Effect Of Soil Amelioration and Organic Amendments on Soil and Crop Attributes On Sandy Duplex Soil With Multiple Constraints

Hassan Sardar[1], Richard Bell[1], Luca De Prato[1], David Minkey[3], Veronika Crouch[2], Joy Valle[2]

[1]Centre for Sustainable Farming Systems, Future Food Institute, Murdoch University, 90 South St, Murdoch WA 6150

[2]Corrigin Farm Improvement Group, PO Box 2, Corrigin WA 6375

[3]WANTFA, 65 Brockway Road Floreat WA 6014

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1. Introduction

1.1. Background

Many paddocks in the WA Wheatbelt have multiple constraints, including non-wetting, soil acidity and compaction. Increasing the productivity on these paddocks often involves physical amelioration and chemical amendments to fix the problem. There is more and more interest in adding organic amendments to increase soil health and productivity. There is limited evidence on the impact these modern farming methods have on soil carbon levels, soil health and productivity.

The trial is aimed at evaluating a range of organic and inorganic amendment options along with soil amelioration (deep ripping) available to farmers to increase soil organic matter. While most amendments or amelioration methods have been evaluated in isolation, this trial site will evaluate the stacking of many combinations of amendments and amelioration methods to try and address multiple soil constraints. The hypothesis is that the synergistic benefits of multiple amendments will lead to a long-term increase in soil health and crop grain yield.

The soil on the field experiment site is a typical duplex with shallow bedrock (roughly 50 cm depth plus). The 1990-2023 rainfall data retrieved from various weather stations in 30 km radius of the experimental site (Fig. 2A) show that the average total annual rainfall for the mentioned period is 327 mm/year ranging from 466 mm in 1990 to 189 mm in 2010. However, the average total annual rainfall for the last 9 years (2015-2023) is 393 mm/year (Fig. 2B) as per the data retrieved from the Kweda weather station of the Western Australian Department of Primary Industries and Regional Development (DPIRD) which is 12 km away from the experimental site.

1.2. Key messages

New approaches, such as incorporating soil amendments, could decrease subsoil constraints and increase water use efficiency by raising soil organic matter and availability of nutrients by increasing subsoil aluminium toxicity, leading to increased soil carbon and soil water retention and crop health, biomass and yield.

1.3. Trial Location: Jeff Edwards Property Kweda, East Pingelly 6308 WA (-32.251° S; 117.24168° E).

1.4. CFIG's contribution: The site has been sub-contracted to the Corrigin Farm Improvement Group (CFIG) working closely with the researchers, growers and farmers in the Corrigin region of Western Australia. CFIG has been looking after the experiment by measuring, recording and reporting various data and information regarding the crop health, growth and productivity such as NDVI via a hand-based device, weeds and plants count, yield etc.

2. Methodology

A detailed study aiming at testing the effect of soil amendments on soil fertility and crop health on duplex sandy soils with low pH and multiple subsoil constraints (Al toxicity, low fertility and possibly compaction, water logging), was conducted at the Jeff Edwards's farm (farm area: 500 m × 250 m) at South Kweda Rd, Pingelly 6306, WA 32°25'16.1"S 117°24'16.8"E. To investigate the potential amelioration on a soil with multiple constraints, a series of amendments were incorporated with a Bednar Terralander on the large plots experiment and small plots experiment (Tables 1-2, Fig.1) in the first year of study, i.e., in 2022. The total experimental area was divided into four blocks (Fig. 1). Each block was divided into seven large plots (250 m × 18 m). Six out of seven plots in each block were utilised to execute the large plot trial with 5 treatments (including control) while control was assigned to two plots in each block (Fig. 1 and Table 2). One out of seven large plots in each block was divided into sub-plots (18 m × 2 m) which were utilised for the small plots trial with 12 treatments (Fig. 1 and Table 2). Each treatment in each experiment was replicated four times in a randomized way using four blocks (Fig. 1 and Table 2). Unripped soil with no soil amendments was used as control in the large plots trial. While soil inverted with Bednar terralander was used as control in the small plots trial. See table 1-2 and Fig.1 for further details regarding the treatments used in each trial.

Table 1. Description of the novel amendments utilised in small plots experiments (applied in 2022).

Novel soil amendments	Description	Novel soil amendments	Description
Hydrotalcite	A MgAl hydrocarbonate positively charged clay	Rescaype	increase water retention and soil carbon
Agrisilica	Natural fertiliser with a silica base: high CEC and water holding capacity	Carbon Ag	Pelletised clay/gypsum: increase soil nutrient uptake and biological activities
Ironman gypsum	Enhanced gypsum high P binding capacity	C-Wise compost	Humiclay compost + bentonite (~5%)
Zeolite	Aluminosilicate mineral: high absorbency and CEC		

Table 2. Soil treatments utilised in the small plots & large plots experiment at Kweda, WA.

