermicompost) for all measured traits, indicating that the response of maize was strongly influenced by the combined management practices. The integrated application of 100% recommended NPK with 6 t ha^{-1} vermicompost consistently produced superior physiological performance, recording the highest chlorophyll content (SPAD = 47.70), relative water content (80.52%), harvest protein yield (964.54 kg ha^{-1}), seed starch (74.22%), phosphorus (0.428%), and potassium (0.360%). These treatments also produced among the highest values for grain yield, biological yield, harvest index, thousand-grain weight, leaf area index, and other productivity-related traits evaluated in the experiment. Compared with the unfertilized control, the optimum treatment increased SPAD, harvest protein, seed starch, phosphorus, and potassium by 84.6%, 330.0%, 14.0%, 41.7%, and 42.9%, respectively, while reducing relative water deficit by 47.3%. Nitrogen concentration and crude protein content reached their maximum values (1.656% and 10.35%, respectively) under full irrigation with 100% recommended NPK, indicating that adequate water availability favored grain nitrogen accumulation, whereas deficit irrigation combined with integrated nutrient management enhanced overall nutrient use efficiency and protein yield. In contrast, the absence of mineral fertilizer and vermicompost consistently resulted in the lowest values for all physiological, nutritional, and yield traits, regardless of irrigation regime. Seasonal differences between the two experimental years were relatively small compared with treatment effects, demonstrating the stability of integrated nutrient management across years.

Conclusions

Overall, the results indicate that combining the recommended NPK dose with 6 t ha^{-1} vermicompost is an effective strategy for improving maize growth, water status, nutrient uptake, grain quality, and productivity under both full and deficit irrigation conditions, thereby contributing to sustainable and resource-efficient maize production.

1. Introduction

Global agriculture is facing increasing challenges due to climate change, declining water resources, and the growing demand for food from an expanding population [1–3]. Among these challenges, water scarcity has become one of the most critical constraints limiting crop productivity and quality, particularly in arid and semi-arid regions [4–6]. Improving crop performance under limited water availability requires the development of integrated crop management practices that enhance resource-use efficiency while maintaining yield and grain quality [7–10]. Consequently, optimizing irrigation practices together with balanced nutrient management has become a major focus of sustainable agricultural production.

Zea mays L. (maize) is one of the world's most important cereal crops, serving as a staple food, livestock feed, and industrial raw material [11, 12]. It is cultivated across diverse agroecological regions because of its high yield potential, wide adaptability, and multiple ends uses [13, 14]. Globally, maize contributes significantly to food security by providing carbohydrates, proteins, vitamins, minerals, and bioactive compounds essential for human and animal nutrition [15]. In addition to direct consumption, maize is extensively utilized in the production of starch, edible oil, sweeteners, bioethanol, pharmaceuticals, and numerous industrial products, making it a crop of considerable economic importance [11, 16, 17]. However, maize productivity and grain quality are highly influenced by environmental conditions, particularly water availability and soil fertility [18–22]. Water deficit reduces chlorophyll content, photosynthetic efficiency, nutrient uptake, and grain filling, ultimately resulting in substantial yield and quality losses [23–25]. Therefore, improving maize productivity through sustainable irrigation and nutrient management practices has become a major priority for ensuring global food security under changing climatic conditions.

Balanced fertilization with nitrogen (N), phosphorus (P), and potassium (K) is equally important for sustaining crop productivity and grain quality [33–36]. Nitrogen is the primary constituent of chlorophyll and proteins, phosphorus is involved in energy transfer and root development, whereas potassium regulates enzyme activation, osmotic adjustment, and stomatal function [35, 37, 38]. Potassium (K) is another essential element for the growth and development of plants; it contributes in growth regulation, signaling, and stress tolerance mechanisms however, its scarcity or excessive level leads to distortion of numerous functions in plants [39, 40]. Phosphorous (P) plays a fundamental role in regulating physiological responses and enhancing abiotic stress tolerance in plant; stimulating root development; regulating water uptake and transport; as well as energy metabolism, nucleic acid synthesis, and membrane function [41–43]. Thus, adequate NPK fertilization enhances photosynthetic efficiency, nutrient assimilation, grain filling, and stress tolerance, particularly under suboptimal moisture conditions.

The use of vermicompost is particularly beneficial under water-limited conditions because it increases soil moisture retention and improves root development, enabling plants to better withstand drought stress [46–49]. Organic matter present in vermicompost enhances soil aggregation and porosity, thereby reducing water loss through evaporation and increasing the efficiency of irrigation water. In addition, the slow-release nature of nutrients supplied by vermicompost ensures a continuous supply of nitrogen, phosphorus, potassium, and micronutrients throughout the crop growth cycle, reducing nutrient losses and improving fertilizer-use efficiency [48, 50, 51]. Furthermore, vermicompost has been reported to enhance the physiological attributes through improved nutrient availability, increased chlorophyll synthesis, enhanced antioxidant activity, and improved water relations [48, 52, 53]. Thus, the integration of vermicompost with appropriate irrigation management may alleviate the adverse effects of water stress by improving soil water availability, enhancing nutrient uptake, and promoting physiological resilience.

Although considerable research has examined the individual effects of irrigation, fertilization, or vermicompost on crop performance, relatively few studies have simultaneously evaluated the interactions among these factors across multiple growing seasons. Furthermore, information linking physiological responses with grain nutritional quality under combined irrigation and NPK management remains limited, particularly under deficit irrigation conditions. Such integrated investigations are necessary for developing efficient management strategies that maximize productivity while conserving water resources.

The present study addresses these knowledge gaps by evaluating the combined effects of two irrigation regimes (full and 70% FC irrigation), three NPK fertilizer levels, and four vermicompost levels over two consecutive growing seasons. The research integrates physiological indicators (SPAD and RWC) with grain quality attributes (crude protein, harvest protein yield, seed starch, and N, P, and K contents), providing a comprehensive understanding of how water availability, nutrient management, and vermicompost application interact to influence crop performance. The findings contribute valuable information for developing integrated irrigation and fertilization strategies that improve physiological efficiency, nutrient utilization, and grain quality under water-limited production systems.

Therefore, the present study aimed to (i) determine the effects of Irrigation, NPK fertilization, and vermicompost application on maize grain quality attributes, including crude protein, harvest protein yield, seed starch, and grain N, P, and K concentrations; and (ii) identify the optimum combination of these fertilizers for improving physiological performance, nutrient accumulation, and grain quality under water-limited production systems.

2. Material and methods

2.1. Experimental Site

The field experiment was conducted during two consecutive growing seasons (2021 and 2022) at the Mahidasht Research Station of the Kermanshah Agricultural and Natural Resources Research and Education Center, Kermanshah Province, Iran. The experimental site is located at 34°08' N, 46°26' E in an altitude of 1365 m above sea level. The long-term (10-year) mean annual precipitation of the site is 335 mm. The ombrothermic diagram of the research station is presented in Fig. 1. The experimental soil is classified as a fine, mixed, thermic Vertic Calcixerept according to the USDA Soil Taxonomy system and has a silty clay surface texture. The soil texture ranges from heavy to very heavy, classified as silty clay to silty clay loam.

2.2. Experimental Design and Treatments

The study consisted of two independent field experiments established at two adjacent sites located approximately 10 m apart. The two sites represented different irrigation regimes; full irrigation (100% of crop water requirement) and deficit irrigation (70% of crop water requirement). At each irrigation regime, treatments were arranged as a split-plot factorial experiment based on a randomized complete block design (RCBD) with three replications (Supplementary Figure). Chemical fertilizer (NPK) was applied at three levels: no fertilizer application, 50% of the recommended fertilizer rate based on soil test recommendations, and 100% of the recommended fertilizer rate according to soil test recommendations. Vermicompost was applied at four rates of 0, 2, 4, and 6 t ha^{-1}. Consequently, each irrigation regime included 24 treatment combinations arranged in 72 experimental plots, resulting in a total of 48 treatment combinations and 144 plots across both irrigation treatments over the two growing seasons. To minimize interference among treatments, four border rows (3 m in length) were established between adjacent main plots. In addition, plots receiving chemical fertilizers were surrounded by two untreated border rows (0.75 m on each side), where no fertilizer was applied, to prevent nutrient movement into neighboring plots.

2.3. Experimental Procedures

2.3.1. Land Preparation and Crop Establishment

The experimental field had been cultivated with seed production canola during the preceding growing season (2020). In both 2021 and 2022, the experiment was conducted in separate sections of the same field. Deep plowing was carried out during autumn, followed by two perpendicular disk harrow operations in spring to control weeds and prepare a suitable seedbed. Before treatment application, composite soil samples were collected and analyzed for soil pH, macro- and micronutrient concentrations, and other physicochemical properties to determine fertilizer requirements for maize production based on regional recommendations. Experimental furrows were subsequently prepared using a furrow maker according to the field layout (Supplementary Figure).

The commercial maize hybrid KSC703 was selected because it occupies more than 50% of the maize-growing area in western Iran. Seeds were sown during the second half of May using a Winterstiger plotman precision experimental planter at a relatively high initial planting density. After seedling emergence and successful crop establishment, plants were manually thinned at the three-leaf stage, before applying nitrogen fertilizer, to obtain the recommended final population of 75,000 plants ha^{-1}.

Following plot establishment, the entire quantities of vermicompost, phosphorus, and potassium fertilizers were weighed individually for each plot, manually incorporated into the soil, and thoroughly mixed using a rotary tiller. Nitrogen fertilizer was applied in three equal splits at the four-leaf stage (V4), seven-leaf stage (V7), and immediately before tassel emergence.

Each subplot measured 7 m in length and 3 m in width (excluding border areas) and consisted of four rows. Row spacing was 0.75 m and within-row plant spacing was 17.7 cm, resulting in the target plant density of 75,000 plants ha^{-1}. To prevent water and nutrient movement between adjacent plots, irrigation was controlled using a Hydrofix irrigation system equipped with calibrated water meters. Each experimental plot was supplied with four independent irrigation outlets fitted with separate control valves to ensure precise water application.

2.3.2. Fertilizer Sources

Triple superphosphate, urea, and potassium sulfate were used as the sources of phosphorus, nitrogen, and potassium, respectively. According to soil test recommendations, the full fertilizer requirement consisted of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}, corresponding to 200 kg N ha^{-1}.

Vermicompost samples were collected from 30 commercial production sites across Iran and analyzed at the Soil and Water Research Laboratory of the Kermanshah Agricultural and Natural Resources Research and Education Center. Based on compliance with quality standards and average nutrient composition, one vermicompost source produced from animal manure was selected for the experiment.

The vermicompost used in this study chemically was analyzed before field application. The pH of vermicompost was 7.1 and electrical conductivity (EC) was 2.65 dS m^{-1}. Organic carbon content was 14.76%, while total nitrogen, phosphorus, and potassium concentrations were 0.94%, 0.79%, and 1.33%, respectively. The concentrations of Fe, Mn, Zn, and Cu were 2141, 396, 380, and 11.5 mg kg^{-1}, respectively, indicating that the vermicompost was a nutrient-rich organic fertilizer suitable for field application.

2.3.3. Irrigation Scheduling

All plots received sprinkler irrigation until the five-leaf stage to ensure uniform crop establishment. At the V5 growth stage, Hydrofix irrigation units and water meters were installed, and irrigation treatments were initiated. Crop water requirements were estimated at 10-day intervals using the FAO Penman–Monteith equation described in FAO Irrigation and Drainage Paper No. 56, based on meteorological data recorded at the experimental site. Crop water requirements were calculated using NETWAT software, which estimates irrigation demand from weather data and crop coefficients corresponding to different growth stages. The irrigation interval was fixed at 10 days.

