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# Comparative effect of different irrigation levels and soil amendments on cabbage productivity in semi-arid Central Namibia

Kuume B. P. Enguwa[1] | Lydia N. Horn[2] | Simon K. Awala[1]

[1]Department of Crop Production and Agricultural Technologies, School of Agriculture and Fisheries Sciences, Faculty of Agriculture, Engineering and Natural Resources, University of Namibia, Oshakati, Namibia

[2]Zero Emissions Research Initiative, Multi-disciplinary Research Centre, University of Namibia, Windhoek, Namibia

**Correspondence**
Kuume B. P. Enguwa, Department of Crop Production and Agricultural Technologies, School of Agriculture and Fisheries Sciences, Faculty of Agriculture, Engineering and Natural Resources, University of Namibia, Oshakati, Namibia 15001.
Email: benenguwa@gmail.com

## Abstract

In semi-arid Central Namibia, poor sandy soils limit sustainable crop production. We assessed cabbage performance in two split-plot field experiments. In Experiment 1, treatments comprised two irrigation levels: full irrigation (watered 3 days a week) and reduced irrigation (watered 2 days a week) as the main plot factor and six soil amendments (biochar; compost; zeolite; nitrogen, phosphorus potassium [NPK]; Be-Grow boost [L] hydrogel; and hoof and horn + bone [HHB] meal) as subplot factors in three replications. Full irrigation produced a significantly higher yield (21.1 t ha$^{-1}$), head weight (0.958 kg) and larger head girths (42.1 cm). Biochar produced the highest marketable heads (24,884 heads ha$^{-1}$), water use efficiency (76.0 kg ha$^{-1}$ mm$^{-1}$) and the largest head girths (42.7 cm). In Experiment 2, water was applied 5 and 4 days a week for full and reduced irrigation; the application rates of compost, HHB meal, Be-Grow boost (L) hydrogel and NPK were modified. The interaction of Be-Grow boost (L) hydrogel, NPK and biochar with full irrigation and HHB meal with reduced irrigation produced more marketable heads (28,935, 28,009, 27,546 and 28,703 heads ha$^{-1}$, respectively). Therefore, full irrigation with these amendments could be used for resilient cabbage production in Central Namibia.

KEYWORDS

cabbage production, irrigation, sandy soils, soil amendments

## Résumé

Dans le centre semiaride de la Namibie, la pauvreté des sols sableux limite la production agricole durable. Nous avons évalué la performance du chou dans le cadre de deux expériences sur le terrain en parcelle divisée. Dans l'expérience 1, les traitements comprenaient deux niveaux d'irrigation, arrosés entièrement trois jours par semaine et arrosés de façon réduite deux jours par

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semaine comme facteur principal de parcelle et six amendements de sol (biochar, compost, zéolite, NPK, hydrogel de croissance (L), et sabot et corne + farine d'os (HHB)) comme facteurs de sous-parcelle en trois réutilisations. L'irrigation complète a produit un rendement nettement plus élevé (21,1 t ha$^{-1}$), un poids de tête (0,958 kg) et une plus grande circonférence de tête (42,1 cm). Le Biochar a produit les têtes commercialisables les plus élevées (24,884 têtes ha$^{-1}$), l'efficacité de l'utilisation de l'eau (76,0 kg ha$^{-1}$ mm$^{-1}$) et la plus grande circonférence de tête (42,7 cm). Dans l'expérience 2, de l'eau a été appliquée cinq et quatre jours par semaine pour une irrigation complète et réduite; Les taux d'application de compost, de farine HHB, d'hydrogel Be-Grow boost (L) et de NPK ont été modifiés. L'interaction entre l'hydrogel Be-Grow boost (L), le NPK et le biochar avec l'irrigation complète et la farine HHB avec l'irrigation réduite a produit plus de têtes commercialisables (28,935, 28,009, 27,546 et 28,703 têtes ha$^{-1}$, respectivement). Par conséquent, l'irrigation complète avec ces amendements pourrait être utilisée pour la production résiliente de chou dans le centre de la Namibie.

**MOTS CLÉS**
Irrigation, Amendements du sol, Sols sableux, Production de chou

# 1 | INTRODUCTION

Crop production in Namibia is experiencing significant challenges, primarily due to poor sandy soils, usually with low water-holding capacity (Mupambwa et al., 2019), leading to food insecurity. In addition, semi-arid Central Namibia is characterized by low rainfall and a high evaporation rate caused by high temperatures (MET, 2019; Mupambwa et al., 2019). Climate change will likely worsen this variability (MET, 2019), possibly leading to intensified severe impacts on crop production, including that of cabbage (*Brassica oleracea* L. var. *capitata*), one of the most preferred vegetables in Namibia and worldwide.

Cabbage production is reportedly increasing among African countries, including Namibia, where it has become one of the most important crops in the socio-economic sector (Mondédji et al., 2021). Equally important, it is a rich source of vitamin C (ascorbic acid), potassium, calcium and antioxidants (Riad et al., 2009). Notwithstanding its importance, cabbage production is affected by various biotic and abiotic factors, including irrigation and soil fertility (Abdrabbo et al., 2015). Vegetable crops are generally sensitive to extreme environmental conditions, such as high temperatures and limited soil moisture, which significantly reduce crop yield (Abou-Hussein, 2012).

Different soil amendments, such as compost and biochar, have been suggested for optimal vegetable production by various researchers (Abdrabbo et al., 2015; Cataldo et al., 2021; Laghari et al., 2016; Şeker & Manirakiza, 2020; Widowati et al., 2020). Organic fertilizers such as compost and hoof and horn (HH) meal serve as sources of soil nutrients for plants (Carla et al., 2016; da Silva et al., 2019; Oluwafisayo & Olusegun, 2023; Papafilippaki et al., 2015). In addition, soil conditioners such as zeolite, biochar and hydrogel polymers can improve nutrient retention and holding capacities and cation exchange capacity (CEC) (Aainaa et al., 2018; Agegnehu et al., 2016; Chen et al., 2017; McDonald et al., 2019; Mondal et al., 2021; Oladosu et al., 2022; Zheng et al., 2018) and regulate the pH of sandy soils (Faloye et al., 2019; Hossain et al., 2020), leading to improved crop production (Akolgo et al., 2020; Nurhidayati et al., 2016; Šimansky et al., 2021). Therefore, the present study investigated the impact of irrigation level and different soil amendments on cabbage yield and yield components for improved vegetable production under semi-arid, sandy soil conditions.

# 2 | MATERIALS AND METHODS

## 2.1 | Study location and environmental conditions

The field study was conducted at the Tsumis Arid Zone Agricultural Centre (TAZAC), Rehoboth Rural Constituency, in the Hardap region. The area is in Central Namibia, bordering Rehoboth Town to the north and Kalkrand Town to the south. It lies between latitude

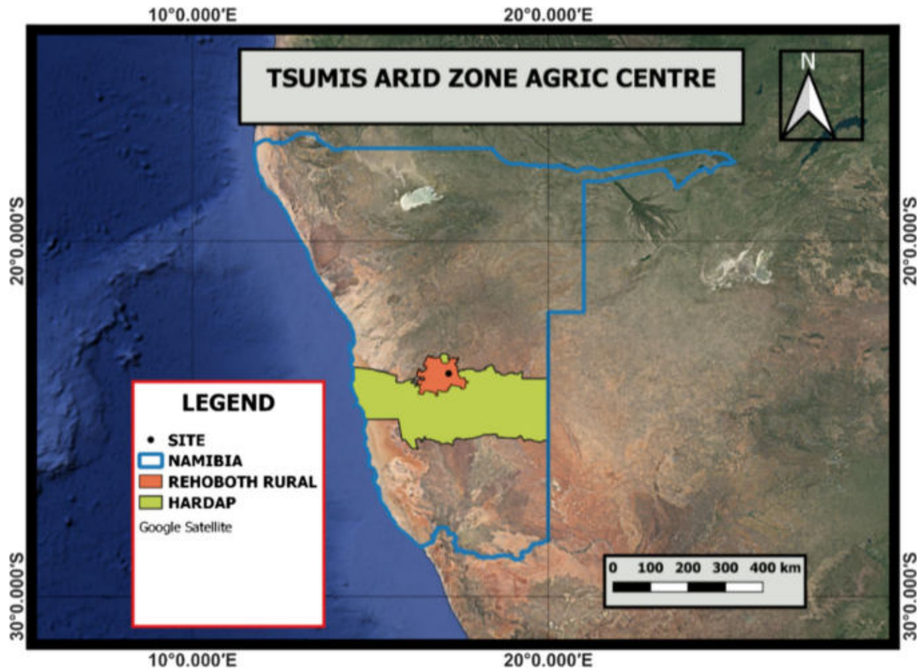


FIGURE 1 Map indicating location of Tsumis Arid Zone Agricultural Centre, where the experimental study was conducted.

23.7308° S and longitude 17.1987° E (Figure 1). Tsumis is characterized as a semi-arid area, with average annual rainfall ranging from 250–300 mm and average minimum and maximum temperatures of 13.5°C and 28.1°C, respectively (Grab & Zumthurm, 2020; Shikangalah et al., 2022).

The weather conditions for the duration of the experiments are indicated in Figure 2. During Experiment 1 (October 2021 to February 2022), the average rainfall and temperature were 32.4 mm and 24.3°C, respectively. The highest rainfall was recorded in January 2022 (133.2 mm), and there was no rainfall in October 2021. In addition, in 2021, the lowest temperature of 3.2°C was recorded in October, while the highest temperature of 42°C was recorded in November. Furthermore, the solar irradiance in Experiment 1 ranged between 25.1 MJ $m^{-2}$ $day^{-1}$ in February and 31.4 MJ $m^{-2}$ $day^{-1}$ in November.