Treatment No.	Treatment	Shade	Trial
1	Control - Unripped		Large plots
2	Bednar only		Large plots
3	Bednar + Gypsum (1.1 t/ha)		Large plots
4	Bednar + C-wise humiclay compost (5 t/ha)		Large plots
5	Bednar + Gypsum (1.1 t/ha) + C-wise humiclay compost (5 t/ha)		Large plots
6	Small Plots + Bednar		Entire Small plots area
7	Hydrotalcite (7 t/ha)		
8	Agrisilica Chip (0.15 t/ha)		Small plots
9	ironman gypsum (15 t/ha)		Small plots
10	Zeolite (30 t/ha)		Small plots
11	Small Plot Control - Bednar only		Small plots
12	Ryscape (0.1 t/ha)		Small plots
13	Carbon Ag (lime/gypsum) (2 t/ha)		Small plots
14	Compost high rate (10 t/ha)		Small plots
15	Compost low rate (2 t/ha)		Small plots
16	Compost med rate (5 t/ha)		Small plots
17	Zeolite (10 t/ha)		Small plots
18	ironman gypsum (5 t/ha)		Small plots
2	Buffers and Bendar only		Small plots

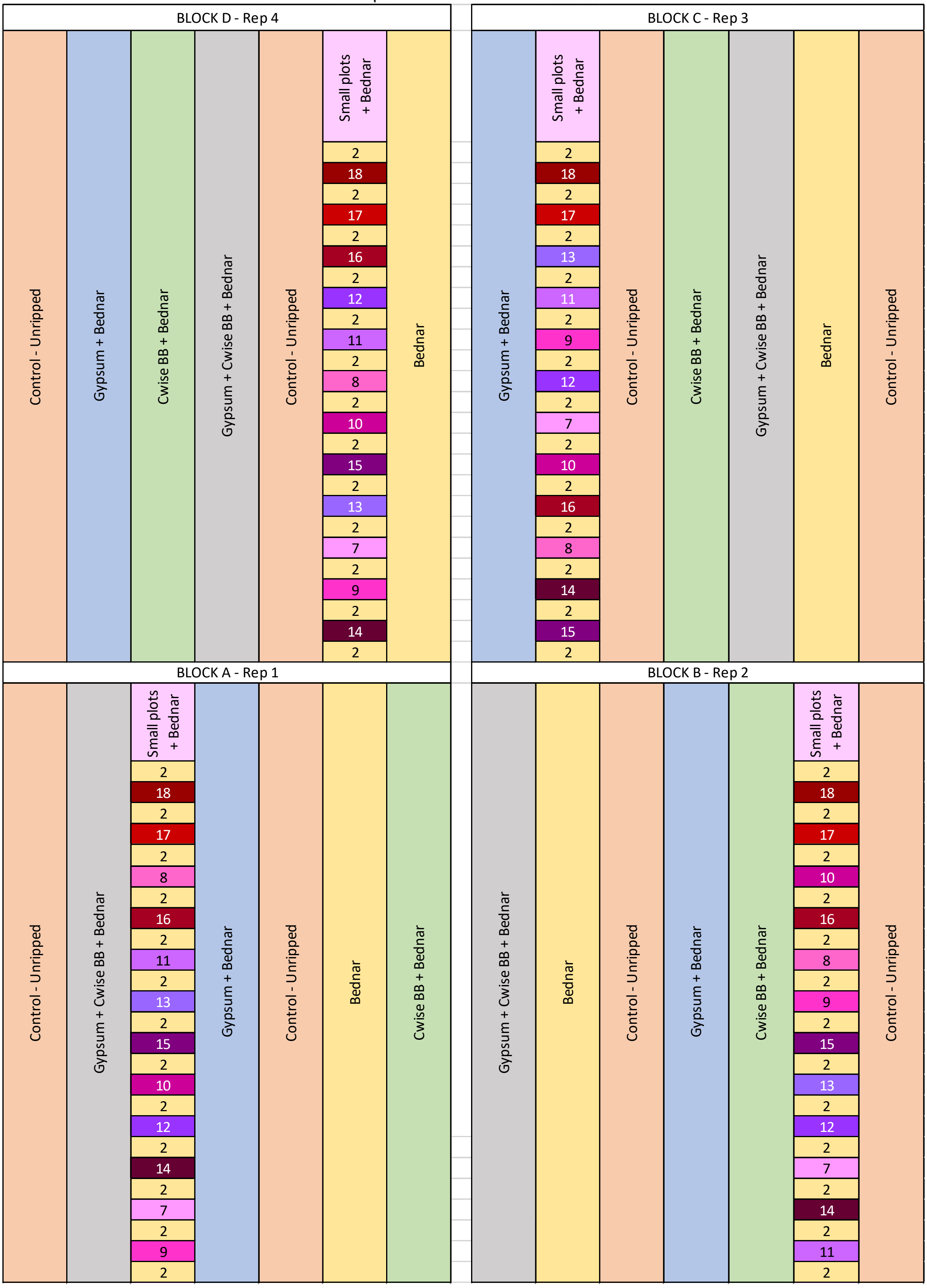


Fig. 1. Experimental lay out and treatment structure of trials conducted at Kweda, WA during 2023. Each small plot was treated with the Bednar along with the other treatment.