The amount of water calculated by the software was considered as the full irrigation treatment (100% crop water requirement), whereas 70% of this amount was applied under the deficit irrigation treatment. Considering the irrigation system efficiency of 90%, an additional 10% of the calculated irrigation water was applied to compensate for distribution losses. The irrigation volume applied to each plot was calculated using the *Eq. 1*.

$$Irrigation\ volume\ (L) = \ Plot\ area\ \left(m^2\right) \times \ Daily\ crop\ water\ requirement\ \left(mm\ day^{-1}\right) \times \ Irrigation\ interval\ (days)\ \ Eq.\ 1$$

2.4. Measured Traits

2.4.1 Grain Yield

Grain yield was determined by harvesting ears from the two central rows of each experimental plot at physiological maturity, when grain moisture content was approximately 20% [54]. To eliminate border effects, the two outer rows and two plants at both ends of each plot were excluded from sampling. Harvested ears were weighed using a digital balance, after which the kernels were separated from the cobs using a mechanical sheller. Grain moisture content was measured with a portable digital moisture meter, and the grain and cob weights were recorded separately. Grain yield for each plot was subsequently adjusted to a standard grain moisture content of 14%, corrected for cob percentage, and expressed as t ha^{-1}.

2.4.2. Thousand-Kernel Weight

Thousand-kernel weight (TKW) was determined according to the International Seed Testing Association (ISTA) guidelines [55, 56]. After shelling, 1,000 kernels were counted using an electronic seed counter, placed in labeled paper bags, and weighed with a precision digital balance. The measured weight was corrected to a standard grain moisture content of 14%, based on moisture values obtained using a digital grain moisture meter, and expressed in grams.

2.4.3. Plant Height

Plant height was measured after complete tassel emergence and simultaneous completion of ear development, when vegetative stem elongation had ceased [57]. Six representative plants were randomly selected from each plot, and the height of each plant was measured from the soil surface at the plant base to the first branch of the tassel. The average of the six measurements was considered the plant height for each experimental plot.

2.4.4. Stem Diameter

Stem diameter was measured following the protocol recommended by CIMMYT [58]. Six representative plants were randomly selected from each experimental plot, and stem diameter was measured at the internode immediately below the primary ear using a digital caliper. The average value of the six measurements was recorded as the stem diameter for each plot.

2.4.5. Grain Quality

Grain quality analyses were performed at the Animal Science Research Laboratory of the Kermanshah Agricultural and Natural Resources Research and Education Center. Grain protein and starch concentrations were determined using a DA7200 Near-Infrared Reflectance (NIR) Analyzer (Perten Instruments, Sweden). [59–62]. Before analysis, the instrument was calibrated specifically for maize according to the manufacturer's instructions. A representative grain sample was randomly collected from each experimental plot, placed in the sample container, and analyzed for protein and starch concentrations.

To verify the accuracy of the NIR measurements, protein concentration in selected samples was also determined using the conventional Kjeldahl method [63]. After grinding the samples, 0.5 g of each sample was poured into the test tube and a catalyst tablet and 7 cc of 98% sulfuric acid were added to it. The test tubes were placed in a protein digester at 220°C for 90 minutes and then removed from the device. After cooling, 25–50 cc distilled water was added to each tube. Then, the sample was placed in the Kegeldahl apparatus, the nitrate vapor of the sample was absorbed by the receiver substance (boric acid) and the amount of protein was obtained by multiplying nitrogen by the coefficient of 6.25. Since no significant differences were observed between protein concentrations determined by the NIR analyzer and those obtained using the Kjeldahl method, the NIR measurements were considered sufficiently accurate and were therefore used for statistical analyses.

2.4.6. Protein Yield

Protein yield (kg ha^{-1}) was calculated based on grain protein concentration and grain yield using the proportional relationship between these two parameters.

2.4.7. Determination of Grain Nitrogen, Phosphorus, and Potassium Concentrations

Grain nitrogen concentration was determined using the Kjeldahl method following sample digestion [64]. For phosphorus determination, 5 mL of the digested sample was mixed with 5 mL of yellow reagent, and the final volume was adjusted to 25 mL with distilled water. Absorbance was measured at 470 nm using a spectrophotometer, and phosphorus concentration was calculated from a standard calibration curve. For potassium determination, 10 mL of the digested extract was diluted at a 1:5 ratio. Potassium concentration was then measured using a flame photometer, where emission intensity is directly proportional to potassium concentration. The final potassium concentration (%) was calculated based on the corresponding standard calibration curve.

2.4-8. Leaf Area Index (LAI)

Leaf area index (LAI) was measured at the flowering stage, when leaf expansion was complete, using a SunScan Canopy Analysis System (Delta-T Devices Ltd., Cambridge, UK). Measurements were taken by positioning the probe beneath the canopy in three orientations: perpendicular to the planting rows, parallel to the planting rows, and at a 45° angle relative to the planting rows. The average of the three readings was considered as the LAI value for each plot, following the method[65].

During measurements, the external light sensor was positioned at canopy height in an east–west orientation outside and adjacent to the experimental plot. Data processing was performed automatically by the instrument's integrated microcomputer. To ensure uniform lighting conditions and improve measurement accuracy, all measurements were conducted between 10:00 a.m. and 2:00 p.m. The recorded data were stored in the instrument's memory and subsequently transferred for analysis.

2.4.9. Leaf Chlorophyll Content

Leaf chlorophyll content was measured at the silking stage, as leaf greenness at this stage provides valuable information regarding crop growth and productivity. Because early detection of plant stress before the appearance of visible symptoms is critical, rapid assessment of leaf chlorophyll content is of particular importance. Chlorophyll content was determined nondestructively using a SPAD-502 chlorophyll meter (Konica Minolta, Japan). The instrument estimates chlorophyll content over a 2 × 3 mm leaf area with an accuracy of ± 1 SPAD unit by measuring leaf transmittance at wavelengths of 650 nm (red light) and 940 nm (near-infrared light) using two light-emitting diodes and corresponding photodetectors. Prior to measurement, the instrument was calibrated and dust was removed from the leaf surface. Measurements were taken at the midpoint of the leaf blade, between the midrib and the leaf margin. Plants exhibiting unusually wide spacing or abnormal height, as well as damaged or wet leaves, were excluded from sampling. In each plot, six leaves of similar physiological position were randomly selected from plants within the central rows while avoiding border effects. Three SPAD readings were obtained from each leaf, and the average value was recorded as the chlorophyll index for the respective plot [66].

2.4.10. Greenness Index (Normalized Difference Vegetation Index, NDVI)

The normalized difference vegetation index (NDVI) was measured using a handheld GreenSeeker optical sensor according to the manufacturer's instructions and the protocol described by [67]. Measurements were conducted at the ten-leaf stage (V10) between 11:00 a.m. and 2:00 p.m., with the sensor positioned approximately 60 cm above the crop canopy in each experimental plot.

2.4.11. Relative Leaf Water Content (RWC) and Relative water deficit (RWD)

Relative leaf water content (RWC) was determined using flag leaves collected one day before irrigation at the flowering stage. Leaf samples were placed in sealed bags immediately after collection and transported to the laboratory. Leaf discs (1 cm in diameter) were excised, and their fresh weight (FW) was determined using a precision digital balance. The discs were then floated on distilled water under low-light conditions for 4 h to achieve full turgidity, after which their turgid weight (TW) was recorded. Subsequently, the samples were oven-dried at 70°C for 48 h to obtain their dry weight (DW). Relative water content was calculated using *Eq. 2*.

$RWC\,(\%) = [FW - DW]/[TW - DW] \times\ 100$ *Eq. 2*

where FW is the fresh weight, TW is the fully turgid weight, and DW is the dry weight of the leaf [68]. Relative water deficit (RWD) was calculated by *Eq. 3*.

$$RWD\,(\%) = 100 - RWC\ \ Eq.3$$

2.4.12. Economic Water Use Efficiency

Economic water use efficiency (EWUE) was defined as the ratio of grain yield to the total amount of water consumed during the growing season. EWUE was calculated using the *Eq. 4*.

$$EWUE\ (Value) = \frac{(Grain\ yield\ per\ ha)\,(kg)}{(Water\ vulume\ per\ ha\ (\ L)}\quad Eq.4$$

2.5. Statistical Analysis

Data collected over the two experimental years were subjected to Levene's test ($P < 0.05$), for homogeneity of variance using IBM SPSS Software (Ver. 27). When homogeneous variances were observed, a combined split-factorial analysis (ANOVA) was conducted and mean comparisons were performed in the Tukey’s HSD test using R 4.2.2 Software. Furthermore, Pearson Correlation Estimation, Principal Component Analysis, and Z-Score Cluster Analysis were conducted using R 4.2.2 and graphical illustrations were prepared.

3. Results

3.1. Variance analysis

Analysis of variance (Table 1) revealed that irrigation, NPK fertilization, and vermicompost application exerted highly significant effects ($P < 0.001$) on almost all measured growth, physiological, yield, and quality traits. Irrigation emerged as the predominant source of variation, significantly influencing leaf area index, plant height, stem diameter, SPAD, relative water content (RWC), 1000-seed weight, seed yield, water-use efficiency (WUE), crude protein, harvest protein, seed starch, and nutrient contents. Similarly, NPK fertilization significantly affected all major agronomic and quality attributes. Vermicompost application also produced highly significant improvements across most traits. Significant two-way interactions were observed mainly for irrigation × NPK and NPK × vermicompost, indicating that crop responses to fertilization depended on water availability and organic nutrient inputs. Furthermore, the irrigation × NPK × vermicompost interaction significantly influenced several key traits, including leaf area index, stem diameter, yield, WUE, crude protein, harvest protein, and nitrogen content, demonstrating the synergistic effects of integrated water and nutrient management. In contrast, most interactions involving year were non-significant, suggesting that treatment responses were generally consistent across the two growing seasons.

3.1. Tukey’s HSD Means Comparison

Leaf Area Index (LAI)

The interaction among, irrigation regime, NPK fertilizer level, and vermicompost application significantly affected leaf area index (LAI) according to Tukey's HSD test ($\alpha = 0.05$). Overall, LAI was markedly greater under the full irrigation (100% field capacity) than under water scarcity (70% FC), indicating that the combined nutrient management treatments were more effective in enhancing canopy development under full irrigation conditions. The highest LAI (4.46) was recorded in Year 2 under full irrigation with 100% of the recommended NPK rate (NPK2 = 100 kg K ha^{-1}, 150 kg P ha^{-1}, and

450 kg urea ha^{-1}) combined with 4 t ha^{-1} vermicompost (V2), and this treatment was statistically grouped among the highest-performing combinations (Fig. 2a). In contrast, the lowest LAI (1.77) was observed in Year 1 under water deficit without NPK fertilizer (NPK0) and without vermicompost (V0). Therefore, application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) combined with 4 t ha^{-1} vermicompost is the best treatment combination which increased LAI by 152.2% relative to the control.