In Experiment 2 (June to November 2022), the average temperature was much lower at 14.5°C, and no rainfall was recorded (Figure 2). The extreme minimum temperatures were between −4.8°C and 0.7°C and were recorded from June to September (Figure 2). In addition, solar irradiance during Experiment 2 was much lower compared with that observed in Experiment 1; June had the lowest solar irradiance with 15.4 MJ $m^{-2}$ $day^{-1}$, while the highest solar irradiance (24.7 MJ $m^{-2}$ $day^{-1}$) was recorded in November (Figure 2). A combination of relatively low temperatures and solar irradiance in the early months of Experiment 2 led to the experiment lasting a month longer to mature than Experiment 1 due to slower cabbage growth. Data on weather conditions during the experiments were obtained from the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) weather station at TAZAC.

The soils in semi-arid Central Namibia are mostly sandy to loamy (Dirk & Hartmut, 2010). To examine the efficiency of these amendments, soils were sampled in the topsoil (5–20 cm) three times during the study period, that is, before applying any treatment for Experiment 1 to obtain baseline information, after harvesting Experiment 1 and again after harvesting Experiment 2. The soil samples were analysed for chemical characteristics, such as pH, CEC, organic carbon (OC), total nitrogen (N), exchangeable potassium (K) and available phosphorus (P) and zinc (Zn). The baseline soil chemical characteristics for Experiment 1 are shown in Table 1. The soil had a pH of 7.40, CEC of 23.30 cmol $kg^{-1}$, OC of 59.00 g $kg^{-1}$, total N of 5.70 g $kg^{-1}$, total K of 25.60 g $kg^{-1}$ and available P and Zn of 717.60 and 22.10 mg $kg^{-1}$, respectively.

Table 2 shows the chemical characteristics after harvesting Experiment 1. The pH level for the different amended plots increased, except for the fully irrigated biochar, which remained at pH 7.40, as in Experiment 1 at baseline. In addition, all other chemical characteristics for all the amended plots drastically decreased, with the fully irrigated plots showing lower values (Table 2). Nitrogen, phosphorus and potassium (NPK)-amended soil under reduced irrigation had the highest pH of 8.23. In addition, reduced-irrigated biochar and NPK had the highest CEC of 7.33 and 6.90 cmol $kg^{-1}$, the highest OC of 10.70 and 10.53 g $kg^{-1}$ and the highest available P of 241.60 and 218.57 mg $kg^{-1}$, respectively, compared with fully irrigated compost (3.37 cmol $kg^{-1}$), fully irrigated control (4.65 g $kg^{-1}$) and fully irrigated

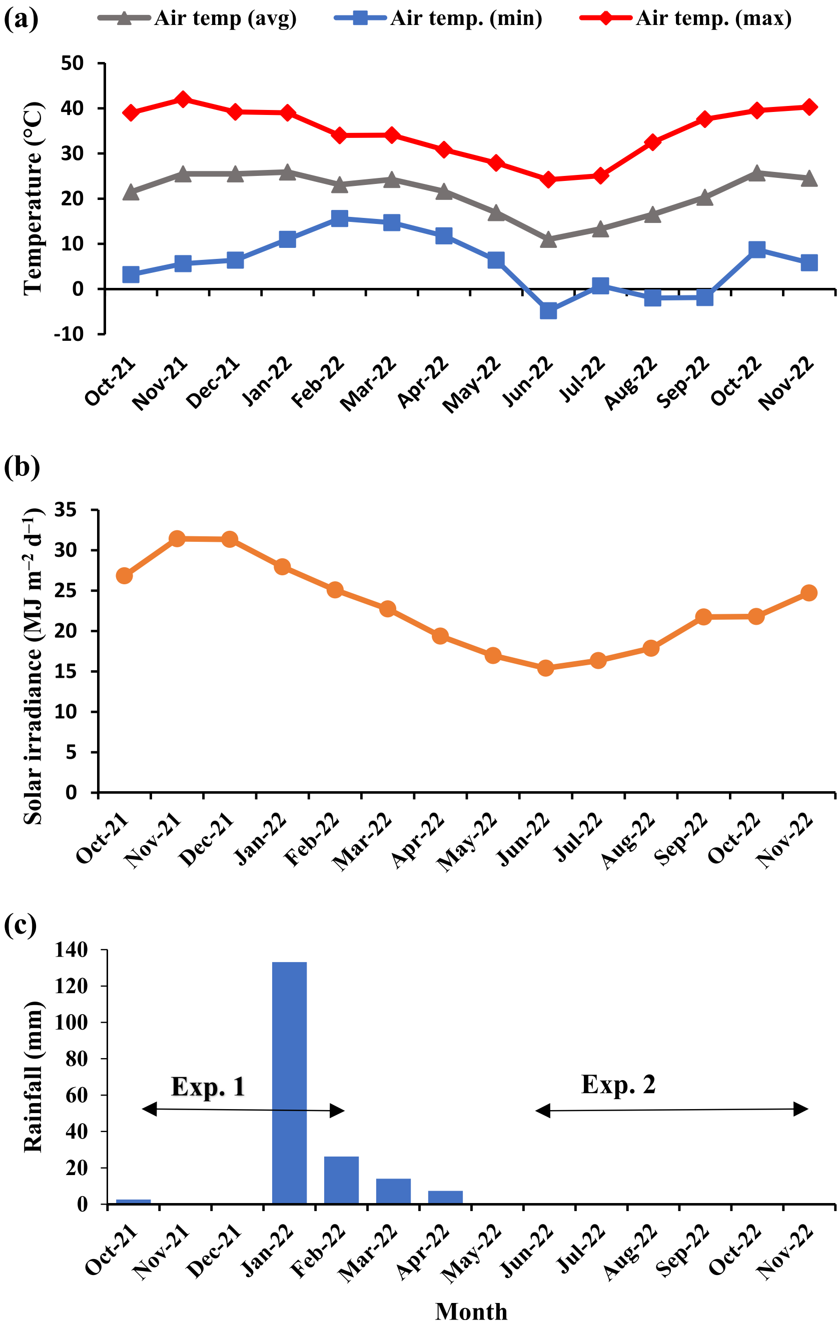


FIGURE 2 Patterns of monthly average, minimum and maximum temperatures (a), monthly average daily solar irradiance (b), and total monthly rainfall (c) for Tsumis Arid Zone Agricultural Centre (TAZAC). avg, average; Exp. 1, Experiment 1; Exp. 2, Experiment 2. *Data source:* TAZAC weather station.

TABLE 1 Baseline soil chemical characteristics for Experiment 1.

| Field soil chemical characteristics | Amounts |
|---|---|
| pH | 7.40 |
| CEC (cmol kg$^{-1}$) | 23.30 |
| Organic carbon (g kg$^{-1}$) | 59.00 |
| Total nitrogen (g kg$^{-1}$) | 5.70 |
| Total potassium (g kg$^{-1}$) | 25.60 |
| Available phosphorus (mg kg$^{-1}$) | 717.60 |
| Available zinc (mg kg$^{-1}$) | 22.10 |

Abbreviation: CEC, cation exchange capacity.

NPK (103.37 mg kg$^{-1}$), which had the lowest respective values. Furthermore, reduced-irrigated NPK-amended soil and biochar had the highest total N at 1.033 and 0.900 g kg$^{-1}$, respectively, compared with the lowest total N of 0.400 g kg$^{-1}$ in the fully irrigated control, NPK and hoof and horn + bone (HHB) meal plots. Moreover, under full irrigation, Be-Grow boost (L) hydrogel-amended soil had the highest total K content of 20.63 g kg$^{-1}$ compared with reduced-irrigated NPK meal (18.37 g kg$^{-1}$). Additionally, the soil under reduced-irrigated and fully irrigated biochar had the highest available Zn at 4.77 and 4.43 mg kg$^{-1}$,

TABLE 2 Soil chemical characteristics after harvesting Experiment 1 and soil used for Experiment 2.

| Irrigation X soil amendment | | pH | CEC (cmol kg$^{-1}$) | Organic carbon (g kg$^{-1}$) | Total nitrogen (g kg$^{-1}$) | Total potassium (g kg$^{-1}$) | Available phosphorus (mg kg$^{-1}$) | Available zinc (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Full | Ctr | 7.95 | 5.20 | 4.65 | 0.400 | 20.50 | 107.25 | 3.40 |
| | NPK | 8.00 | 5.47 | 5.53 | 0.400 | 20.33 | 103.37 | 3.63 |
| | Co | 7.70 | 3.37 | 6.43 | 0.533 | 19.87 | 134.53 | 2.97 |
| | Bio | 7.40 | 5.03 | 7.47 | 0.600 | 19.97 | 140.40 | 4.43 |
| | HHB | 7.63 | 4.77 | 4.93 | 0.400 | 20.20 | 114.77 | 3.10 |
| | Ze | 7.97 | 5.37 | 6.20 | 0.533 | 20.07 | 117.63 | 3.30 |
| | Be | 7.93 | 4.60 | 6.40 | 0.533 | 20.63 | 154.67 | 2.63 |
| Reduced | Ctr | 7.90 | 6.07 | 9.17 | 0.733 | 19.20 | 187.43 | 3.20 |
| | NPK | 8.23 | 6.90 | 10.53 | 1.033 | 18.37 | 218.57 | 3.97 |
| | Co | 8.10 | 5.77 | 7.57 | 0.600 | 19.67 | 173.67 | 3.80 |
| | Bio | 8.10 | 7.33 | 10.70 | 0.900 | 19.13 | 241.60 | 4.77 |
| | HHB | 7.90 | 5.30 | 5.97 | 0.500 | 19.67 | 139.53 | 3.63 |
| | Ze | 8.07 | 5.73 | 9.00 | 0.833 | 18.50 | 182.87 | 3.83 |
| | Be | 7.95 | 5.55 | 7.650 | 0.550 | 18.60 | 129.10 | 1.75 |