2.1. Inputs used in 2022

Lime was applied to the entire site at the rate of 1.2 t/ha as a one-off treatment 3-4 months before the start of the trial in 2022.

2.1.1. Seeding: Barley (*cv.* Scope) was seeded @ 70 kg/ha on 11th May 2022 using a seeder having 16 m bar with knives and pressed wheels (25 cm between rows).

2.1.2. Fertilisers application before seeding: On 1st May 2022 (before seeding), Muriate of Potash was applied @ 50 kg/ha (K @ 24.75 kg/ha).

2.1.3. Fertilisers application at seeding (11th May 2022): Nutrien's Bulk N solution (42% N) was applied at the time of seeding @ 60L/ha. Muriate of Potash was applied @ 25.5 kg/ha (K @ 12.62 kg/ha). Crop Builder 16 was applied @ 59.5 kg/ha (N @ 7.97 kg/ha, P @ 9.52 kg/ha, S @ 4.11 kg/ha).

In season fertilisers: On 1st July 2022, Cereal Plus (containing 57 g/L N, 123 g/L P, 35 g/L K, 28 g/L S, 21 g/L Mg, 18 g/L Zn, 27 g/L Mn, 3.1 g/L Cu, 2.8 g/L Fe, 3.0 g/L B, 0.1 g/L Co, 0.2 g/L Mo) was applied @ 2 L/ha.

On 24th June 2022, Nutrien's Bulk N solution (42% N) was applied @ 50L/ha. Another dose of Nutrien's Bulk N solution (42% N) was applied @ 60L/ha on 12th August 2022 followed by a 30 L/ha application of Bulk N solution on 20th August 2022.

2.1.4. Herbicides and fungicides used: 1st knockdown was applied on 20th April 2022 (3 weeks before seeding). 2nd knockdown was applied on 8th May 2022 (3 days before seeding). 3rd knockdown was applied on 10th May 2022 (a day before seeding). Invertix herbicide along with other herbicides was applied on 1st July 2022 (7 weeks after seeding) to control wild radish and other weeds (Table 3). Maxentis EC fungicide was applied on 20th August 2022 (14 weeks after seeding) to control fungal diseases. Details of the herbicides and fungicides used in 2022 are given in table 3.

Table 3. Details of the herbicides/fungicides used in 2022 cropping season.

Name of chemical	Active ingredients	Rate of application	Time of application
Roundup Ultra Max Herbicide	Glyphosate as Potassium Salt	1 L/ha	20 April 2022 (3 weeks before seeding)
Pacific's 2,4-D LVE 680 Herbicide	2,4-D as the ethylhexyl ester	300 ml/ha	20 April 2022 (3 weeks before seeding)
Roundup Ultra Max Herbicide	Glyphosate as Potassium Salt	1 L/ha	08 May 2022 (3 days before seeding)
Boxer Gold Herbicide	800 g/L Prosulfocarb + 120 g/L S-Metolachlor	3 L/ha	08 May 2022 (3 days before seeding)
Genfarm Paraquat 250	Paraquat dichloride	600 mL/ha	10 May 2022 (a day before seeding)
Titan's Treflan herbicide	480g/L Trifluralin	2 L/ha	10 May 2022 (a day before seeding)
Genfarm's Metribuzin 750 WG Herbicide	Metribuzin	125 g/ha	10 May 2022 (a day before seeding)
Intervix® Herbicide	33 g/L Imazamox present as Ammonium Salt + 15 g/L Imazapyr present as Ammonium Salt	400 mL/ha	1st July 2022 (7 weeks after seeding)
Polo 570 LVE Herbicide	MCPA present as the 2-Ethyl Hexyl Ester @ 570gm/L	450 mL/ha	1st July 2022 (7 weeks after seeding)
Genfarm Bromoxynil 400 Herbicide	400 g/L Bromoxynil present as the N-Octanoyl Ester	300 mL/ha	1st July 2022 (7 weeks after seeding)
Hasten Spray Adjuvant	Ethyl and Methyl Esters of Canola Oil Fatty Acids	400 mL/100 L	1st July 2022 (7 weeks after seeding)
Maxentis® EC Fungicide	Azoxystrobin 133 g/L + Prothioconazole 100 g/L	350 mL/ha	20 August 2022 (14 weeks after seeding)