Plant Height

Plant height was significantly affected by main effects and some two-way interactions among treatments (α = 0.05). In general, plants grown under deficit irrigation (70% field capacity) exhibited substantially lower height than those receiving full irrigation, particularly when mineral fertilizer was integrated with vermicompost. The highest plant height (235.7 cm) was recorded in Year 1 under full irrigation with 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (100% of the recommended NPK rate) combined with 6 t ha^{-1} vermicompost (V3), although this treatment was statistically comparable to the combinations of 100% of the recommended NPK (NPK2) + 4 t ha^{-1} vermicompost (V2) and 50% of the recommended NPK rate (NPK1) + 6 t ha^{-1} vermicompost (V3) under the same irrigation regime (Fig. 2b). Conversely, the lowest plant height (148.3 cm) was observed in Year 1 under 70% FC irrigation without fertilization (NPK0; V0). Relative to the fertilizers control at 65% FC, 100% of the recommended NPK rate combined with 6 t ha^{-1} vermicompost increased plant height by 58.87%.

Under full irrigation, increasing NPK fertilizer and vermicompost application generally resulted in progressive improvements in plant height. Under shortage irrigation, the beneficial effects of integrated nutrient management were also evident; however, the maximum plant height (173.0 cm) remained markedly lower than that achieved under full irrigation.

Stem Diameter

Stem diameter was significantly influenced by the interaction among irrigation regime, NPK fertilizer level, and vermicompost application (α = 0.05). Overall, stem diameter was substantially smaller under the 70% field capacity than under full irrigation, particularly when mineral fertilizer was integrated with vermicompost. The highest stem diameter (34.37 mm) was recorded in Year 2 under full irrigation with 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) combined with 6 t ha^{-1} vermicompost (V3), and this treatment was statistically superior to most other treatment combinations (Fig. 2c). In contrast, the lowest stem diameter (16.88 mm) was observed in Year 1 under 70% FC irrigation without NPK fertilizer (NPK0) and without vermicompost (V0). Consequently, the optimum treatment (100% NPK + 6 t ha^{-1} vermicompost), at full irrigation condition, increased stem diameter by 103.6% relative to the lowest recorded value under 70% FC without fertilizer application.

Under full irrigation, increasing the rate of NPK fertilizer in combination with vermicompost markedly enhanced stem diameter, whereas treatments lacking both mineral fertilizer and organic amendment produced considerably smaller stem diameters. Application of 50% of the recommended NPK rate (NPK1) together with 6 t ha^{-1} vermicompost also resulted in relatively high stem diameter values (29.65–31.52 mm), indicating that vermicompost partially compensated for the reduced mineral fertilizer input. Under water shortage, integrated nutrient management similarly improved stem diameter; however, the maximum value remained substantially lower than that recorded under full irrigation.

1000-Seed Weight

The weight of 1000-seed was significantly affected by main effects and some two-way interactions among treatments (α = 0.05). In general, maize plants grown under deficit irrigation (I2 = 70% field capacity) produced lighter kernels than those under full irrigation, particularly when mineral fertilizer was integrated with vermicompost. The highest 1000-seed weight (342.13 g) was obtained in Year 2 under full irrigation with application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (100% recommended NPK rate (NPK2)) combined with 6 t ha^{-1} vermicompost (V3), although this treatment did not differ significantly from the corresponding treatments receiving 4 t ha^{-1} (V2) or 2 t ha^{-1} (V1) vermicompost (Fig. 2d). In contrast, the lowest 1000-seed weight (213.33 g) was recorded in Year 1 under 70% FC irrigation without NPK fertilizer (NPK0) and without vermicompost (V0). Consequently, application of 100% recommended NPK rate (NPK2) combined with 6 t ha^{-1} vermicompost (superior treatment) increased 1000-seed weight by 60.4% compared with non- fertilizer application under 70% FC irrigation (the frailest treatment).

Under full irrigation, progressive increases in NPK fertilizer and vermicompost application generally resulted in significant improvements in kernel weight. Although integrated nutrient management also enhanced kernel weight under deficit irrigation, the maximum value (291.55 g) remained substantially lower than that obtained under full irrigation.

Grain Yield

The interaction among irrigation regime, NPK fertilizer level, and vermicompost application significantly affected maize grain yield (α = 0.05). The highest grain yield was obtained in Year 2 under full irrigation with application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) and 6 t ha^{-1} vermicompost (V3), reaching 10,168.99 kg ha^{-1}, which belonged to the highest statistical group (a), which was statically similar to some other treatments (Fig. 3a), indicating that high NPK fertilization combined with vermicompost consistently maximized grain production under the full irrigation regime across both years.

In contrast, the lowest grain yield (2,512.58 kg ha^{-1}) was recorded in Year 1 under deficit irrigation without NPK fertilizer (NPK0) and without vermicompost (V0), followed closely by the corresponding Year 2 treatment (2,587.50 kg ha^{-1}), both belonging to the lowest statistical group (q) (Fig. 3a). Comparing the best treatment (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) and 6 t ha^{-1} vermicompost (V3) under full irrigation) and weakest treatment (70% FC irrigation without fertilization) revealed an absolute yield increase of 7,656.41 kg ha^{-1}, corresponding to an approximately 304.7% increase over the minimum yield. These findings demonstrate that integrating the full recommended NPK dose with 6 t ha^{-1} vermicompost under the full irrigation regime produced the greatest improvement in grain yield, highlighting the strong synergistic effects of balanced mineral nutrition and organic amendment on maize productivity. Moreover, increasing vermicompost application generally enhanced grain yield within each NPK level, with the greatest response observed when vermicompost was combined with the full recommended NPK dose.

Water Use Efficiency

The interaction among irrigation regime, NPK fertilizer level, and vermicompost application had a significant effect on water use efficiency (WUE). The highest WUE was recorded in Year 2 under full irrigation in response to 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) + 6 t ha^{-1} vermicompost (V3), reaching 1.45 kg m^{-3}, which belonged to the highest statistical group (a), indicating that under full irrigation, application of adequate mineral nutrition and vermicompost consistently produced the greatest efficiency of water utilization across both years (Fig. 3b).

However, the lowest WUE (0.55 kg m^{-3}) was observed in Year 1 under shortage irrigation without NPK fertilizer (NPK0) and without vermicompost (V0), followed by the corresponding treatment in Year 2 (0.57 kg m^{-3}), both belonging to the lowest statistical group (p). Grain yield under full irrigation and application of highest levels of NPK + vermicompost absolutely was increased by 0.90 kg m^{-3}, representing an approximately 162.9% improvement in water use efficiency.

Greenness Index

The interaction among irrigation regime, NPK fertilizer level, and vermicompost application significantly influenced the greenness index of maize. The highest greenness index was recorded under full irrigation with using of 100% of the recommended NPK rate (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2)) and 6 t ha^{-1} vermicompost (V3), reaching 0.79, and this treatment belonged to the highest statistical group (a) (Fig. 3c), demonstrating that high NPK fertilization, particularly when combined with vermicompost under the full irrigation regime, consistently maintained the highest leaf greenness across both experimental years.

Conversely, the lowest greenness index (0.61) was observed in Year 1 under deficit irrigation without NPK fertilizer (NPK0) and without vermicompost (V0), followed closely by the corresponding treatment in Year 2 (0.62), both belonging to the lowest statistical group (s–rs) (Fig. 3c). Application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) + 6 t ha^{-1} vermicompost improved the greenness index by an approximately 28.7% compared with its value observed under water shortage without fertilization.

Chlorophyll Index (SPAD)

The main effects and some tow-way interaction among irrigation regime, NPK fertilizer level, and vermicompost application significantly affected the SPAD chlorophyll index of maize ($\alpha = 0.05$). The highest SPAD value was recorded in Year 1 under full irrigation combined with 100% of the recommended NPK rate (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}) + 6 t ha^{-1} vermicompost (V3), reaching 47.70, and this treatment belonged to the highest statistical group (a) (Fig. 3d).

In contrast, the lowest SPAD value (25.85) was observed in Year 2 under deficit irrigation without NPK fertilizer (NPK0) and without vermicompost (V0), while the corresponding treatment in Year 1 produced a similarly low value (26.17). Both treatments belonged to the lowest statistical group (m) (Fig. 3d). Comparison of the highest and lowest SPAD values revealed an absolute increase of 21.85 SPAD units, corresponding to an approximately 84.5% improvement over the minimum value. Overall, increasing NPK and vermicompost application progressively increased SPAD readings under both irrigation regimes over tow experimental years.

Relative Water Content (RWC)

The Tukey HSD analysis revealed that the main effects and some two-way interactions among, irrigation, NPK fertilization, and vermicompost application significantly affected leaf relative water content (RWC) in maize. The highest RWC (80.52%) was recorded in Year 1 under field capacity irrigation × NPK0 (0% recommended NPK) × V3 (6 t ha^{-1} vermicompost), although this treatment was statistically similar to nearly all other full-irrigated treatments (group a), indicating that full irrigation combined with vermicompost effectively maintained leaf water status regardless of mineral fertilizer level. Contrarywise, the lowest RWC (63.058%) was observed in Year 2 under scarcity irrigation × NPK2 (100% recommended NPK) without vermicompost application (V0) (group k) (Fig. 4a). The difference between the highest and lowest RWC was 17.46 percentage points, corresponding to a 27.7% increase in RWC under the full irrigation and 6 t ha^{-1} vermicompost relative to the poorest treatment (70% FC + 100% recommended NPK). Overall, full irrigation treatments consistently exhibited higher RWC values (77.72–80.52%) than deficit irrigation treatments (63.06–70.76%), suggesting that the imposed irrigation regime, together with vermicompost application, enhanced plant water retention and osmotic adjustment. Furthermore, increasing vermicompost generally improved RWC within each NPK level, with the 6-t ha^{-1} vermicompost treatment (V3) producing the greatest leaf water content across both years.

Relative Water Deficit (RWD)

Also, the Tukey HSD analysis revealed that the main effects and some two-way interactions between irrigation, NPK fertilization, and vermicompost application significantly influenced the relative water deficit (RWD) of maize plants. The highest RWD (36.94%) was observed in Year 2 under 70% FC irrigation + NPK2 (100% recommended NPK) (Fig. 4b), which belonged to the highest statistical group (a), indicating the greatest level of leaf water deficit. In contrast, the lowest RWD (19.48%) was recorded in Year 1 under field capacity irrigation + 6 t ha^{-1} vermicompost (group k), although this treatment was statistically similar to all other full-irrigated treatments.

Crude Protein

The Tukey HSD analysis indicated that the interaction among irrigation regime, NPK fertilization, and vermicompost application significantly affected the crude protein content of maize grains. The highest crude protein content (10.35%) was obtained in first year under deficit irrigation with application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2; 100% recommended NPK), which belonged to the highest statistical group (a) (Fig. 4c). This treatment was statistically comparable with deficit-irrigation treatments receiving high NPK and vermicompost in each two experimental years, indicating that adequate mineral nutrition under water shortage condition was sufficient to maximize grain protein concentration. In contrast, the lowest crude protein content (7.09%) was recorded in year 2 under full irrigation without fertilization (group r). Overall, increasing NPK application from 0 to 100% recommended value markedly enhanced grain protein concentration under both irrigation regimes, while vermicompost exerted a smaller but generally positive effect, especially when combined with NPK fertilization.