Abbreviations: Be, Be-Grow boost (L) hydrogel; Bio, biochar; CEC, cation exchange capacity; Co, compost; Ctr, control; HHB, hoof and horn + bone meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

TABLE 3 Soil chemical characteristics after harvesting Experiment 2.

| Irrigation X soil amendment | | pH | CEC (cmol kg$^{-1}$) | Organic carbon (g kg$^{-1}$) | Total nitrogen (g kg$^{-1}$) | Total potassium (g kg$^{-1}$) | Available phosphorus (mg kg$^{-1}$) | Available zinc (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Full | Ctr | 7.50 | 10.93 | 5.60 | 0.267 | 18.47 | 72.63 | 0.03 |
| | NPK | 8.03 | 12.93 | 8.16 | 0.467 | 20.60 | 116.50 | 2.13 |
| | Co | 7.70 | 11.37 | 6.90 | 0.433 | 19.83 | 108.13 | 1.17 |
| | Bio | 5.67 | 13.97 | 9.70 | 0.600 | 18.83 | 142.83 | 6.13 |
| | HHB | 7.23 | 11.50 | 6.10 | 0.333 | 19.47 | 102.03 | 1.23 |
| | Ze | 8.03 | 11.33 | 6.50 | 0.367 | 18.07 | 103.97 | 1.00 |
| | Be | 8.50 | 11.33 | 7.00 | 0.433 | 19.83 | 148.10 | 0.73 |
| Reduced | Ctr | 8.03 | 12.23 | 8.10 | 0.433 | 18.77 | 143.27 | 0.00 |
| | NPK | 8.67 | 10.80 | 10.50 | 0.733 | 21.50 | 132.90 | 5.10 |
| | Co | 8.00 | 12.07 | 8.73 | 0.567 | 21.73 | 135.37 | 1.50 |
| | Bio | 8.73 | 13.40 | 10.70 | 0.700 | 18.43 | 114.27 | 5.17 |
| | HHB | 7.90 | 9.53 | 6.90 | 0.500 | 18.00 | 86.40 | 2.13 |
| | Ze | 8.73 | 11.00 | 10.10 | 0.767 | 21.07 | 134.57 | 0.90 |
| | Be | 8.53 | 11.00 | 8.03 | 0.533 | 19.80 | 151.80 | 4.90 |

Abbreviations: Be, Be-Grow boost (L) hydrogel; Bio, biochar; CEC, cation exchange capacity; Co, compost; Ctr, control; HHB, hoof and horn + bone meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

respectively. The reduced-irrigated Be-Grow boost (L) hydrogel had the least available Zn at 1.75 mg kg$^{-1}$ (Table 2). The soil chemical properties after harvesting Experiment 2 are presented in Table 3.

The borehole irrigation water applied in both experiments was also analysed for pH and electrical conductivity (EC) using a pH/EC meter. The irrigation water had a pH of 7.32 and an EC of 0.0017 dS m$^{-1}$.

## 2.2 | Treatments and plant materials

The experimental design was a split-plot model with two irrigation levels (full and reduced irrigation) as the main plots and six soil amendments (biochar, compost, zeolite, NPK [2:3:2(35) + Procote Zn], Be-Grow boost [L] hydrogel and HHB meal) and control (without soil amendment) as subplots, replicated three times. The total experimental area was 900 $m^2$ (39.9 m × 22.5 m). With an area of 14.4 $m^2$ (4.8 m × 3 m), each subplot consisted of 64 plants, spaced 0.75 m between rows and 0.30 m within rows. In Experiment 1, the cabbage variety Star 3301 F1 hybrid was used to test the effect of irrigation levels and amendments on cabbage performance. In Experiment 2, a different variety (Menzania) was used due to the unavailability of the Star 3301 F1 hybrid variety on the market. Cabbage was selected as test crop due to its high nutritional requirement and responsiveness to different soil treatments (Carla et al., 2016).

## 2.3 | Irrigation management

In this study, the surface drip irrigation method was adopted. Flowmeters (Sensus Z15NRV02 XNP Plastic Meter, Xylem Inc., South Africa) were connected to each supply pipe to measure the amount of irrigation water applied. During the first 3 weeks after transplanting, all plots received the same amount of water according to the requirement of the crop, after which the irrigation scheduling was automated using a controller (Hunter node-400, Hunter Industries, South Africa). The drip pipes used had a discharge rate of 1 L $h^{-1}$ per dripper and a dripper spacing of 30 cm. For both irrigation levels, each irrigation schedule was set to run for an hour (supplying approximately 1 L per plant per day) based on the cabbage water requirement of 4 mm/day (Beshir, 2017). However, the difference in irrigation was initiated by varying irrigation frequency for full and reduced irrigation levels. In sandy soils, cabbage requires frequent irrigation on at least 3 days a week (Beshir, 2017; Bute et al., 2021; Nyatuame et al., 2013; Rasanjalia et al., 2020). Thus, in Experiment 1, irrigation was scheduled for 3 days per week for the full irrigation level and 2 days per week for the reduced irrigation level. The 2 days of irrigation per week for the reduced-irrigation treatment was designed to create a water stress condition for the plants. Eventually, 79.6 and 39.6 $m^3$ of water were applied for the full and reduced irrigation levels, respectively.

For Experiment 2, irrigation frequencies were increased due to the slightly poor cabbage heads observed in Experiment 1, which were assumed to be due to insufficient irrigation. Therefore, in Experiment 2, water was applied more frequently than in Experiment 1. In particular, water was applied five times a week for the full-irrigation treatment and four times a week for the reduced-irrigation treatment, finally giving 136.0 and 124.8 $m^3$ of water under full irrigation and reduced irrigation levels, respectively. The details of the irrigation treatments are presented in Table 4.

## 2.4 | Soil amendment management

In Experiment 1, all soil amendment plots were tilled with a broad fork and levelled with a rake before the amendments were applied. Biochar and compost were broadcast and incorporated into the soil, while zeolite and HHB meal were spread along the rows and incorporated into the soil. The Be-Grow boost (L) hydrogel and synthetic NPK fertilizer (2:3:2[35] + 2.9% S + Procote Zn) were applied to transplanting holes. HH and bone (B) meals were mixed in a 1:1 ratio to prepare the HHB meal treatment. HH meal has a higher N concentration (12%) but a lower P concentration (2%), while B meal is a rich source of P (15%) but contains only approximately 3% N (Joshi, 2015; Möller & Schultheiß, 2015; Oluwafisayo & Olusegun, 2023). Therefore, in this experiment, the HH meal served as the N source, while the B meal served as the P source in the HHB meal treatment. In addition, biochar, zeolite, HHB meal and compost were applied at 20 (Hossain et al., 2020; Toková et al., 2020), 14 (Chen et al., 2017; Zheng et al., 2018), 2 (Wang et al., 2017) and 97 t $ha^{-1}$ (Carla et al., 2016; Papafilippaki et al., 2015), respectively. The Be-Grow boost (L) hydrogel was applied at 44 kg $ha^{-1}$ (1 g per planting hole) (Yang et al., 2019) at a depth of 20 cm. Due to the limited amount of nutrients in biochar, zeolite and Be-Grow boost (L) hydrogel, they were complemented with synthetic fertilizers at a total application rate of 21 kg $ha^{-1}$ N, 31 kg $ha^{-1}$ P, 21 kg $ha^{-1}$ K and 6 kg $ha^{-1}$ S. Of the total synthetic fertilizer application rate, 50% was applied at transplanting and the other half as top dressing 6 weeks later. Additionally, the same application rates were used in the NPK treatment plots as the laboratory soil analysis recommended. The organic fertilizers (compost and HHB meal) and the control were not complemented with synthetic fertilizers.

The chemical properties of the applied soil amendments are presented in Table 5. Biochar, HH meal, B meal and zeolite were analysed for K, Zn, Na, Mn, Ca and Fe but not for pH, N and P. However, based on the literature, biochar has a pH level of 4.7–11.5 (Alburquerque et al., 2013; Hossain et al., 2020; Silva

**TABLE 4** Treatments for Experiments 1 and 2 comprising different soil amendments and irrigation regimes.

| Experiment 1 | | Experiment 2 | | |
|---|---|---|---|---|
| **Irrigation (Factor 1)** | **Soil amendment (Factor 2)** | **Irrigation** | **Soil amendment** | **Treatments** |
| Full (3 irrigation days week$^{-1}$) | Ctr | Full (5 irrigation days week$^{-1}$) | Ctr | Full Ctr |
| | NPK (21:31:21 + 6 [S] kg ha$^{-1}$ + Procote Zn) | | NPK (88:40:27 + 8 [S] kg ha$^{-1}$ + Procote Zn) | Full NPK |
| | Co (97 kg ha$^{-1}$) | | Co (24 t ha$^{-1}$) | Full Co |
| | Bio (20 t ha$^{-1}$) + NPK | | Bio + NPK | Full Bio |
| | HHB (2 t ha$^{-1}$) | | HHB (2.8 t ha$^{-1}$) | Full HHB |
| | Ze (14 t ha$^{-1}$) + NPK | | Ze + NPK | Full Ze |
| | Be (44 kg ha$^{-1}$) + NPK | | Be (88 kg ha$^{-1}$) + NPK | Full Be |
| Reduced (2 irrigation days week$^{-1}$) | Ctr | Reduced (4 irrigation days week$^{-1}$) | Ctr | Reduced Ctr |
| | NPK (21:31:21 + 6 [S] kg ha$^{-1}$ + Procote Zn) | | NPK (88:40:27 + 8 [S] kg ha$^{-1}$ + Procote Zn) | Reduced NPK |
| | Co (122 kg ha$^{-1}$) | | Co (24 t ha$^{-1}$) | Reduced Co |
| | Bio (20 t ha$^{-1}$) + NPK | | Bio + NPK | Reduced Bio |
| | HHB (2 t ha$^{-1}$) | | HHB (2.8 t ha$^{-1}$) | Reduced HHB |
| | Ze (14 t ha$^{-1}$) + NPK | | Ze + NPK | Reduced Ze |
| | Be (44 kg ha$^{-1}$) + NPK | | Be (88 kg ha$^{-1}$) + NPK | Reduced Be |

Abbreviations: Be, Be-Grow boost (L) hydrogel; Bio, biochar; Co, compost; Ctr, control; HHB, hoof and horn + bone meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite; Zn, zinc.