2.2. Inputs used in 2023

Narrow leaf Lupin (*cv.* Jurien) was planted on 15th May 2023 using air seeder. Seeding rate was 90 kg/ha. At seeding, Nutrien's Cropbuilder16 was applied @ 35 kg/ha (N @ 4.69 kg/ha, P @ 5.60 kg/ha, S @ 2.42 kg/ha). Muriate of potash was applied @ 15 kg/ha (K @ 7.43 kg/ha) at seeding. To maintain the soil moisture at seeding, SACOA's SE14™ (active ingredients: Polyethylene Glycol / Ethoxylated Alcohol) was applied @ 2 L/ha at seeding. At 14 weeks after seeding, FertiMax Manganese Sulphate (active ingredients: Manganese Sulphate Monohydrate) was applied @ 1 kg/ha using Boomspray. Details of herbicides and other chemicals applied are given in table 4. Herbicides were applied using boom spray.

Crop was harvested on 1st December 2023.

Table 4. Details of the herbicides/pesticides/insecticides used in 2023 cropping season.

Name of chemical	Active ingredients	Rate of application	Time of application
Roundup Ultra Max	Glyphosate as Potassium Salt	1 L/ha	19 April 2023 (4 weeks before seeding)
Genfarm 2,4-D LV Ester 680 Herbicide	2,4-D as the ethylhexyl ester	300 ml/ha	19 April 2023 (4 weeks before seeding)
Nutrian Wetter 1000 Adjuvant	Alcohol ethoxylate	0.2 L/ha	14 May 2023 (a day before seeding)
Simazine 900 WG	Simazine	1 kg/ha	14 May 2023 (a day before seeding)
Chemfarm Metribuzin 750 WG	Metribuzin	0.3 kg/ha	14 May 2023 (a day before seeding)
Genfarm Paraquat 250	Paraquat dichloride	1.5 L/ha	14 May 2023 (a day before seeding)
Ultro 900 WG	Carbetamide	1 kg/ha	14 May 2023 (a day before seeding)
Genfarm Clethodim 360	Clethodim	350 ml/ha	28 June 2023 (5-6 leaf stage)
Nufarm Factor Herbicide	Butroxydim	180 g/ha	28 June 2023 (5-6 leaf stage)
Hasten Spray Adjuvant	Ethyl and Methyl Esters of Canola Oil with Non-ionic Surfactants	1 % (0.8 L/ha)	28 June 2023 (5-6 leaf stage)
Genfarm Ammonium Sulphate 417	Ammonium Sulphate	1 % (0.8 L/ha)	28 June 2023 (5-6 leaf stage)
Chemfarm Metribuzin 750 WG	Metribuzin	80 g/ha	15 July 2023 (8 weeks after seeding)
Brodal Options Selective Herbicide	Diflufenican	100 ml/ha	15 July 2023 (8 weeks after seeding)

2.3. Inputs used in 2024

2.3.1. Seeding: Canola (cv. Bonito) was seeded through direct seeding @ 3.5 kg/ha on 19th April 2024.

2.3.2. Fertilisers at Seeding (19th April 2024): Granular Sulphate of Ammonia was applied @ 100 kg/ha (N @ 21 kg/ha, S @ 24 kg/ha). SACOA's SE14™ (active ingredients: Polyethylene Glycol / Ethoxylated Alcohol) was applied @ 2 L/ha. CroPbuilder16 Trace was applied @ 59.5 kg/ha (N @ 8.09 kg/ha, P @ 9.46 kg/ha, S @ 4.05 kg/ha, Cu @ 0.06 kg/ha, and Zn @ 0.12 kg/ha). Muriate of Potash was applied @ 25.5 kg/ha (K @ 12.62 kg/ha).

The site was infested with the high ryegrass and radish weeds before knockdowns applied. Details of herbicides/pesticides and other chemicals are as under:

2.3.3. Pre-emergence and Knockdown (18th April 2024): A 1.0 % solution of the Herbicide Adjuvant, Genfarm's Ammonium Sulphate 417 (active ingredients: 417 g/L Ammonium Sulphate) was applied @ 0.8 L/ha**.** Genfarm's Atrazine 900 WG Herbicide (active ingredients: 900g/kg Atrazine) was applied @ 1.1 kg/ha. Rustler selective herbicide (active ingredients: 500 g/L Propyzamide) was applied @ 1 L/ha. Genfarm's Alpha Cypermethrin 250SC Insecticide (active ingredients: 250g/L ALPHA-cypermethrin) was applied @ 50 mL/ha. Genfarm's Genfarm Panzer 450 Herbicide (active ingredients: 450 g/L Glyphosate present as the isopropylamine salt) was applied @ 1.8 L/ha. A 0.2 % solution of the Wetter 1000 (active ingredients: 800 g/L Nonyl Phenol Ethoxylate, 200 g/L Diethylene Glycol Monobutyl Ether) was applied @ 160 mL/ha. These chemicals were applied using self-propelled Boom-spray.