Harvest Protein Yield

The Tukey HSD analysis revealed that the interaction among irrigation regime, NPK fertilization, and vermicompost application significantly influenced harvest protein yield in maize. The highest harvest protein yield (964.54 kg ha^{-1}) was obtained in year 2 under full capacity irrigation + 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2; 100% recommended NPK) + 6 t ha^{-1} vermicompost (V3), which belonged to the highest statistical group (a) and was statistically similar to several other treatments receiving full irrigation combined with high NPK and vermicompost (Fig. 4d). In contrast, the lowest harvest protein yield (223.66 kg ha^{-1}) was recorded under year 1 at deficit irrigation condition without fertilization (group n). Overall, harvest protein yield was markedly greater under full capacity irrigation than under shortage irrigation, primarily because the substantial increase in grain yield under full irrigation more than compensated for the slightly lower grain protein concentration. Increasing NPK fertilization from 0 to 100% progressively enhanced harvest protein yield under both irrigation regimes, while vermicompost application further improved protein production, with the 6-t ha^{-1} vermicompost treatment (V3) consistently producing the highest values within each fertilizer level.

Seed Starch Content

The Tukey HSD test demonstrated that the main effects of all treatments and tow-way interaction among NPK fertilization and vermicompost application significantly affected seed starch content in maize. The highest seed starch content (74.22%) was recorded in year 2 under field capacity irrigation plus + 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2; 100% recommended NPK) + 6 t ha^{-1} vermicompost (V3), which belonged to the highest statistical group (a). This treatment was statistically comparable with several full-irrigated treatments receiving high NPK and vermicompost, indicating that the combination of mineral and organic fertilization under full irrigation promoted starch accumulation in the grain. In contrast, the lowest seed starch content (65.10%) was observed in year 2 under shortage irrigation (group w) (Fig. 5a). The starch content was obtained under full irrigation combined with 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) + 6 t ha^{-1} vermicompost (V3), was higher by 14.00% compared with it value recorded under 70% field capacity irrigation without fertilization. Overall, seed starch content was consistently higher under full irrigation than under deficit irrigation, with full-irrigated treatments ranging from 69.89 to 74.22%, whereas deficit-irrigation treatments ranged from 65.10 to 69.62%. Increasing NPK fertilization generally enhanced starch accumulation, and vermicompost application further improved seed starch content within each fertilizer level, with the 6-t ha^{-1} vermicompost treatment (V3) consistently producing the highest values.

Nitrogen concentration (N)

The three-way interaction among irrigation regime, NPK fertilization, and vermicompost application significantly affected seed nitrogen concentration. Nitrogen concentration ranged from 1.13% to 1.66% across the treatment combinations. The highest nitrogen concentration (1.66%) was recorded in year 1 under 70% field capacity with 100% of the recommended NPK rate (NPK3), and no vermicompost (Fig. 5b). In contrast, the lowest nitrogen concentration (1.13%) was observed in year 2 under full irrigation, no NPK fertilizer (NPK1), and no vermicompost (V1), falling into the lowest significance group (r).

Overall, deficit irrigation consistently promoted greater nitrogen accumulation than full irrigation, regardless of year or vermicompost level. Increasing mineral fertilizer progressively enhanced seed nitrogen concentration, demonstrating the dominant role of balanced mineral nutrition in improving grain nitrogen content. Under deficit irrigation, treatments receiving the highest NPK rate generally occupied the upper statistical groups, whereas treatments without NPK fertilizer under full irrigation consistently produced the lowest nitrogen concentrations. Vermicompost exerted a comparatively smaller influence than mineral fertilization.

Potassium concentration (K)

The main effects of all treatments and tow-way interaction among NPK fertilization and vermicompost application significantly influenced seed potassium concentration. The highest potassium concentration (0.36%) was obtained in year 1 under full irrigation and application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} plus 6 t ha^{-1} vermicompost (V4), which belonged to the highest statistical group (a) (Fig. 5c). In contrast, the lowest potassium concentration (0.25%) was recorded in year 2 under deficit irrigation (70% field capacity), no NPK fertilizer, and no vermicompost application, falling into the lowest significance group (q).

Under full irrigation and application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} plus 6 t ha^{-1} vermicompost potassium concentration of seed increased by 42.9% compared with deficit irrigation without fertilization. Overall, potassium concentration increased progressively with increasing NPK application and vermicompost rate. Conversely, the absence of mineral fertilization (NPK0) resulted in the lowest potassium concentrations regardless of irrigation regime. Vermicompost supplementation further enhanced potassium accumulation, especially when combined with adequate mineral fertilization, suggesting a synergistic effect between organic and inorganic nutrient sources. Although both irrigation regimes supported relatively high potassium concentrations under adequate fertilization, several of the highest-ranking treatments occurred under deficit irrigation (70% field capacity), indicating that moderate water limitation did not impair potassium accumulation in maize grain when nutrient availability was sufficient.

Phosphorus concentration (P)

The main effects of all treatments and tow-way interaction among NPK fertilization and vermicompost application significantly influenced seed phosphorous concentration. Overall, the greatest P concentration was obtained under the highest NPK fertilizer rate (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}) combined with vermicompost, whereas the lowest values occurred in the unfertilized treatments. The highest phosphorus concentration (0.43%) was recorded in year 2 under full irrigation + NPK2 (100% recommended NPK) + V3 (6 t ha^{-1} vermicompost), which belonged to the highest statistical group (a) (Fig. 5d). The highest value of phosphorus concentration which obtained under the best treatment (full irrigation + 100% recommended NPK + 6 t ha^{-1} vermicompost) showed an improvement by 41.7% compared with the unfertilized control under deficit irrigation.

The results further indicate that increasing NPK fertilization substantially enhanced phosphorus accumulation, particularly when combined with vermicompost application. The year-to-year variation was relatively small, indicating that treatment effects were more influential than seasonal differences.

3.3 Correlation Estimation

Pearson correlation analysis (Fig. 6) revealed strong relationships among growth, physiological, yield, and grain quality traits, demonstrating that improved vegetative growth was closely associated with enhanced productivity and grain quality. Leaf area index (LAI) showed very strong positive correlations with plant height (r = 0.91), grain yield (r = 0.91), seed starch (r = 0.90), greenness index (r = 0.88), harvest protein (r = 0.84), and relative water content (RWC; r = 0.82), indicating that greater canopy development promoted light interception, photosynthetic capacity, and biomass accumulation. Plant height was positively associated with grain yield (r = 0.86), RWC (r = 0.91), seed starch (r = 0.92), and harvest protein (r = 0.76). Stem diameter also showed strong positive relationships with grain yield (r = 0.90), harvest protein (r = 0.87), water-use efficiency (WUE; r = 0.77), and 1000-seed weight (r = 0.80), emphasizing the importance of stem development in supporting assimilate transport and grain filling.

Grain yield exhibited strong positive correlations with harvest protein (r = 0.98), WUE (r = 0.87), LAI (r = 0.91), stem diameter (r = 0.90), plant height (r = 0.86), and seed starch (r = 0.83). Similarly, SPAD values were positively correlated with WUE (r = 0.82), harvest protein (r = 0.78), potassium (r = 0.76), phosphorus (r = 0.72), and grain yield (r = 0.69), indicating that higher chlorophyll content supported greater photosynthetic efficiency and nutrient assimilation. Crude protein showed an almost perfect positive correlation with grain nitrogen concentration (r = 0.99), reflecting the central role of nitrogen in protein synthesis.

3.4. PCA

Principal component analysis (PCA) (Fig. 7) was performed to investigate the relationships among agronomic, physiological, and grain quality traits and to identify treatment combinations associated with superior maize performance under different irrigation, NPK fertilizer, and vermicompost regimes. The first two principal components explained 93.40% of the total variation, with PC1 accounting for 65.83% and PC2 for 27.57%, indicating that these components effectively summarized treatment variability.

PC1 represented the overall crop growth and productivity axis. It was strongly and positively associated with grain yield (0.98), leaf area index (0.96), 1000-seed weight (0.96), stem diameter (0.95), harvest protein (0.95), greenness index (0.94), plant height (0.91), seed starch (0.90), water-use efficiency (0.85), relative water content (0.79), and SPAD value (0.78). In contrast, relative water deficit (RWD) showed a strong negative loading (-0.79), indicating that increasing plant water stress was closely associated with reductions in growth, physiological activity, and productivity. Thus, PC1 effectively differentiated vigorous, high-yielding treatments from water-stressed, low-performing treatments. PC2 primarily reflected grain nutritional quality and nutrient accumulation. Nitrogen and crude protein exhibited the highest positive loadings (0.97 each), followed by phosphorus (0.71), potassium (0.66), SPAD (0.55), water-use efficiency (0.49), and RWD (0.58), whereas relative water content (-0.58), plant height (-0.38), and seed starch (-0.37) loaded negatively. These relationships indicate that grain protein and nutrient accumulation varied partially independently of biomass production.

The PCA biplot clearly separated treatments according to irrigation and nutrient management. Fully irrigated treatments receiving the highest mineral fertilizer rate (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}; NPK2) were positioned on the positive side of PC1 and were strongly associated with superior yield, harvest protein, SPAD values, water-use efficiency, seed starch, and vegetative growth. The addition of higher vermicompost rates (particularly 6 t ha^{-1}) further enhanced treatment performance, demonstrating a synergistic interaction between mineral fertilization and organic amendment. In contrast, deficit-irrigated treatments without mineral fertilizer (NPK0) clustered on the negative side of PC1, reflecting poor growth, lower productivity, and reduced physiological activity. Increasing vermicompost progressively shifted these treatments toward positive PC1 values, indicating partial mitigation of nutrient deficiency.

Treatments from both experimental years occupied nearly identical positions in the biplot, confirming the stability and reproducibility of treatment responses across seasons. Moreover, the close grouping of yield, leaf area index, stem diameter, greenness index, harvest protein, and 1000-seed weight agreed with the correlation analysis, whereas RWD was positioned in the opposite direction, confirming its negative association with crop performance. Overall, PCA demonstrated that integrating NPK2 with 6 t ha^{-1} vermicompost was the most effective management strategy for improving maize growth, physiological performance, grain yield, harvest protein, and water-use efficiency under both full and deficit irrigation while maintaining consistent performance across growing seasons.

3.5. Clustering

Hierarchical cluster analysis (HCA) demonstrated a clear classification of treatments according to irrigation regime and nutrient management while confirming the consistency of treatment responses across the two growing seasons. Corresponding treatments from both years occupied nearly identical positions within the dendrogram, indicating excellent reproducibility and suggesting that the observed differences were primarily driven by irrigation and fertilization practices rather than seasonal variation. The first major cluster comprised treatments subjected to deficit irrigation combined with no or low mineral fertilizer inputs (NPK0 or NPK1; 50 kg K ha^{-1}, 75 kg P ha^{-1}, and 225 kg urea ha^{-1}). These treatments consistently exhibited the lowest grain yield, harvest protein, SPAD values, water-use efficiency, nutrient uptake, and overall physiological performance, reflecting the combined effects of water limitation and insufficient nutrient availability. Although increasing vermicompost application (0–6 t ha^{-1}) gradually enhanced treatment performance within this cluster, the improvements remained limited, indicating that organic amendment alone could not fully compensate for reduced mineral fertilization.

A second cluster consisted of deficit-irrigated treatments receiving the highest mineral fertilizer rate (NPK2; 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}). Compared with the first cluster, these treatments displayed greater vegetative growth, leaf area index, stem diameter, grain weight, and improved physiological traits. The close grouping of different vermicompost levels within this cluster suggests that mineral fertilization exerted a stronger influence than vermicompost under water-deficit conditions, although vermicompost provided additional improvements in crop performance.