Gonzaga et al., 2019), HH meal of 6.1–7.9 (Möller & Schultheiß, 2015), B meal of 6.4–6.5 (Möller & Schultheiß, 2015) and zeolite of 7.1–8.0 (Sindesi & Ncube, 2021; Youssef, 2013). Furthermore, biochar has N concentrations of 0.3%–1.4% (Agegnehu et al., 2016; Vitkova et al., 2017), HH meal of 12%–15% (Nordi et al., 2022; Oluwafisayo & Olusegun, 2023), B meal of 3%–6% (Joshi, 2015; Oluwafisayo & Olusegun, 2023) and zeolite of 0.47–0.49 g kg$^{-1}$ (Głąb et al., 2021). Regarding P, biochar has a P concentration of 0.02%–0.5% (Silva Gonzaga et al., 2019), HH meal of 2% (Oluwafisayo & Olusegun, 2023), B meal of 12%–15% (Joshi, 2015; Oluwafisayo & Olusegun, 2023) and zeolite of 0.01% (Aainaa et al., 2018). The properties of NPK and Be-Grow boost (L) hydrogel amendments were not analysed.

In Experiment 2, the experimental area was not tilled. In addition to the increase in irrigation levels due to slightly poor cabbages produced in Experiment 1, the application rates of HHB meal and Be-Grow boost (L) hydrogel were increased to 2.8 t ha$^{-1}$ and 88 kg ha$^{-1}$ (2 g per transplanting hole), respectively. Furthermore, the synthetic fertilizer was also increased to a total application rate of 88 kg ha$^{-1}$ N, 40 kg ha$^{-1}$ P, 27 kg ha$^{-1}$ K and 8 kg ha$^{-1}$ S. For N, 15% was applied at transplanting, 70% as a top dressing 6 weeks later and the remaining 15% at Week 8 after transplanting. In the case of P and K, 50% of each was applied at transplanting and the remaining half as top dressing at Week 8 after transplanting. The compost application rate was reduced to 24 t ha$^{-1}$ (down from 97 t ha$^{-1}$ in Experiment 1) as plants performed poorly under the high application rate in Experiment 1. The application methods were the same for the respective amendments as in Experiment 1. Biochar and zeolite were not reapplied in Experiment 2; both biochar (Maroušek et al., 2017) and zeolite (Soudejani et al., 2019) are reported to remain stable in the soil for many years. The treatment details are shown in Table 4.

## 2.5 | Data collection

In both experiments, six plants from the two middle rows of each subplot were randomly selected for data collection. Cabbage head girths were measured at the head midcentre, and the cabbage heads from the selected plants were weighed. Other yield variables studied included the number of marketable heads extrapolated to a hectare. Furthermore, the number of marketable heads and the average head weight were used to calculate cabbage yield (t h$^{-1}$). Moreover, to evaluate the contribution

**TABLE 5** Chemical properties of soil amendments applied in Experiments 1 and 2.

| Soil amendment | pH | Nitrogen (%) | Phosphorus (%) | Available zinc (mg kg$^{-1}$) | Available potassium (mg kg$^{-1}$) | Available sodium (mg kg$^{-1}$) | Available manganese (mg kg$^{-1}$) | Available calcium (mg kg$^{-1}$) | Available iron (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| NPK | – | – | – | – | – | – | – | – | – |
| Co | 7.10 | 0.92 | 0.33 | 140.00 | – | 1906.00 | 199.00 | – | 4902.00 |
| Bio | – | – | – | 54.04 | 684.74 | 5147.13 | 47.71 | 21149.51 | 1003.78 |
| HH | – | – | – | 68.52 | 911.40 | 7654.81 | 9.41 | 62663.52 | 434.41 |
| B | – | – | – | 58.52 | 954.97 | 11525.23 | 6.18 | 97573.53 | 310.36 |
| Ze | – | – | – | 32.67 | 1359.26 | 1238.64 | 46.86 | 142428.26 | 1274.79 |
| Be | – | – | – | – | – | – | – | – | – |

Abbreviations: –, not analysed; B, bone meal; Be, Be-Grow boost (L) hydrogel; Bio, biochar; Co, compost; HH, hoof and horn meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

of a unit amount of water to cabbage yield, cabbage water use efficiency (WUE) was determined according to Terefa (2021) using the following formula:

$$\mathrm{TWUE} = \frac{T_{\mathrm{y}}}{T_{\mathrm{wu}}}, \tag{1}$$

where TWUE is the total WUE, kg ha$^{-1}$ mm$^{-1}$; $T_{\mathrm{y}}$ is the fresh cabbage head yield, t ha$^{-1}$; and $T_{\mathrm{wu}}$ is the total crop water consumption, mm ha$^{-1}$. WUE can be maximized by employing irrigation schedules that increase crop yield (Beshir, 2017).

### 2.6 | Statistical analysis

Quantitative agronomic data were subjected to a normality test to ascertain whether the data collected were normally distributed. Analysis of variance (ANOVA) was then run to test for significant differences among treatment means using General Statistics Software (GenStat 64-bit Release 20.1, PC/Windows 8–10). The treatment means were separated at a 5% least significant difference (LSD) for a significant difference. A split-plot model arranged in a randomized complete block design (RCBD) was applied for the ANOVA as follows:

$$y_{\mathrm{hik}} = \mu + b_{\mathrm{h}} + w_{\mathrm{i}} + \varepsilon(1)_{\mathrm{hi}} + s_{\mathrm{k}} + (w \times s)_{\mathrm{ik}} + \varepsilon(2)_{\mathrm{hik}}, \tag{2}$$

where $y_{\mathrm{hik}}$ denotes the response variables (head girth, marketable head weight, total marketable heads, yield and WUE), $\mu$ denotes the grand mean of each response parameter, $b_{\mathrm{h}}$ denotes the differences between the blocks/replicates, $w_{\mathrm{i}}$ denotes the irrigation level (whole plot) effect, $\varepsilon(1)_{\mathrm{hi}}$ denotes the irrigation level (whole plot) error, $s_{\mathrm{k}}$ represents the soil amendment (subplot) effect, $(w \times s)_{\mathrm{ik}}$ represents the interaction effect between irrigation levels and soil amendments, and $\varepsilon(2)_{\mathrm{hik}}$ represents the error for the irrigation level and soil amendment interaction effect.

## 3 | RESULTS

### 3.1 | Parametric ANOVA

ANOVA showed that in Experiment 1 the difference in irrigation levels had a significant effect on cabbage head girth ($p \leq 0.05$), single head weight ($p \leq 0.01$) and yield ($p \leq 0.001$) (Table 6). However, there was no significant effect on cabbage number of marketable heads and WUE due to the difference in irrigation (Table 6). In addition, the different soil amendments had a significant effect on cabbage head girth ($p \leq 0.01$), number of

**TABLE 6** Mean of square values and significance test of six soil amendments on cabbage performance under two irrigation regimes.

| Source of variation | DF | Head girth (cm) | Single head weight (kg) | No. of marketable heads ha$^{-1}$ | Yield (t ha$^{-1}$) | WUE (kg ha$^{-1}$ mm$^{-1}$) |
|---|---|---|---|---|---|---|
| Experiment 1 | | | | | | |
| Rep | 2 | 52.31 | 0.0872 | 173,000,340 | 289.96 | 3502.40 |
| Irrigation | 1 | 85.71* | 0.339** | 51,548,593 ns | 433.00*** | 0.10 ns |
| Error (a) | 2 | 0.93 | 0.00215 | 10,067,745 | 0.21 | 96.50 |
| Amendment | 6 | 34.25** | 0.0284 ns | 114,313,524*** | 159.14* | 1592.40* |
| Irrigation: amendment | 6 | 12.99 ns | 0.0255 ns | 12,161,299 ns | 49.94 ns | 308.70 ns |
| Error (b) | 24 | 8.87 | 0.0187 | 20,229,890 | 45.91 | 454.90 |
| Experiment 2 | | | | | | |
| Rep | 2 | 53.96 | 0.284 | 121,801,106 | 1018.90 | 8605.00 |
| Irrigation | 1 | 7.71 ns | 0.122 ns | 39,969,161 ns | 311.80 ns | 457.00 ns |
| Error (a) | 2 | 15.37 | 0.0520 | 9,312,790 | 46.00 | 536.00 |
| Amendment | 6 | 75.17*** | 0.363*** | 132,328,062*** | 701.30** | 5746.00** |
| Irrigation: amendment | 6 | 12.66 ns | 0.0990 ns | 60,245,383** | 252.90 ns | 2026.00 ns |
| Error (b) | 24 | 10.45 | 0.0670 | 13,902,077 | 146.00 | 1202.0 |

Abbreviations: ns, not significant; WUE, water use efficiency.
*Denotes significance at the $p \le 0.05$ significance level for each experiment.
**Denotes significance at the $p \le 0.01$ significance level for each experiment.
***Denotes significance at the $p \le 0.001$ significance level for each experiment.

marketable heads ($p \le 0.001$), yield ($p \le 0.05$) and WUE ($p \le 0.05$) but not on single head weight. The interaction between irrigation levels and soil amendments did not significantly affect cabbage yield or yield components (Table 6).