2.3.4. Bug Spray (17 May 2024) through Boom Spray: Genfarm's miticide/insecticide, Bifenthrin 250 EC (active ingredients: 250 g/L Bifenthrin) was applied @ 80 mL/ha. Chlorpyrifos 500 Insecticide (active ingredients: 500 g/L Chlorpyrifos) was applied @ 400 mL/ha.

2.3.5. Herbicides/insecticides applied on 4th June 2024: A selective herbicide, Genfarm Clethodim 360 (active ingredients: 360 g/L Clethodim) was applied @ 330 mL/ha. The herbicide**,** Genfarm Atrazine 900 WG (active ingredients: 900g/kg Atrazine) was applied @ 1.1 kg/ha. Herbicide, Genfarm QPE 200 (active ingredients: 200g/L Quizalofop-P-Ethyl) was applied @ 200 mL/ha. Insecticide, Omethoate 290 (active ingredients: 290 g/L Omethoate) was applied @ 150 mL/ha. A 1.0 % solution of Hasten Spray Adjuvant (active ingredients: 704 g/L Ethyl and Methyl Esters of Vegetable Oil with 196 g/L Non-ionic Surfactants) was also applied @ 0.8 L/ha to improve the spreading, wetting and retention of chemicals. These chemicals were applied using self-propelled Boom-spray.

2.3.6. Top dressing N on 30th May 2024 (6 weeks after seeding): Nutrien Urea (46% N) was applied @ 80 kg/ha (N applied @ 36.8 kg/ha) using rotary spreader.

2.3.7. Herbicide applied on 13th June 2024: Lontrel® 750 SG (active ingredients: 750 g/kg clopyralid present as potassium salt) was applied @ 120 g/ha. A 0.5 % solution of Uptake Spraying Oil (active ingredients: 582 g/L paraffinic oil and 240 g/L alkoxylated alcohol non-ionic surfactants) was applied @ 0.4 L/ha.

2.3.8. Liquid N application on 2nd August 2024 (6 weeks after seeding): Bulk-N (42% N w/v) was applied @ 70 L/ha.

Fig. 2. (A) Ute-based soil sampler used for soil sampling before seeding (14 May 2024). **(B)** Loggers fenced after harvest to avoid sheep's damage (Dec-2023 to March-2024). **(C)** Digging out Loggers and Probes before seeding at Kweda (March-2024). **(D)** Picture of the crop taken on 1st July 2024 while taking crop establishment data. **(E)** Picture of the crop taken on 6th August (11 weeks after seeding).

2.4. Soil sampling

Soil samples were collected a couple of months before seeding each year by a ute-based drill system (Fig. 2A), collecting a bulk sample of 15-20 cores from each plot. Samples were sent to the CSBP lab at Bibra Lake, WA for chemical/nutrients analysis. Diviner tubes were disconnected before seeding and reconnected after seeding. Soil moisture data loggers at Kweda were completely taken out before seeding (Fig. 2C) and mounted back after seeding. Previous moisture data was retrieved from loggers, new batteries were installed, and loggers were tested to make sure they are working perfectly. Loggers were fenced in the non-crop period (December 2023 to March 2024) to avoid damage by the sheep. Crop establishment data (number of plants and weeds m^{-2}) and NDVI through the hand device were collected by the Corrigin Farm Improvement Group on 1st July 2024 at Kweda (Fig. 2D).

During a visit to the site in March-2024, left over of sheep was noticed in the filed indicating sheep grazing activity.