The third and most distinct cluster included fully irrigated treatments supplied with NPK2 together with higher vermicompost rates (4–6 t ha^{-1}). These treatments consistently produced the highest grain yield, harvest protein, SPAD values, greenness index, water-use efficiency, nutrient accumulation, and overall physiological performance. Their clear separation from all other treatment groups corresponded closely with the positive region of PC1 identified in the principal component analysis, confirming that integrated nutrient management under full irrigation represented the most effective production strategy. In contrast, fully irrigated treatments without mineral fertilizer formed a separate subgroup with relatively poor agronomic and physiological performance, emphasizing that adequate irrigation alone could not maximize maize productivity without balanced nutrient supply.

The gradual transition of treatments toward high-performing clusters with increasing vermicompost rates demonstrated its cumulative and complementary role in improving soil fertility, nutrient availability, and crop resilience.

4. Discussion

The combined analysis demonstrated that the interaction among irrigation regime, NPK fertilizer level, and vermicompost application significantly influenced all measured growth, physiological, and yield traits of maize. Overall, the highest values for leaf area index, plant height, stem diameter, 1000-seed weight, grain yield, water use efficiency, and greenness index were consistently obtained under the combination of the highest NPK level (100% recommended fertilizer) together with moderate-to-high vermicompost application (4–6 t ha^{-1}), confirming their superiority over other treatment combinations.

Leaf area index responded strongly to the interaction of irrigation, mineral fertilization, and vermicompost. The maximum LAI (4.46) was obtained during the second year under the full irrigation regime combined with 50 kg K ha^{-1}, 75 kg P ha^{-1}, and 225 kg urea ha^{-1} (50% recommended NPK) and 2 t ha^{-1} vermicompost, although treatments receiving 4 t ha^{-1} vermicompost produced statistically similar values. In contrast, the lowest LAI (1.77) occurred under the deficit irrigation treatment without NPK and vermicompost during the first year. Increasing NPK availability markedly increased LAI because nitrogen promotes chlorophyll synthesis, protein formation, and cell division, resulting in faster leaf expansion and greater canopy development [69–72]. Likewise, vermicompost further improved leaf development by supplying slow-release nutrients, humic substances, plant growth regulators, and beneficial microorganisms that improve nutrient uptake and root growth [73–75]. The larger canopy produced under integrated fertilization likely increased light interception and photosynthetic capacity, thereby contributing to greater biomass accumulation.

Plant height exhibited a pattern similar to LAI. The tallest plants (235.67 cm) were recorded during Year 1 under full irrigation with 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (100% recommended NPK) and 6 t ha^{-1} vermicompost, whereas the shortest plants (148.33 cm) occurred under deficit irrigation without fertilizer amendments. The increase in plant height under integrated nutrient management can be attributed to enhanced nitrogen availability, improved phosphorus uptake for energy metabolism, and potassium-mediated enzyme activation [76–79]. Vermicompost further stimulates root development and microbial activity, enhancing nutrient acquisition throughout the growing season. Consequently, internode elongation and vegetative growth were promoted [80, 81].

Stem diameter significantly increased with increasing nutrient supply and vermicompost application. The greatest stem diameter (34.37 mm) was observed during year 2 under full irrigation with 100% NPK (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}) and 6 t ha^{-1} vermicompost. Conversely, unfertilized plants under full irrigation exhibited the smallest stem diameter. Thicker stems indicate greater assimilate accumulation and improved structural development. Potassium plays an essential role in lignin activity, carbohydrate transport and stem strengthening [82–84], while vermicompost improves soil structure and water retention, thereby facilitating continuous nutrient absorption [85–87]. Stronger stems also reduce lodging risk and improve the translocation of assimilates toward reproductive organs.

Kernel weight, grain yield, and WUE responded positively to integrated nutrient management. The maximum 1000-seed weight (342.13 g), grain yield (10,168.99 kg ha^{-1}), and WUE (1.446 kg m^{-3}), were obtained during the second year under full irrigation with 100% NPK (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}) and 6 t ha^{-1} vermicompost, whereas the minimum values (approximately 213 g) occurred under unfertilized treatments receiving no vermicompost. Higher kernel weight reflects improved assimilate production during grain filling [88]. Nitrogen enhances photosynthetic capacity, phosphorus supports ATP production and grain development, and potassium facilitates carbohydrate translocation from leaves to developing kernels [89]. Vermicompost likely prolonged photosynthetic activity by improving nutrient availability and mobility during the reproductive stage and grain filling [48, 90, 91] .

Yield improvement under integrated fertilization is explained by cumulative improvements in canopy development, plant height, stem diameter, chlorophyll content, and grain filling [92, 93]. The synergistic interaction between mineral fertilizer and vermicompost likely enhanced nutrient use efficiency while improving soil physical, chemical, and biological properties [94, 95]. Such improvements increase nutrient availability throughout the growing season and sustain photosynthesis during reproductive growth.

Integrated nutrient management enhances WUE through several mechanisms. Improved root growth enables plants to extract water more effectively, while greater leaf area and chlorophyll concentration increase photosynthetic efficiency per unit of water consumed [96–98]. Potassium also regulates stomatal conductance, improving water conservation without substantially reducing carbon assimilation [99–101].

The superiority of combining mineral fertilizer with vermicompost likely results from complementary mechanisms. Mineral fertilizers rapidly supply readily available nutrients, whereas vermicompost provides gradual nutrient release, improves cation exchange capacity, enhances soil microbial activity, increases organic matter content, and improves soil water-holding capacity [102–104]. These combined effects improve nutrient availability throughout crop development and increase nutrient use efficiency.

Treatments including 100% of the recommended NPK rate together with 4–6 t ha^{-1} vermicompost consistently produced the highest leaf area index, plant height, stem diameter, grain weight, grain yield, water use efficiency, and greenness index across both years. These findings indicate that integrating mineral fertilizers with vermicompost is an effective strategy for improving maize productivity, enhancing physiological performance, increasing water-use efficiency, and promoting sustainable soil fertility management under contrasting irrigation conditions. The chlorophyll accumulation, greenness Index, and RWC was strongly influenced by the combined management practices. The highest SPAD values, greenness index, and RWC were recorded under full irrigation combined with the highest fertilizer rate (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}; NPK2), particularly with 6 t ha^{-1} vermicompost (V3). The consistently greater SPAD readings under NPK2 indicate that adequate nutrient availability, especially nitrogen, promoted chlorophyll synthesis because nitrogen is a structural component of chlorophyll molecules and photosynthetic proteins [105, 106]. Higher greenness values indicate greater chlorophyll concentration and improved leaf nitrogen status. Nitrogen is the principal constituent of chlorophyll molecule, vermicompost further enhanced leaf greenness through its gradual nutrient release, improved microbial activity, and the supply of humic substances that stimulate micronutrients uptake such as iron and magnesium that participate directly in chlorophyll synthesis [73–75].

Relative water content represents the hydration status of plant tissues and is a reliable indicator of plant water relations during drought. Surprisingly, the highest RWC values were observed under full irrigation, while deficit irrigation resulted in lower RWC and correspondingly higher RWD values.

This pattern suggests that plants subjected to full irrigation developed effective osmotic adjustment mechanisms and enabled greater tissue hydration. Vermicompost likely improved soil water retention through its high organic matter content and increased soil porosity, while balanced NPK fertilization enhanced root development and water uptake efficiency. The combination of these factors probably enabled plants to maintain cellular turgor even under limited irrigation.

Crude protein and nitrogen concentration exhibited very similar responses because crude protein is directly derived from nitrogen concentration. The highest protein contents were obtained under deficit irrigation with the highest NPK level, especially when combined with vermicompost. Increasing fertilizer rate significantly enhanced protein concentration due to improved nitrogen availability throughout crop growth [107, 108]. Simultaneously, vermicompost supply slowly available nitrogen, improving microbial mineralization, and enhancing fertilizer use efficiency [102–104]. Consequently, treatments receiving both mineral fertilizer and vermicompost consistently maintained higher grain nitrogen than unfertilized treatments. Unlike protein concentration, harvest protein yield was greatest under full irrigation combined with NPK2 and V3. Harvest protein yield reflects both grain yield and protein concentration. Although deficit irrigation increased protein percentage, full irrigation apparently produced substantially greater grain yield in this experiment, leading to higher total protein production per hectare. The improvement in harvest protein yield under NPK and vermicompost application demonstrates the complementary roles of mineral fertilizers and vermicompost in sustaining productivity under water-supply conditions. Mineral fertilizers ensured sufficient nutrient supply for biomass production, whereas vermicompost likely enhanced nutrient retention, improved soil structure, increased microbial activity, and reduced drought stress through improved water-holding capacity.

Seed starch concentration increased under full irrigation and was further enhanced by increasing NPK and vermicompost levels. Balanced fertilization enhanced photosynthetic activity and carbohydrate synthesis [109, 110], while vermicompost improved nutrient availability and maintained physiological activity during grain filling [46, 111]. Consequently, the combined application of NPK2 and V3 produced the highest starch concentrations in both years.

Grain nutrient concentrations were significantly affected by the interaction among irrigation, fertilizer application, and vermicompost. Higher fertilizer rates increased grain nitrogen due to greater nitrogen availability and uptake, whereas vermicompost improved nitrogen retention and reduced nutrient losses through gradual mineralization.

Phosphorus and potassium concentration increased markedly with NPK2 and vermicompost. Organic amendments can enhance phosphorus availability by releasing organic acids that reduce phosphorus fixation and improve phosphate solubility. Improved root growth under vermicompost application also increases phosphorus acquisition from the soil. Potassium plays essential roles in osmotic regulation, enzyme activation, and stomatal function, making adequate potassium particularly important under water-limited conditions [112–114]. Higher potassium accumulation in plants receiving vermicompost may have contributed to improved drought tolerance by maintaining cellular osmotic balance and enhancing water-use efficiency.

The beneficial effects of vermicompost were particularly evident when combined with mineral fertilizers, indicating synergistic interactions rather than simple additive responses. These findings demonstrate that integrating balanced mineral fertilization with vermicompost can improve nutrient uptake, maintain plant water status, and enhance grain quality under limited water availability, thereby providing an effective strategy for sustainable crop production in water-scarce environments.

Conclusion

This study demonstrated that irrigation regime, NPK fertilization, and vermicompost application interacted significantly to influence crop physiology, grain quality, and nutrient composition across two growing seasons. The significant three-way interactions confirmed that crop performance was determined by the combined effects of water and nutrient management rather than by individual factors alone. Among all treatment combinations, the highest NPK rate (100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1}; NPK2) combined with 6 t ha^{-1} vermicompost (V3) consistently produced the best overall performance. This treatment enhanced SPAD values, relative water content, seed starch concentration, harvest protein yield, and grain N, P, and K concentrations, demonstrating the synergistic effects of combining mineral fertilizers with vermicompost. These benefits are attributed to improved nutrient availability, enhanced soil physical properties, greater microbial activity, and increased nutrient-use efficiency. Although moderate deficit irrigation increased grain nitrogen concentration and crude protein content, full irrigation combined with NPK2 and V3 maximized physiological performance, yield-related traits, nutrient uptake, starch accumulation, harvest protein yield, and overall resource-use efficiency. Vermicompost likely alleviated the effects of reduced water availability by improving soil moisture retention, promoting root growth, and sustaining nutrient uptake. The consistency of these responses across both experimental years highlights the reliability of integrated nutrient management under varying environmental conditions. Overall, full irrigation with application of 100 kg K ha^{-1}, 150 kg P ha^{-1}, and 450 kg urea ha^{-1} (NPK2) combined with 6 t ha^{-1} vermicompost (V3) represented the optimum treatment for maximizing growth, productivity, grain quality, and resource-use efficiency, whereas deficit irrigation × NPK2 without vermicompost was most effective for increasing grain nitrogen concentration and crude protein content, illustrating a trade-off between maximizing yield and enhancing grain nutritional quality. These findings support the adoption of integrated water and nutrient management practices, particularly the combined application of NPK2 and 6 t ha^{-1} vermicompost, as an effective strategy for improving crop productivity while promoting sustainable resource use. Future research should investigate the long-term impacts of repeated vermicompost application on soil fertility, microbial communities, and carbon sequestration under different irrigation regimes, as well as evaluate the economic feasibility, water productivity, and physiological mechanisms underlying improved drought resilience in integrated cropping systems.