In Experiment 2, ANOVA showed that the two irrigation levels had similar effects on cabbage yield and yield components. The different soil amendments showed a significant impact on cabbage head girth ($p \le 0.001$), single head weight ($p \le 0.001$), number of marketable heads ($p \le 0.001$), yield ($p \le 0.01$) and WUE ($p \le 0.01$) (Table 6). Additionally, the interaction between irrigation levels and soil amendments had a considerable impact on the number of marketable heads ($p \le 0.01$) (Table 6).

## 3.2 | Effect of irrigation levels on yield and its components

For Experiment 1, the results indicated that cabbages under full irrigation had significantly larger head girths of 41.2 cm compared with 38.4 cm under the reduced-irrigation treatment and produced considerably heavier heads (0.927 kg) compared with 0.747 kg under the reduced-irrigation treatment (Figure 3). Most importantly, plots under the full-irrigation treatment produced a significantly higher yield (21.1 t ha$^{-1}$) than the 14.7 t ha$^{-1}$ recorded under reduced irrigation. In addition, the results showed that the full-irrigation treatment had 6% larger cabbage head girths and produced 22% heavier cabbage heads than the reduced-irrigation treatment (Figure 3). Furthermore, full irrigation gave a 44% higher yield than reduced irrigation.

In Experiment 2, no significant differences were observed between irrigation levels on all parameters; however, except for head girth, full irrigation slightly outperformed reduced irrigation on all parameters (Table 6 and Figure 4).

## 3.3 | Effect of soil amendments on cabbage performance

In Experiment 1, biochar significantly affected cabbage head girths (42.7 cm) (Figure 5). In addition, the comparison of mean data showed that biochar produced a 15% larger cabbage head girth than the control, which had the smallest head girth of 37.8 cm (Figure 5). Furthermore, the results indicated that biochar, Be-Grow boost (L) hydrogel, zeolite and NPK had significantly the highest and statistically similar numbers of marketable heads of 24,884, 23,958, 22,801 and 22,454 heads ha$^{-1}$, respectively. Biochar produced 90% more marketable heads than the control (Figure 5). Moreover, the mean values showed that zeolite, biochar and Be-Grow boost

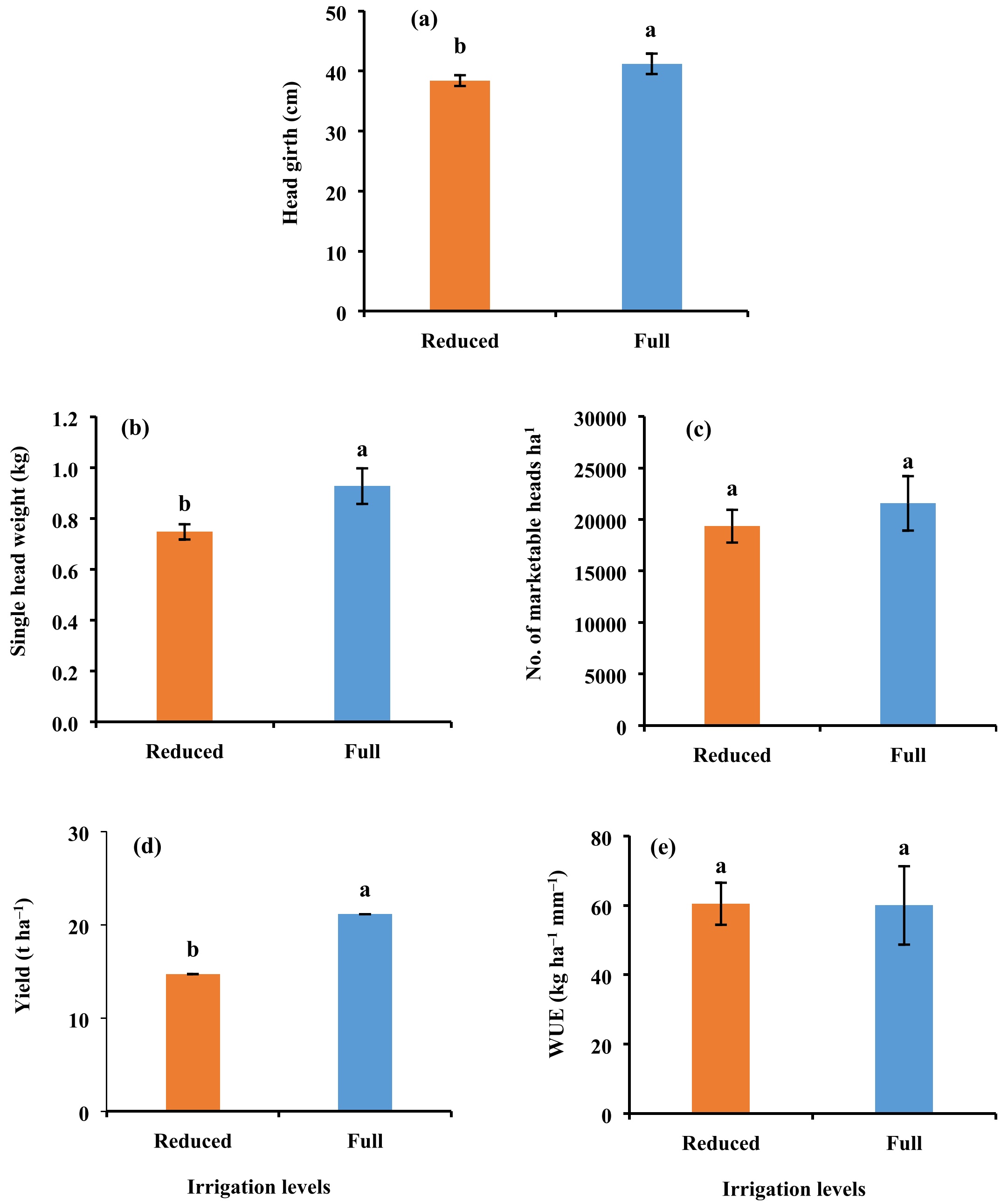


FIGURE 3 Effect of irrigation levels on cabbage yield and yield components in Experiment 1. Panels (a)–(e) represent cabbage head girth, single head weight, number of marketable heads, yield and water use efficiency (WUE), respectively. Bars with different letters on each graph indicate significant differences by Fisher's protected least significant difference (LSD) at 5% probability level.

(L) hydrogel produced the highest and statistically similar yields of 22.7, 22.6 and 22.3 t ha$^{-1}$, respectively. Equally important, biochar had the highest WUE of 76.0 kg ha$^{-1}$ mm$^{-1}$ (113% higher than the control), although it was similar to zeolite and Be-Grow boost (L) hydrogel at 74.3 and 74.4 kg ha$^{-1}$ mm$^{-1}$, respectively. Zeolite produced 102% more yield than the control. The different soil amendments did not significantly influence cabbage head weight. Notably, HHB meal produced smaller, lighter heads than the control (Figure 5).

In Experiment 2, HHB meal, Be-Grow boost (L) hydrogel, biochar and compost had the largest and statistically similar cabbage head girths of 62.57, 59.28, 58.95 and 58.12 cm, respectively (Figure 6). The mean data comparison indicates that the HHB meal produced 22% larger cabbage head girths than the control. In addition, HHB meal, followed by biochar and Be-Grow boost (L) hydrogel, produced the heaviest heads of 1.91, 1.69 and 1.66 kg, respectively. The mean data comparison indicates that the cabbage heads under HHB meal were