2.5. Satellite based NDVI (2024)

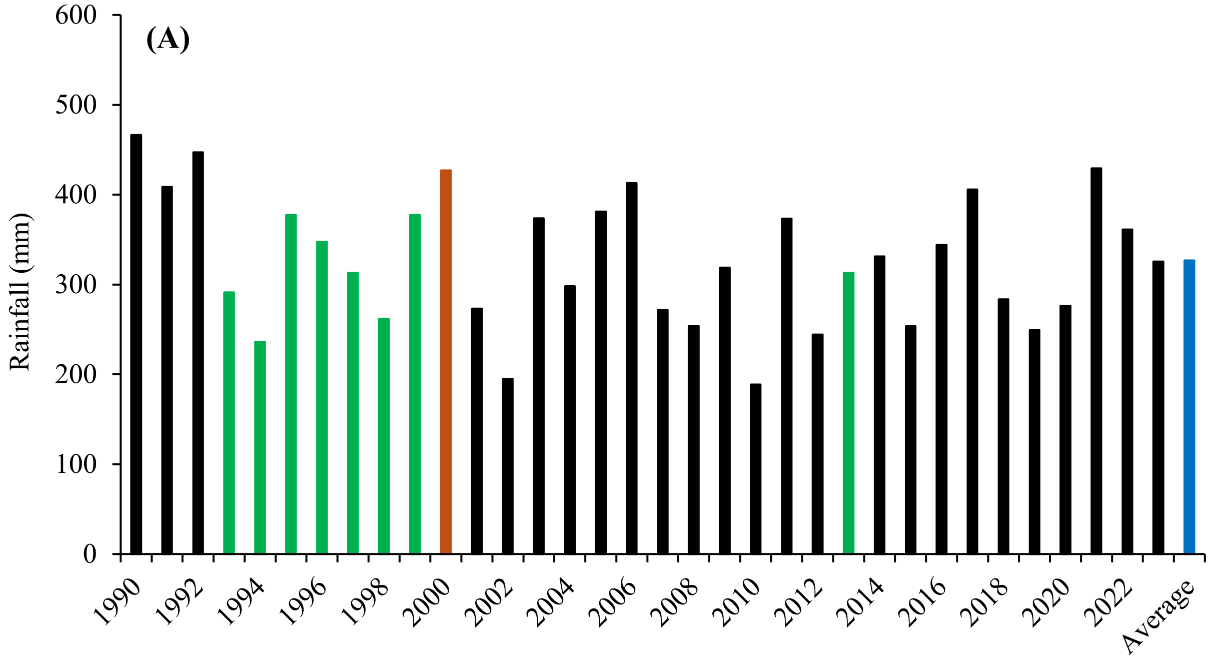
In 2024, the satellite based NDVI was recorded by the contractor (Data Farming Pty Ltd.) on 18th June (8 weeks after seeding), 5th July (11 weeks after seeding) and 30th August (19 weeks after seeding). Weather was a bit cloudy during the captures taken on 18th June 2024. Captures were taken at 50 cm resolution. 1300-1400 counts were used to calculate the NDVI values for each plot. The experimental plots are wider enough which allowed to create a 1.5m inner buffer around each plot to minimise error from slight inaccuracy in the plots' locations.

Diviner tubes data have not yet been recorded in 2024 season because of some issues with the diviner device, i.e., the battery needed to be replaced by a technician which has been sorted out now, however, the diviner rod broke later which has now been delivered and data collection is now planned in October-2024.

2.6. Rainfall (2022-2024)

Rainfall data were retrieved from the online resources of the nearby weather stations. The nearest weather stations are in Bulyee and Kweda WA which are 11 and 12 km away from the site, respectively. The Bulyee station (Station number 10527) is monitored by the Bureau of meteorology, Government of Australia. The Kweda station (KW001) is monitored by the Department of Primary Industries and regional Development of Western Australia.

The long-term rainfall data (1990-2023) from various weather stations in and around Kweda region show that the region receives an average annual rainfall of 327 mm (Fig. 3A). However, the last 9 years rainfall data (2015-2023) reported by the Kweda weather station show that the average annual rainfall received was 393 mm (Fig. 3B).