Declarations

Ethics approval and consent to participate

This study is not a clinical trial and no human participants involved in this research.

Consent for publication

The authors declare their consent to the publication of this article.

Competing interests

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Author Contribution

A. Sh. conducted the research; M. SH. analyzed the data; The A. Sh. and M. SH. wrote the manuscript in cooperation.

Data availability

All data generated during this study are included in this article.

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Figures

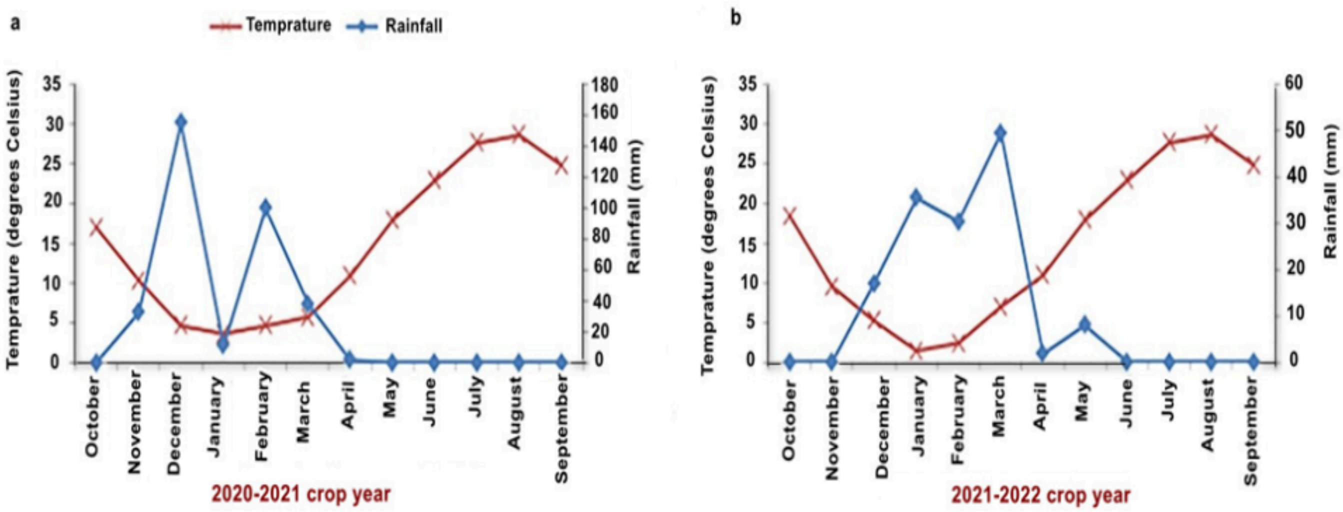

Figure 1

The monthly ombrothermic diagram of the crop years 2020-2021 and 2021-2022

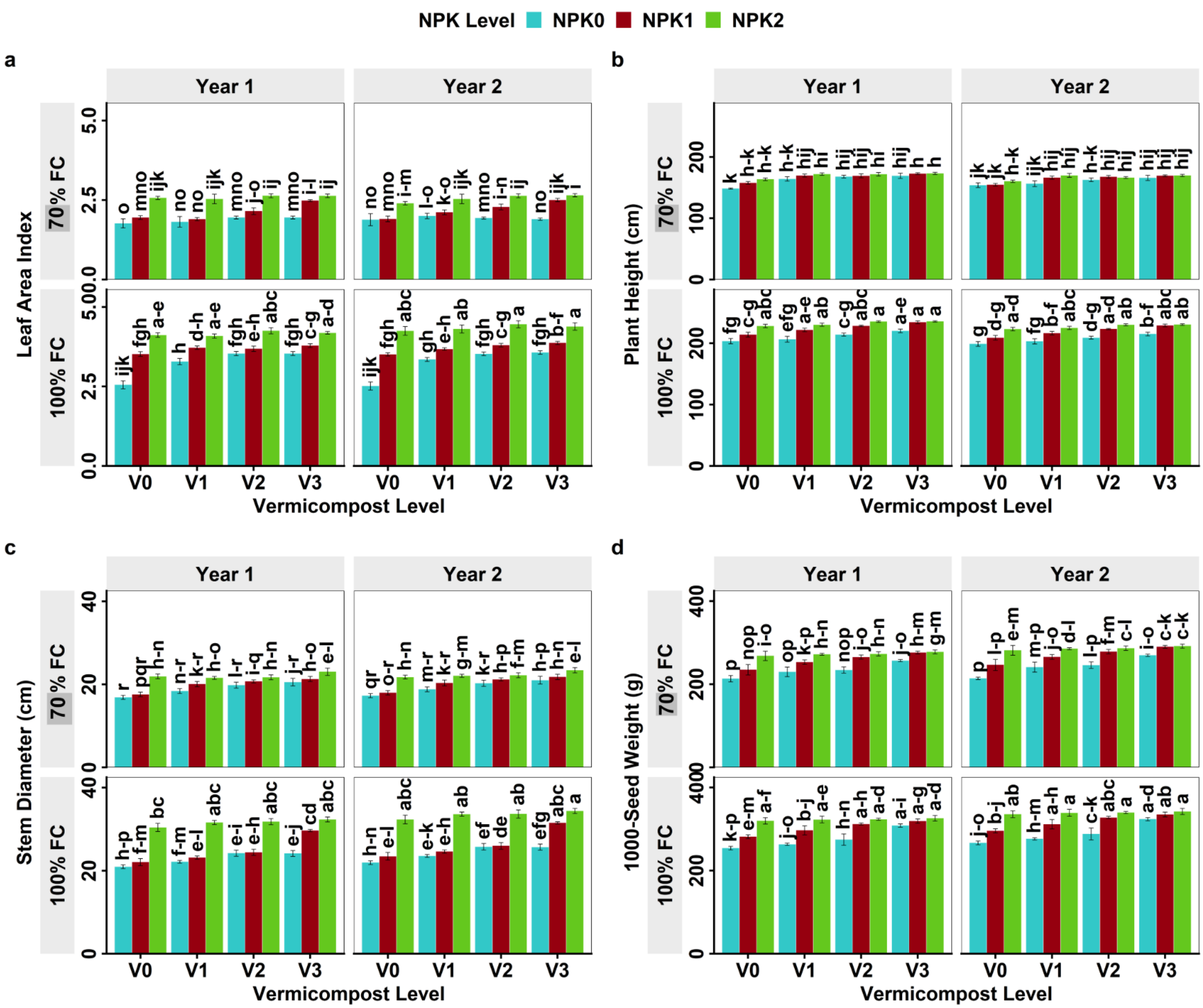

Figure 2

The means comparison for leaf area index (a), plant height (b), stem diameter (c), and 1000-seed weight (d) of *Zea maize* L. (hybrid KSC703) under different irrigation levels, NPK levels, and vermicompost fertilization (Tukey's HSD test, a= 0.05, r=3, n= 144). NPK0: 0% recommended amount based on soil analysis, NPK1: 50% recommended amount based on soil analysis, and NPK2: 100% recommended amount based on soil analysis), as well as vermicompost levels including V1: 0 Ton/ha, V2: 2 Ton/ha, V3; 4 Ton/ha, and V4: 6 Ton/ha).

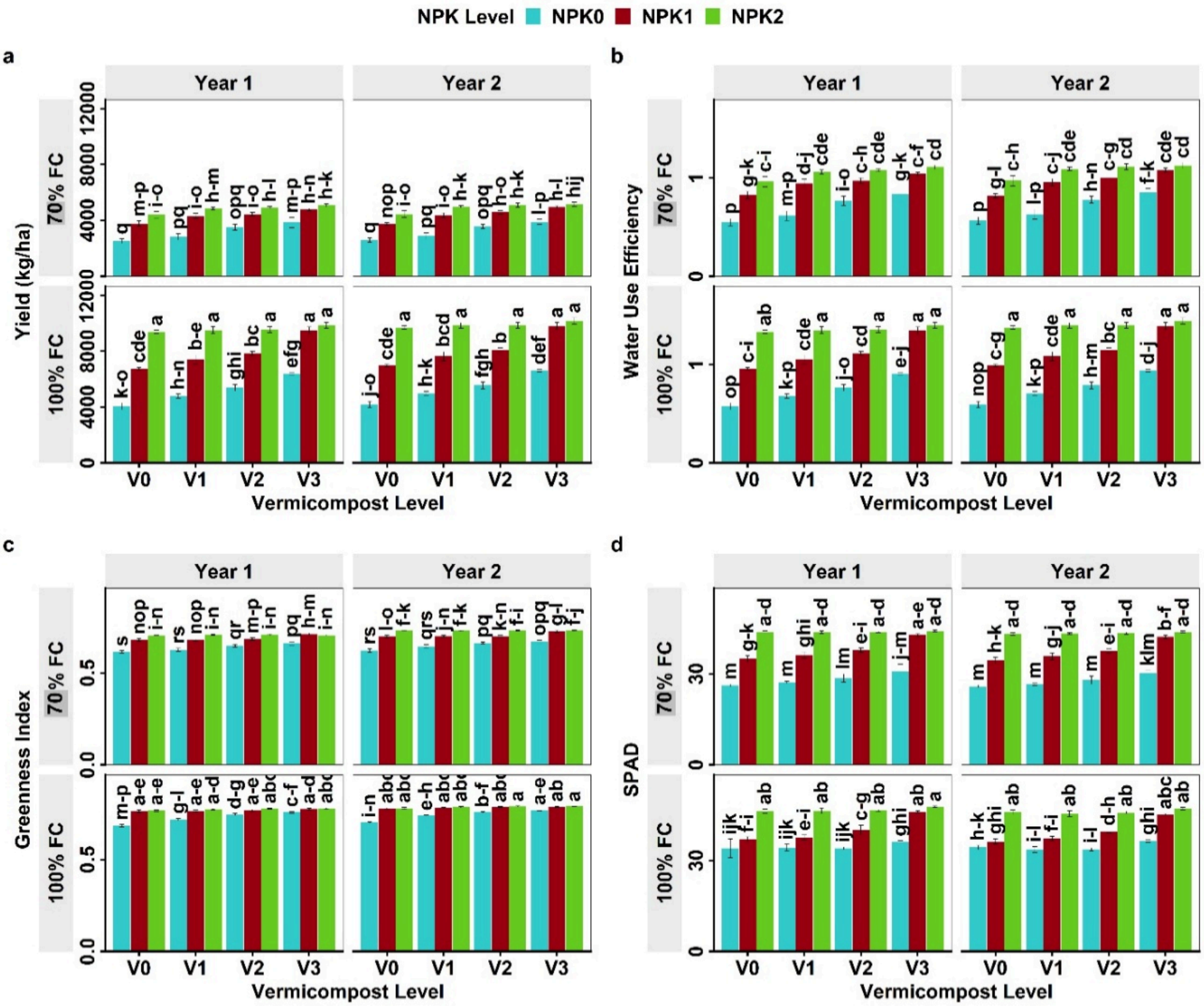

Figure 3

The means comparison for grain yield (a), water use efficiency (b), greenness index (c), and SPAD value (d) of *Zea maize* L. (hybrid KSC703) under different irrigation levels, NPK levels, and vermicompost fertilization (Tukey's HSD test, a= 0.05, r=3, n= 144). NPK0: 0% recommended amount based on soil analysis, NPK1: 50% recommended amount based on soil analysis, and NPK2: 100% recommended amount based on soil analysis), as well as vermicompost levels including V1: 0 Ton/ha, V2: 2 Ton/ha, V3; 4 Ton/ha, and V4: 6 Ton/ha).