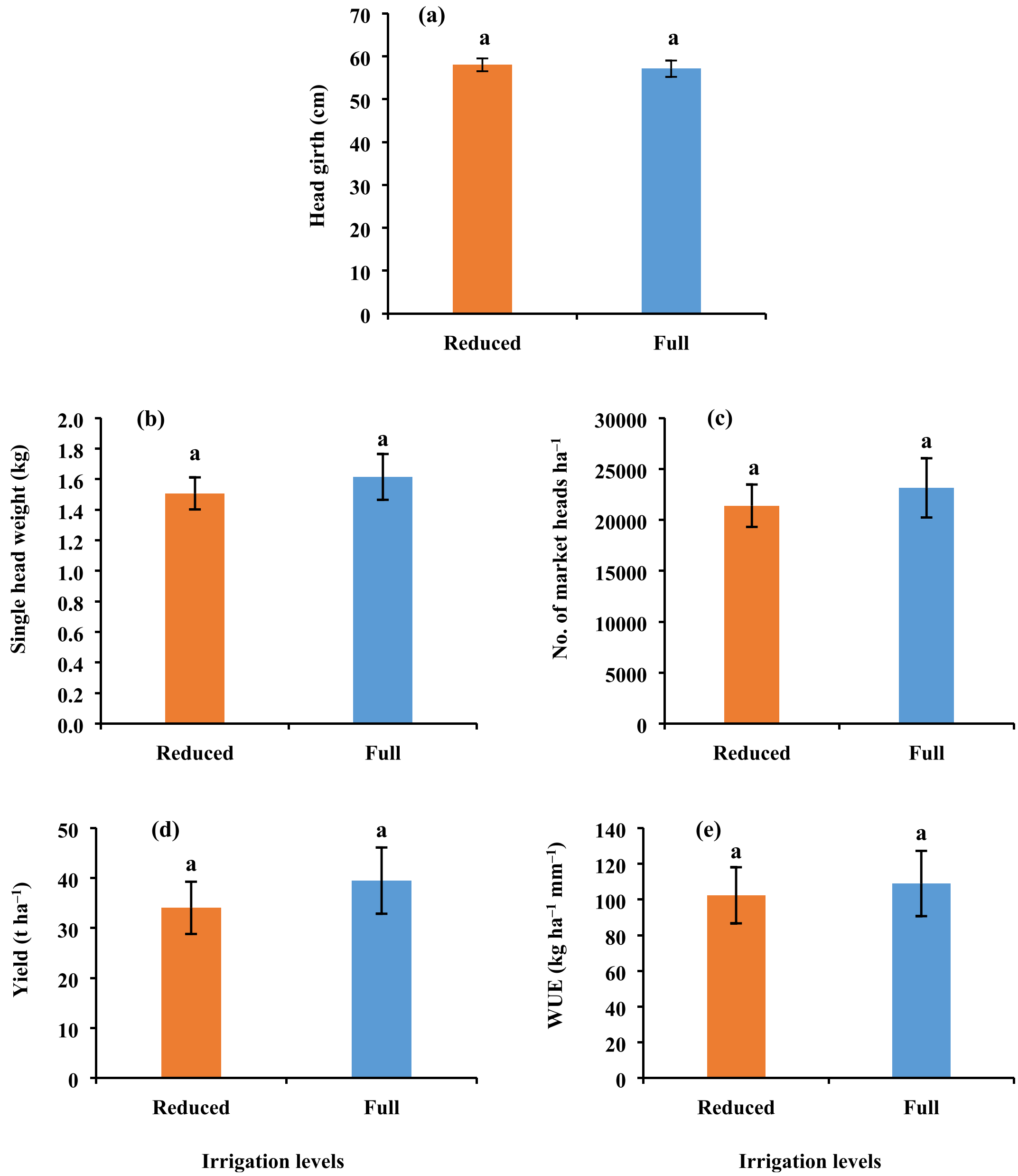


FIGURE 4 Effect of irrigation levels on cabbage yield and yield components in Experiment 2. Panels (a)–(e) represent cabbage head girth, single head weight, number of marketable heads, yield and water use efficiency (WUE), respectively. Bars with different letters on each graph indicate significant differences by Fisher's protected least significant difference (LSD) at 5% probability level.

72% heavier than those in the control. Furthermore, the Be-Grow boost (L) hydrogel, followed by HHB meal and biochar, produced the highest and statistically similar number of cabbage marketable heads of 27,489, 25,296 and 25,296 heads ha$^{-1}$, respectively, where the Be-Grow boost (L) hydrogel treatment produced 85% more marketable heads than the control.

Most importantly, HHB meal had the highest cabbage yield of 49.5 t ha$^{-1}$, 188% more than that of the control treatment. Similarly, HHB meal had the highest WUE of 143.3 kg ha$^{-1}$ mm$^{-1}$, 184% more than that of the control (Figure 6).

## 3.4 | Effect of irrigation levels and soil amendment interaction on cabbage performance

The treatment interaction effects for Experiment 1 are illustrated in Figure 7. The results showed no

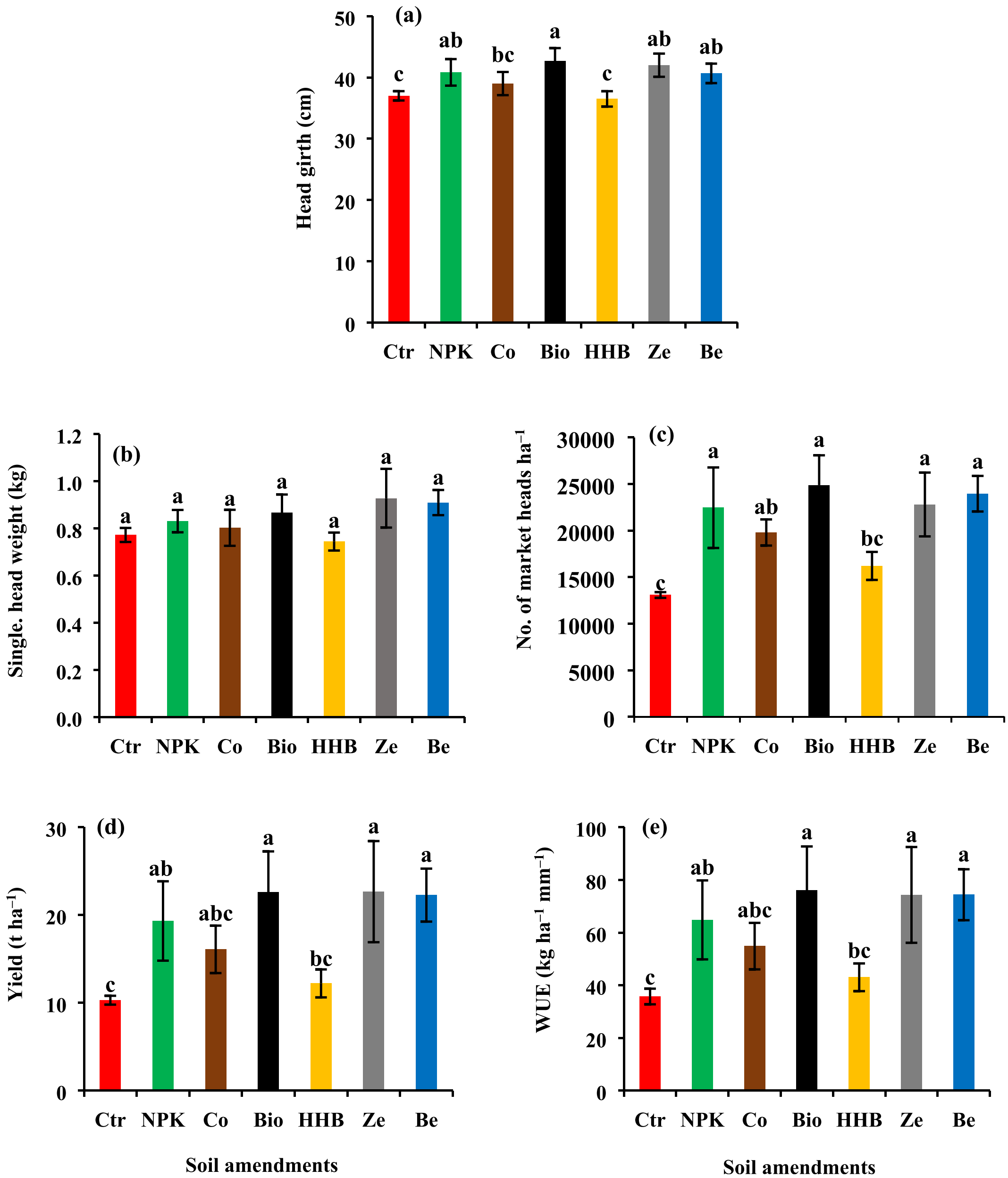


**FIGURE 5** Cabbage yield and yield components as influenced by different soil amendments in Experiment 1. Panels (a)–(e) represent cabbage head girth, single head weight, number of marketable heads, yield and water use efficiency (WUE), respectively. Bars with different letters on each graph indicate significant differences by Fisher's protected least significant difference (LSD) at 5% probability level. Be, Be-Grow boost (L) hydrogel; Bio, biochar; Co, compost; Ctr, control; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

significant interaction between different irrigation levels and soil amendments on all parameters (Table 6 and Figure 7). However, full irrigation with zeolite, Be-Grow boost (L) hydrogel, biochar and NPK performed slightly better on all parameters than other treatments (Figure 7).

Figure 8 shows the interactive effect of irrigation levels and soil amendments on cabbage performance for Experiment 2. The results indicated that Be-Grow boost (L) hydrogel under full irrigation, followed by HHB meal under reduced irrigation, NPK under full irrigation and biochar under full irrigation produced the statistically highest and similar number of marketable heads of 28,935, 28,703, 28,009 and 27,546 heads $ha^{-1}$, respectively. The lowest number of marketable heads was recorded under the fully irrigated control, totalling 9028 heads $ha^{-1}$. The fully irrigated Be-Grow boost (L) hydrogel produced 220% more marketable cabbage heads than the fully irrigated control (Figure 8). There was no significant interactive effect of irrigation with different soil amendments on cabbage head girth, head weight, yield or WUE (Table 6 and Figure 8).