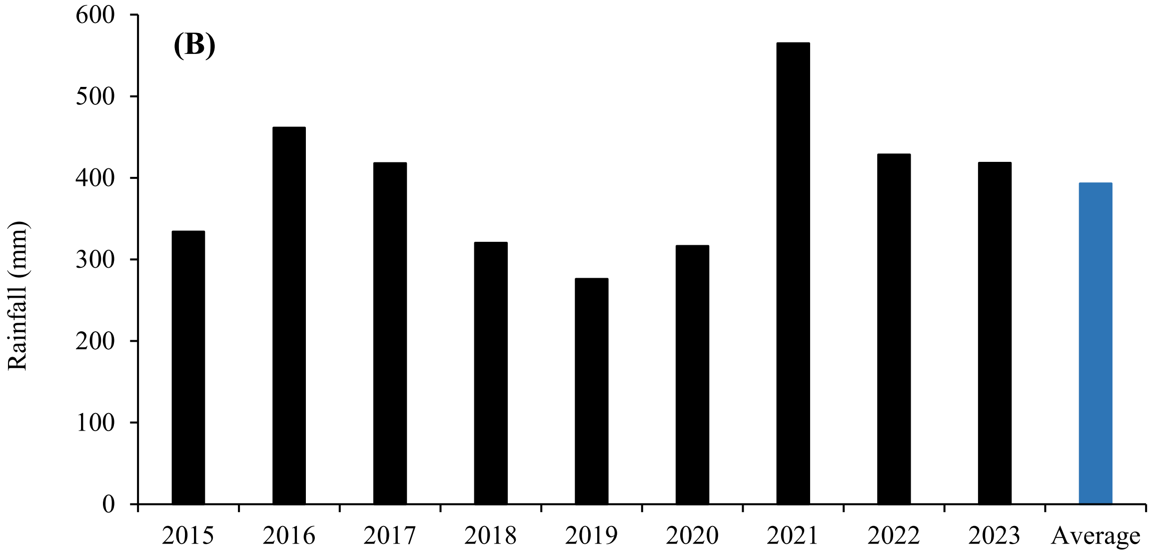
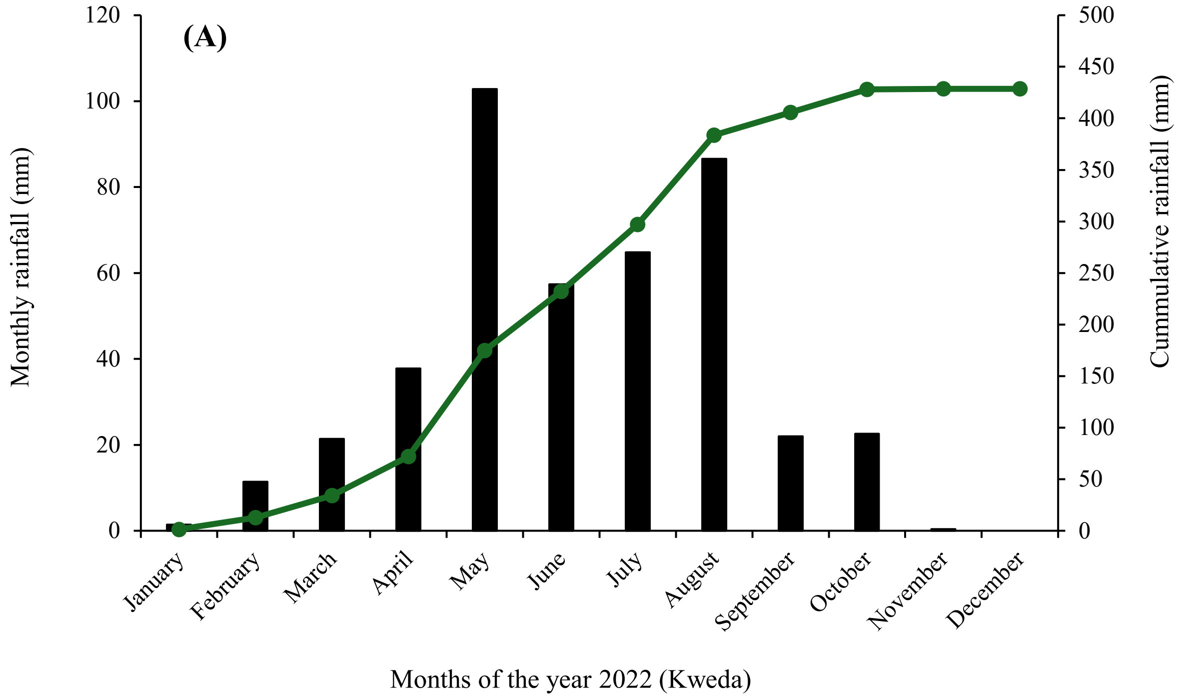
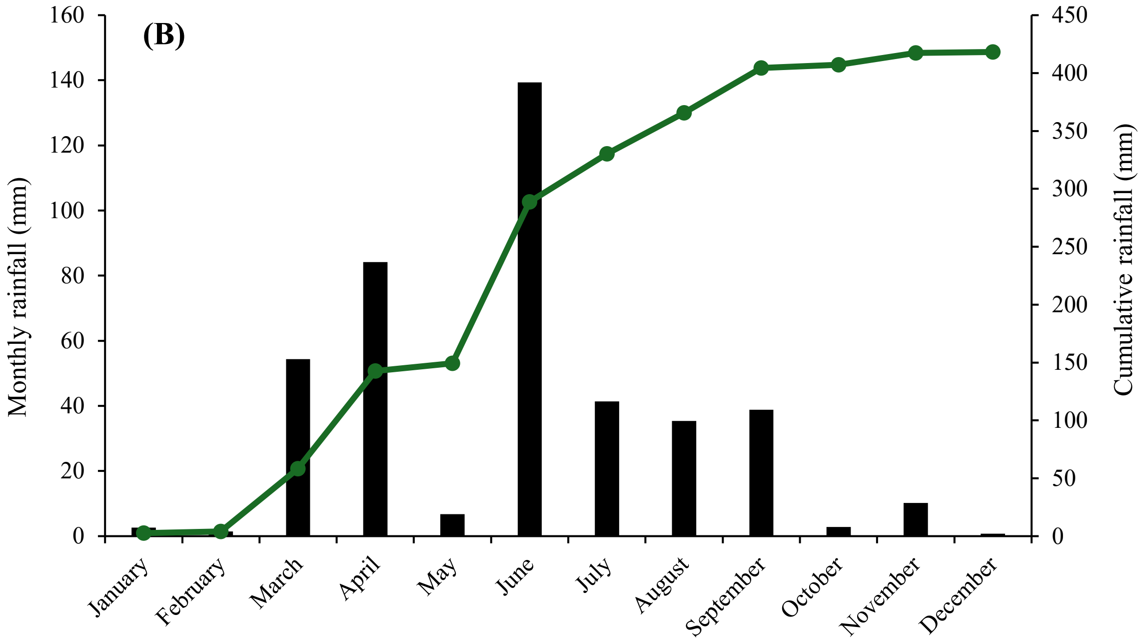