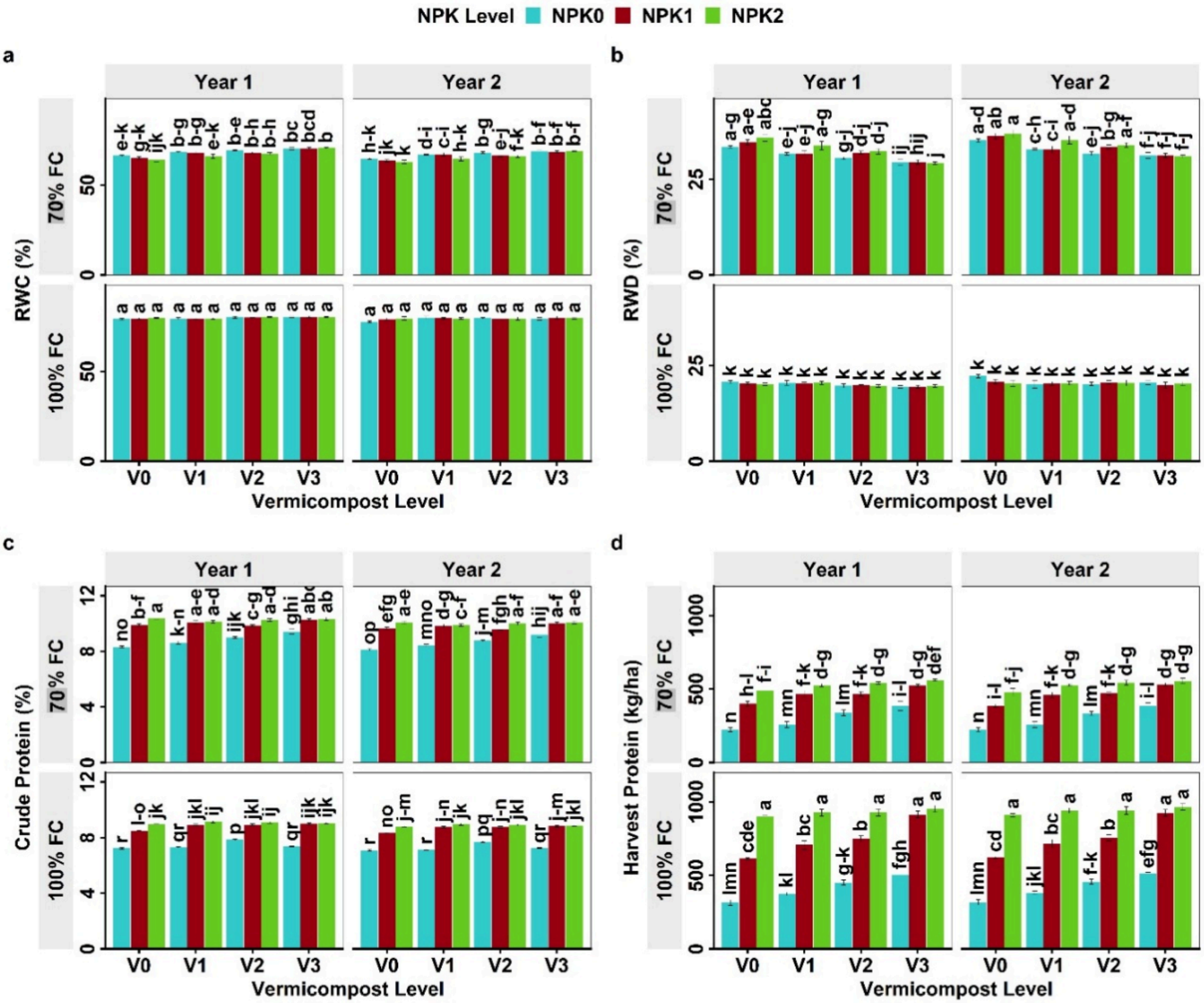

Figure 4

The means comparison for relative water content of leaves (RWC) (a), relative water deficiency of leaves (RWD) (b), crude protein of grains (c), harvest protein (d) of *Zea maize* L. (hybrid KSC703) under different irrigation levels, NPK levels, and vermicompost fertilization (Tukey's HSD test, a= 0.05, r=3, n= 144). NPK0: 0% recommended amount based on soil analysis, NPK1: 50% recommended amount based on soil analysis, and NPK2: 100% recommended amount based on soil analysis), as well as vermicompost levels including V1: 0 Ton/ha, V2: 2 Ton/ha, V3; 4 Ton/ha, and V4: 6 Ton/ha).

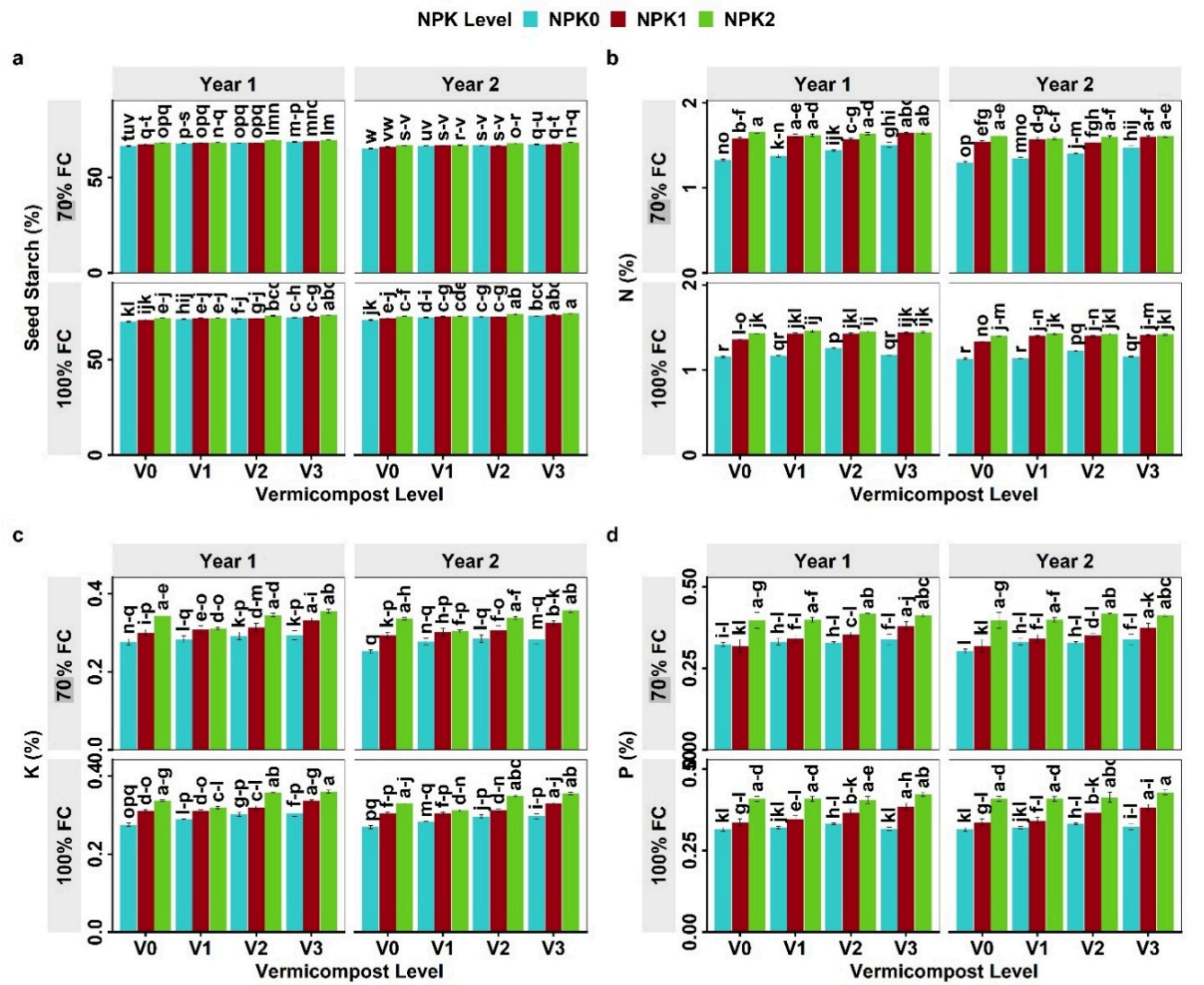

Figure 5

The means comparison for starch content (a), nitrogen content (b), K content (c), and phosphorous content of seeds (d) of *Zea maize*L. (hybrid KSC703) under different irrigation levels, NPK levels, and vermicompost fertilization (Tukey's HSD test, a= 0.05, r=3, n= 144). NPK0: 0% recommended amount based on soil analysis, NPK1: 50% recommended amount based on soil analysis, and NPK2: 100% recommended amount based on soil analysis), as well as vermicompost levels including V1: 0 Ton/ha, V2: 2 Ton/ha, V3; 4 Ton/ha, and V4: 6 Ton/ha).