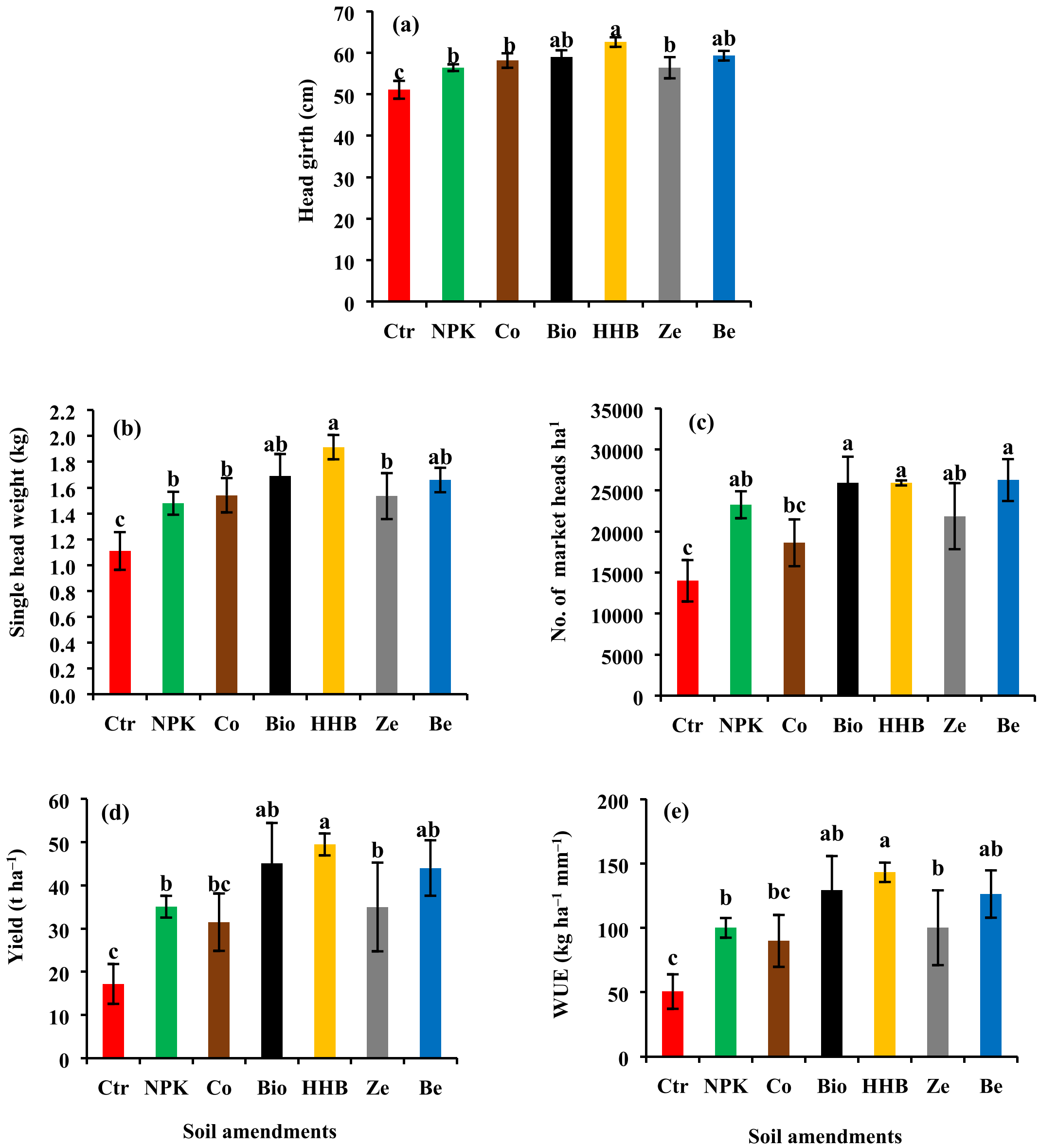


FIGURE 6 Cabbage yield and yield components as influenced by different soil amendments in Experiment 2. Panels (a)–(e) represent cabbage head girth, single head weight, number of marketable heads, yield and water use efficiency (WUE), respectively. Bars with different letters on each graph indicate significant differences by Fisher's protected least significant difference (LSD) at 5% probability level. Be, Be-Grow boost (L) hydrogel; Bio, biochar; Co, compost; Ctr, control; HHB, hoof and horn + bone meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

# 4 | DISCUSSION

## 4.1 | Cabbage performance under different irrigation levels and soil amendments

This study aimed to determine the specific soil amendment(s) that can improve cabbage performance under different irrigation levels. In Experiment 1, the results showed that full irrigation produced significantly larger and heavier cabbage heads and higher cabbage yields (Figure 3). The positive effect of full irrigation on cabbage performance can be attributed to the sufficient availability of water, which facilitated the dissolution and subsequent absorption of more nutrients by the plant roots. On the other hand, the negative impact of reduced irrigation may be attributable to reduced development and elongation of cells and tissues in different plant organs, especially in leaves and stems, due to limited nutrition. Thus, the impact of reduced irrigation can be noticed when plants are stunted, with a reduced leaf area due to a decrease in total photosynthetic capacity, which is reflected negatively in yield. These results are similar to those of (Büyükcangaz, 2018; Kumar & Sengar, 2013;

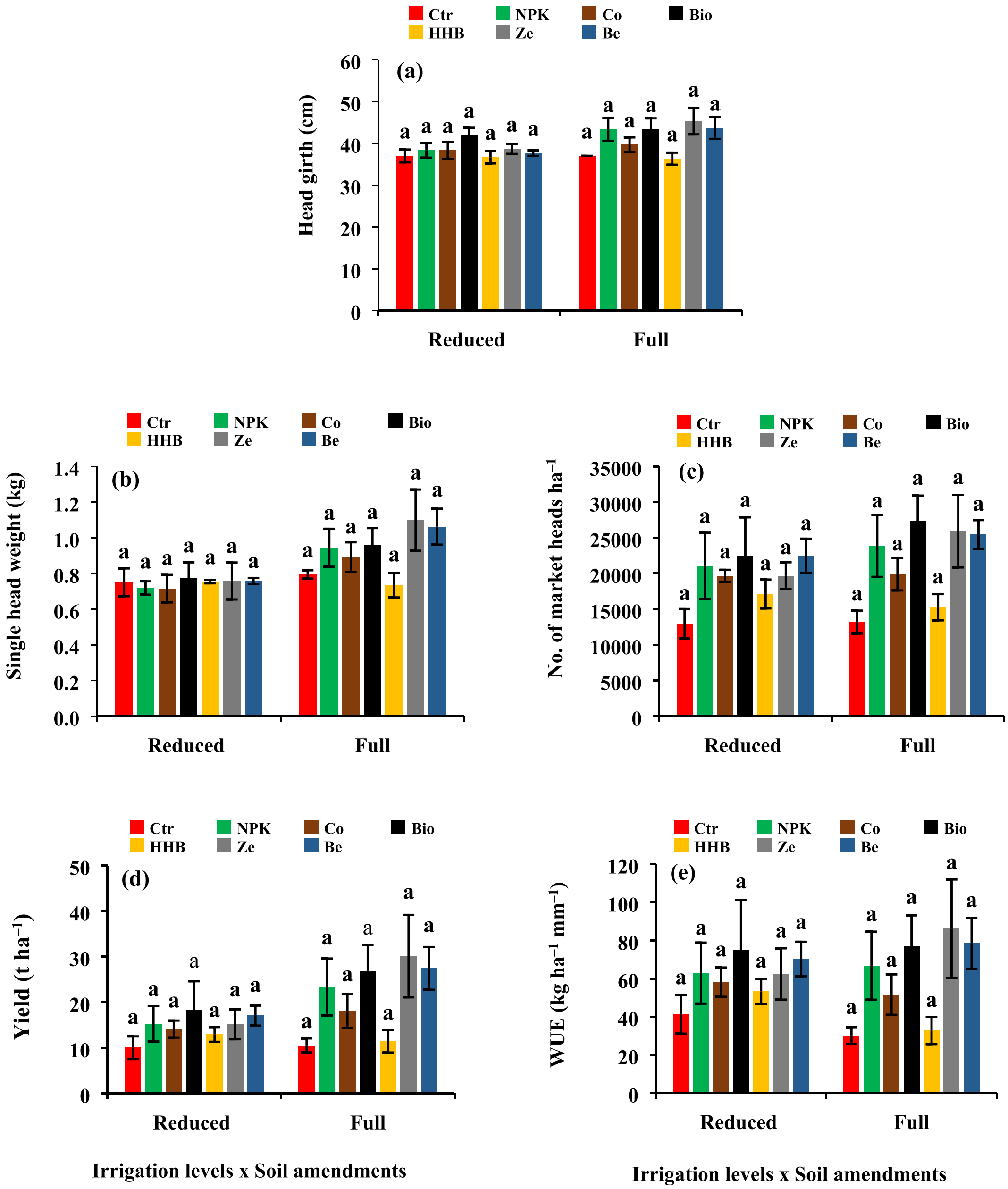


FIGURE 7 Interactive effect of irrigation levels and soil amendments in Experiment 1. Panels (a)–(e) represent cabbage head girth, single head weight, number of marketable heads, yield and water use efficiency (WUE), respectively. Bars with different letters on each graph indicate significant differences by Fisher's protected least significant difference (LSD) at 5% probability level. Be, Be-Grow boost (L) hydrogel; Bio, biochar; Co, compost; Ctr, control; HHB, hoof and horn + bone meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

Xu & Leskovar, 2014). For instance, Büyükcangaz (2018) and Kumar and Sengar (2013) reported that the fully irrigated cabbage plots produced a significantly higher yield, head girth and head weight compared with the least irrigated cabbage.

Furthermore, Experiment 1 showed that plots treated with biochar, Be-Grow boost (L) hydrogel and zeolite had significantly higher cabbage yield and yield parameters (Figure 5). This could suggest that these amendments positively impact soil nutrients and water-holding capacities more than others studied. Notably, although biochar-treated soil had more marketable heads than zeolite, zeolite slightly outperformed biochar in yield due to slightly heavier heads (Figure 5). The positive effect of biochar, Be-Grow boost (L) hydrogel and zeolite on crop performance, including that of cabbage, wheat and maize, has also been previously reported by other researchers (Khalid Abdulrahman et al., 2020; Singh