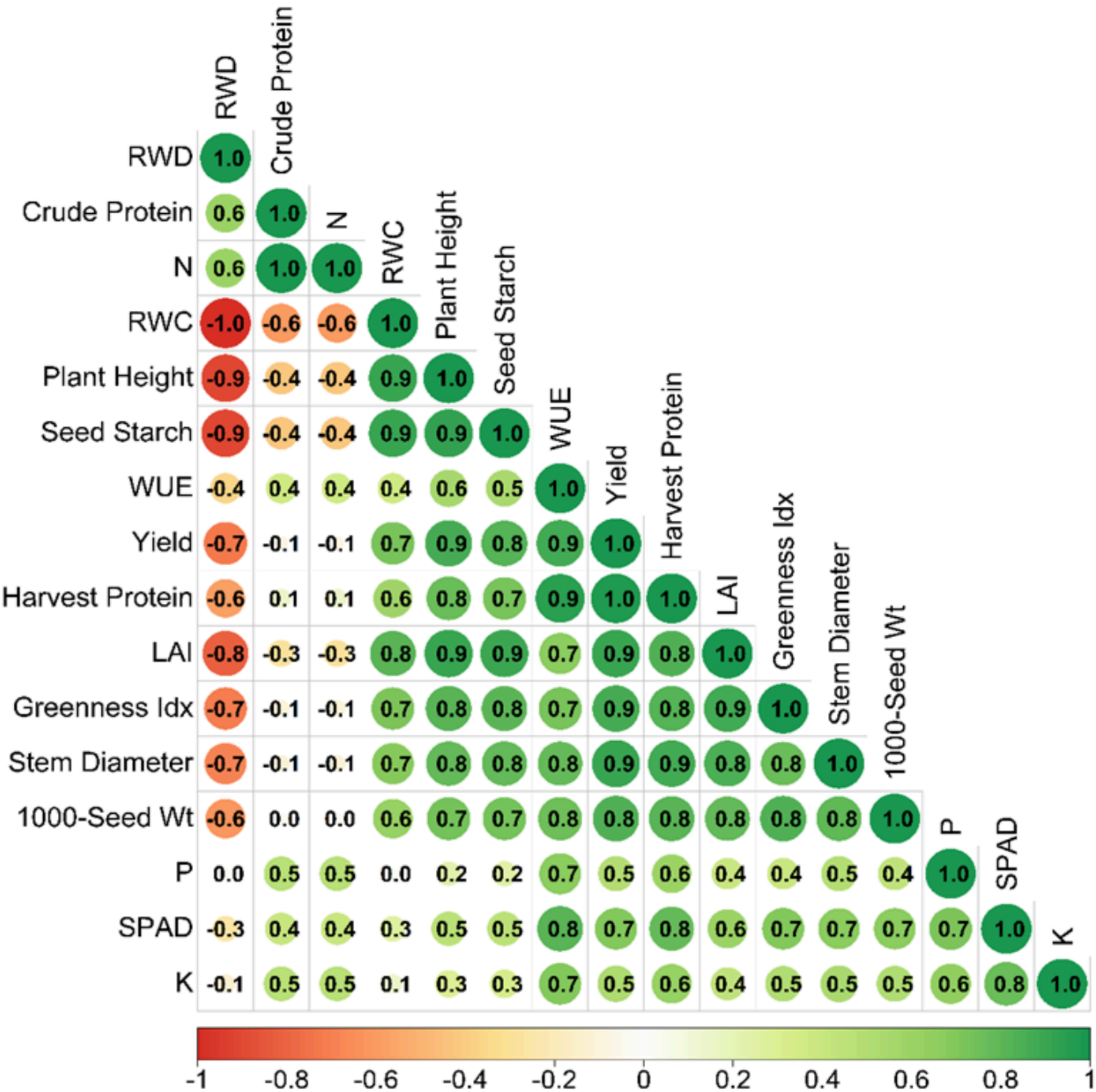

Figure 6

The Pearson Correlation Matrix for different morpho-physiological, yield and yiled related traits, and grain quality of *Zea maize* L. (hybrid KSC703) cultivated under different irrigation levels, NPK levels, and vermicompost fertilization.

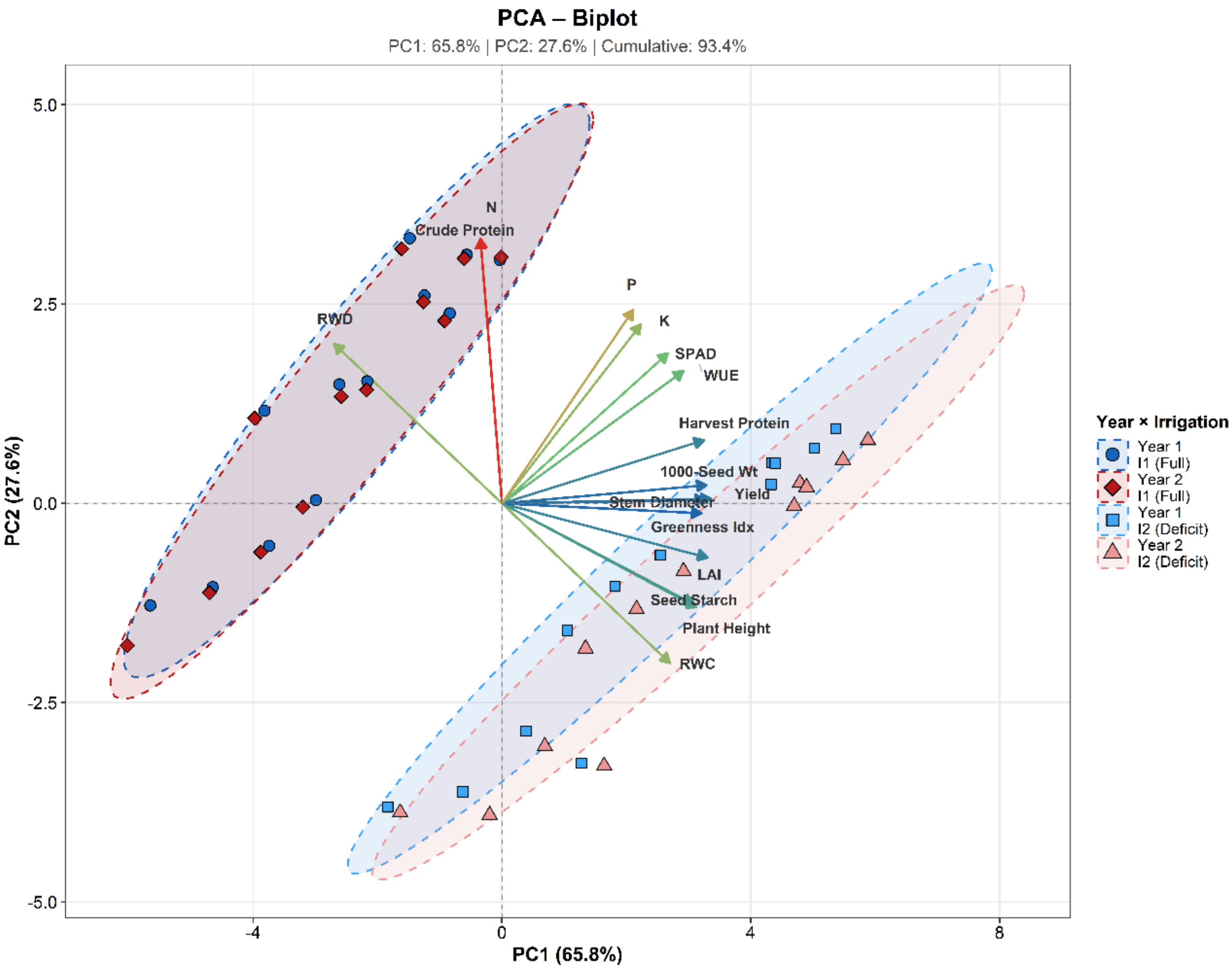

Figure 7

The Pearson Correlation Matrix for different morpho-physiological, yield and yiled related traits, and grain quality of *Zea maize* L. (hybrid KSC703) cultivated under different irrigation levels, NPK levels, and vermicompost fertilization. I1: deficit irrigation, I2: full irrigation.

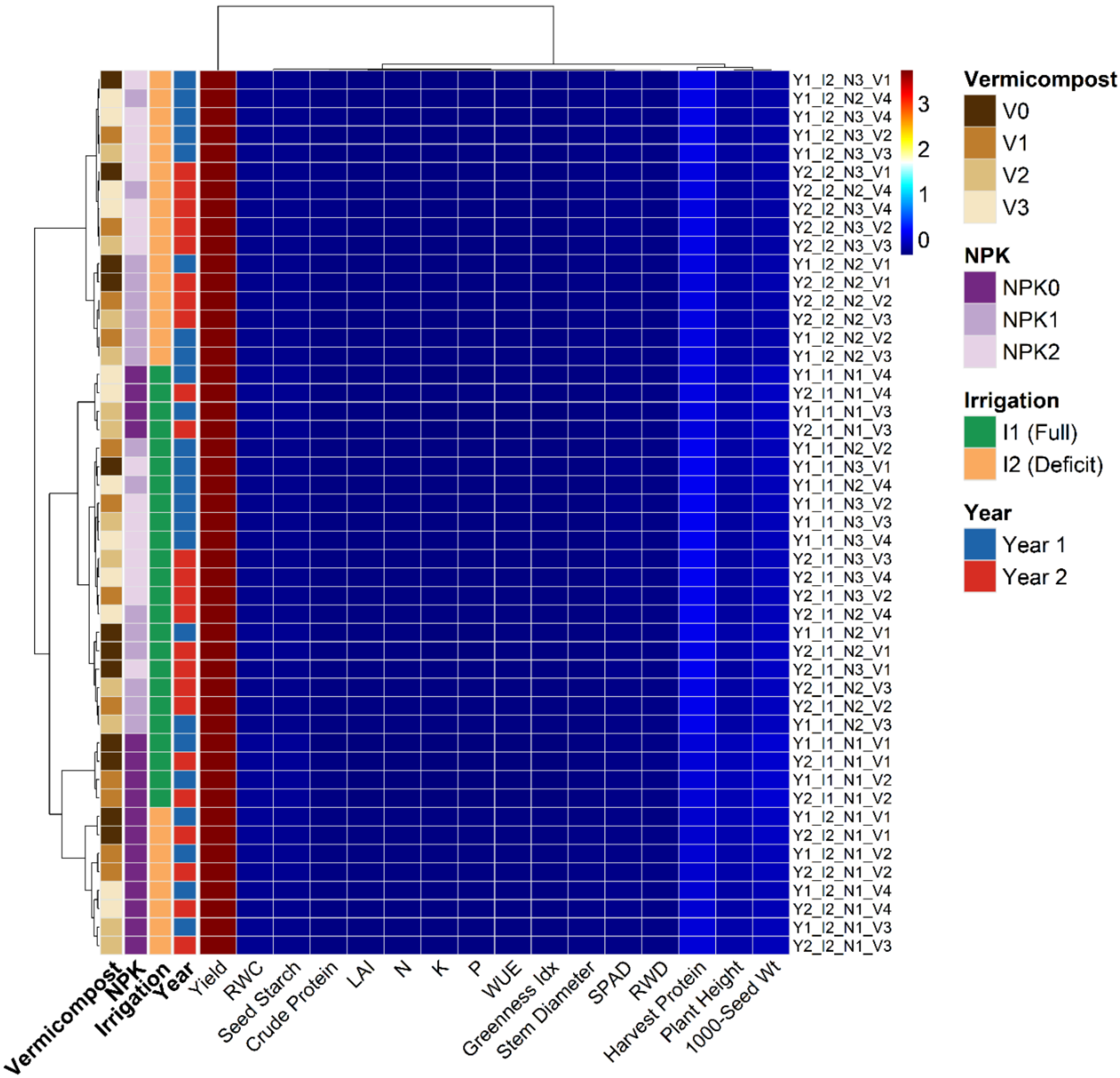

Figure 8

The Pearson Correlation Matrix for different morpho-physiological, yield and yiled related traits, and grain quality of *Zea maize* L. (hybrid KSC703) cultivated under different irrigation levels, NPK levels, and vermicompost fertilization. I1: deficit irrigation, I2: full irrigation NPK0: 0% recommended amount based on soil analysis, NPK1: 50% recommended amount based on soil analysis, and NPK2: 100% recommended amount based on soil analysis), as well as vermicompost levels including V1: 0 Ton/ha, V2: 2 Ton/ha, V3; 4 Ton/ha, and V4: 6 Ton/ha).

Supplementary Files

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

- Table1supplementary.docx
- Fig1supplementary.docx