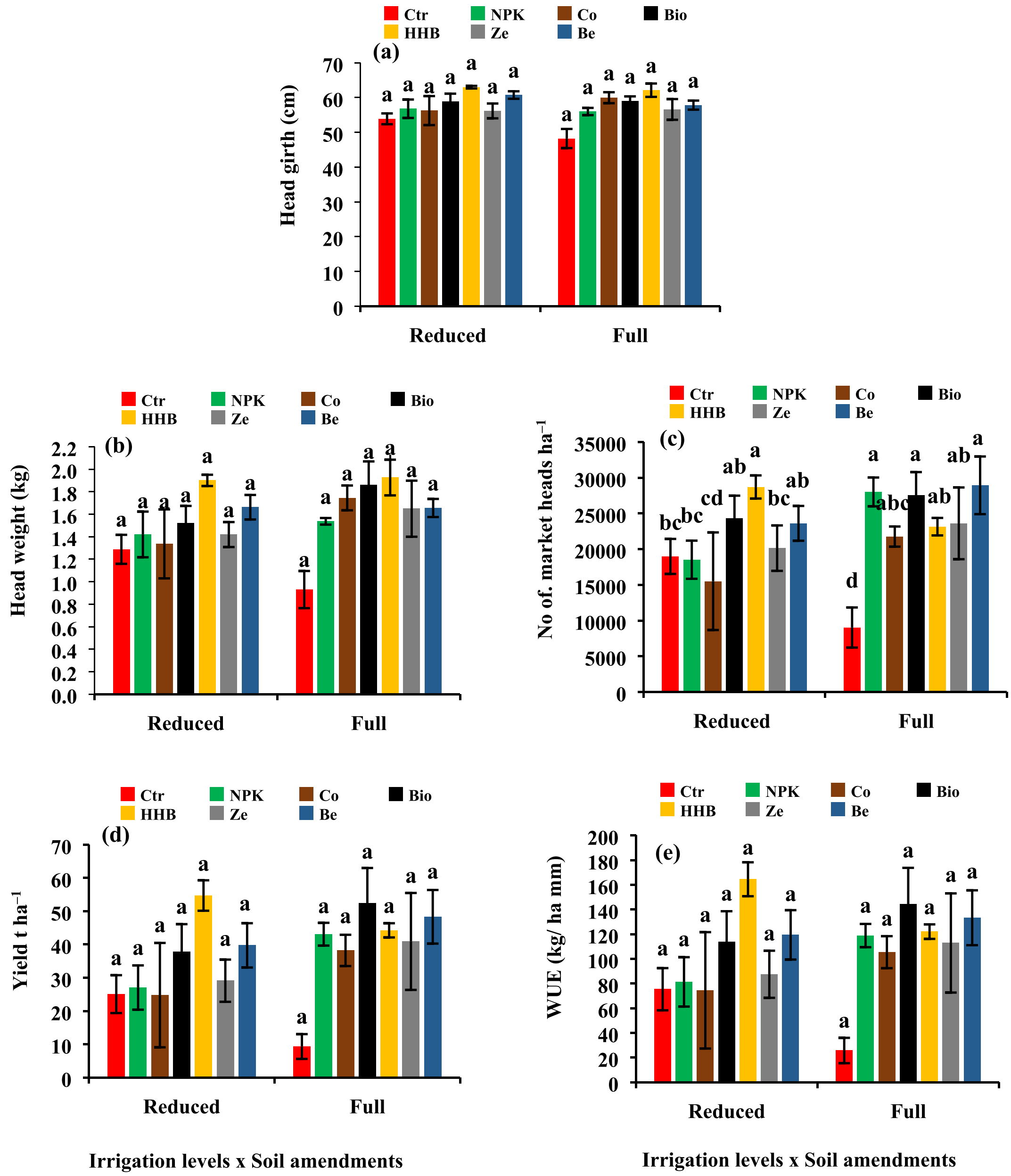


FIGURE 8 Interactive effect of irrigation levels and soil amendments for Experiment 2. Panels (a)–(e) represent cabbage head girth, single head weight, number of marketable heads, yield and water use efficiency (WUE), respectively. Bars with different letters on each graph indicate significant differences by Fisher's protected least significant difference (LSD) at 5% probability level. Be, Be-Grow boost (L) hydrogel; Bio, biochar; Co, compost; Ctr, control; HHB, hoof and horn + bone meal; NPK, nitrogen, phosphorus and potassium; Ze, zeolite.

et al., 2019). For instance, McDonald et al. (2019) found that the application of biochar significantly improved cabbage yield compared with the control. In a study by Agegnehu et al. (2016) on the effect of biochar, compost and biochar + compost on maize performance, the results showed that the application of biochar significantly improved maize grain yield as well as the total biomass yield compared with the control. Likewise, Singh et al. (2019) found that applying biochar significantly improved wheat grain yield, straw yield and water productivity. Biochar has a good nutrient retention capacity and improves soil properties, improving crop production (Hossain et al., 2020).

On hydrogel polymer, Naik et al. (2020) reported that applying hydrogel significantly improved the caster's number of capsules and subsequently increased the overall seed yield by 43%. Similarly, Dorraji et al. (2010) found that applying a superabA200 polymer resulted in significantly higher root and aboveground biomass and WUE of corn in both loamy sandy soil and sandy clay loam soil.

Hydrogels improve crop growth and yield by holding more water for extended periods (Naik et al., 2020).

Regarding zeolite, Sindesi and Ncube (2021), in their study on cabbage and Swiss chard yield responses in zeolite-amended sandy soil, found that zeolite significantly improved both cabbage and Swiss chard dry matter yields. Similarly, Zheng et al. (2018) reported that zeolite significantly improved rice grain yield, effective panicles, spikelets per panicle and 1000-grain weight. Zeolites improve N use efficiency and crop yields (Zheng et al., 2018) by acting as a chemical sieve, allowing ions to pass through and blocking some (Hazrati et al., 2017).

In Experiment 2, the irrigation difference did not significantly affect cabbage performance (Figure 4), likely due to a slight difference between the amount of water applied under the two irrigation levels. However, in this experiment, treating the soil with HHB meal, biochar and Be-Grow boost (L) hydrogel significantly improved cabbage performance (Figure 6). The crop performance under biochar-treated plots reflects the amendment's relatively low pH and high levels of other chemical characteristics (Tables 2 and 3). Although plots treated with Be-Grow boost (L) hydrogel and biochar produced statistically more marketable heads than those treated with HHB meal, the HHB meal-treated plots produced significantly higher cabbage yields as the cabbage heads under this treatment were slightly heavier. The excellent effect of HHB meal could be attributed to its accumulation in the soil over the preceding experiment. HHB meal is a slow-release organic fertilizer as its decomposition takes longer than other amendments (Jain, 2019; Joshi, 2015; Peter et al., 2019). Thus, it has a high nutrient use efficiency due to its consistent level of releasing nutrients over time, mainly influenced by soil moisture and temperature (Jain, 2019).

Compared with other amendments, the poor performance of zeolite in Experiment 2 (Figure 6) could be due to the poor structural behaviour of zeolite over time. In this regard, Sindesi and Ncube (2021) noted from their study investigating the influence of zeolite on irrigation water requirement over two growing seasons that the water requirement of the zeolite-amended soil significantly exceeded that of the control in the second season, unlike in the first season where a reduction in water requirement with an increased application of zeolite was observed. Since zeolite was applied in granule form (± 1 cm in diameter) in the present study, it could be ideal to apply the amendment in powder form to increase the soil surface area and water-holding capacity; thus, further study is needed.

Furthermore, Be-Grow boost (L) hydrogel, NPK and biochar under full irrigation and HHB meal under reduced irrigation produced significantly more marketable heads (Figure 8). The interactive effect of full irrigation with Be-Grow boost (L) hydrogel and biochar reflects a relatively high available P amount in the two treatments (Tables 2 and 3), which leads to faster growth and larger cabbage heads (Malhotra et al., 2018) compared with the other amendments. NPK reflects a higher CEC, suggesting that more applied nutrients were available to the plants in the sole NPK amendment than in the other tested soil treatments.

The positive effect of the interaction between full irrigation and different soil amendments is widely documented. For instance, Badawi et al. (2020) reported from a two-season study that the interaction between the 100% irrigation requirement and pressed olive cake gave a significantly higher pepper yield and fresh and dry shoot weights compared with the 60% irrigation requirement in the control treatment. Moreover, 100% of the irrigation requirement with pressed olive cake produced significantly taller plants and more leaves than 60% of the irrigation requirement in the control treatment. Increasing irrigation water leads to faster and more vigorous plant growth, resulting in improved yield.

Another study by Ibrahim et al. (2011) on the effect of irrigation levels and rice straw compost applications on the yield, chemical composition and WUE of cabbage (*B. oleracea* var. *capitata* L.) found that the application of 10 t/fed rice straw compost under irrigation of 65% and 55% of the soil water-holding capacity (full irrigation) resulted in a significant improvement in marketable cabbage yield, head weight and head girth, while the lowest performance was observed under reduced irrigation (45% water-holding capacity), where no rice straw compost was added.

The excellent performance of HHB meal under the reduced-irrigation treatment could be attributed to less leaching than under the full-irrigation treatment, where leaching could have been more intense, leading to more of the applied fertilizer, especially N, being more available for plant uptake under the reduced-irrigation treatment (Ibrahim et al., 2011). Considering the more positive effect of HHB meal (organic fertilizer) than NPK (synthetic fertilizer), HHB meal could be an alternative to synthetic fertilizer for organic crop production. Similarly, HHB meals could supplement soil conditioners with poor plant nutrients, such as biochar, instead of synthetic fertilizers.

## 5 | CONCLUSION

The results of the present study provide crucial knowledge regarding the effectiveness of soil amendment application on cabbage production in the semi-arid central part of Namibia. The results showed that plots treated with biochar and Be-Grow boost (L) hydrogel consistently produced the highest cabbage yield and number of marketable heads. In contrast, HHB meal-treated plots showed the potential to produce the highest total yield and number of marketable heads when applied over time, from one season to another. Fully irrigated Be-Grow boost (L) hydrogel, NPK, biochar and moderately irrigated HHB meal treatments positively impacted marketable cabbage heads. However, further research should be carried out on the combined application of organic soil amendments, such as biochar + HHB meal, for organic production. More research is also needed to determine the effective application technique(s) of zeolite in semi-arid Central Namibian soil.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

## ORCID

*Kuume B. P. Enguwa* https://orcid.org/0009-0006-3116-3656
*Lydia N. Horn* https://orcid.org/0000-0001-6962-3300
*Simon K. Awala* https://orcid.org/0000-0001-5244-519X

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