Fig. 3. (A) Total annual rainfall per year and average rainfall data (1990-2023) retrieved from various weather stations located around Kweda experimental site. **(A)** Data retrieved from Bulyee (12 km away), South Caroling (24 km away) and Glenmore (31 km away) weather stations of the Bureau of Meteorology, Australia. **(B)** Data retrieved from Kweda weather station of DPIRD which is 12 km away from the experimental site. Where the data wasn't available at the nearest station, data from the next nearest station was utilised. **(C)** Monthly and cumulative rainfall data recorded by the weather station at Kweda, WA during 2022, monitored by the Department of Primary Industries and Regional Development (DPIRD) of the Government of Western Australia. Data was retrieved from the official website: https://weather.agric.wa.gov.au/.

Rainfall data of the Kweda weather station (KW001) show that total rainfall received during 2022 and 2023 was 429 and 418 mm respectively (Fig. 4A-B). May was recorded as the wettest month in 2022 with 103 mm rainfall followed by August with 87 mm (Fig. 4A). However, in 2023, the wettest month recorded was June with receiving 139 mm rainfall followed by April receiving 84 mm (Fig. 4B). So far in 2024, July and August have been recorded with the highest monthly rainfall (Fig. 4C). The total rainfall received in 2024 by the end of August reported by the Kweda weather station (KW001) is 345 mm.


(A)
Monthly rainfall (mm)
Cummulative rainfall (mm)
January
February
March
April
May
June
July
August
September
October
November
December
0
20
40
60
80
100
120
0
50
100
150
200
250
300
350
400
450
500
Months of the year 2022 (Kweda)


(B)
Monthly rainfall (mm)
Cumulative rainfall (mm)
January
February
March
April
May
June
July
August
September
October
November
December
0
20
40
60
80
100
120
140
160
0
50
100
150
200
250
300
350
400
450

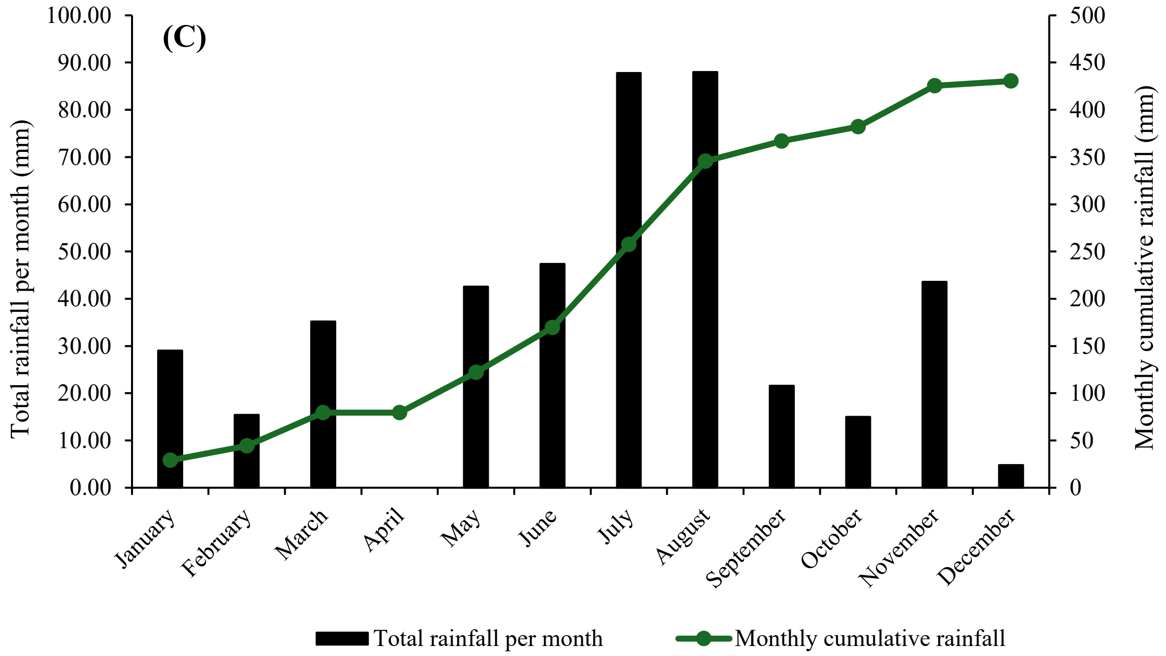


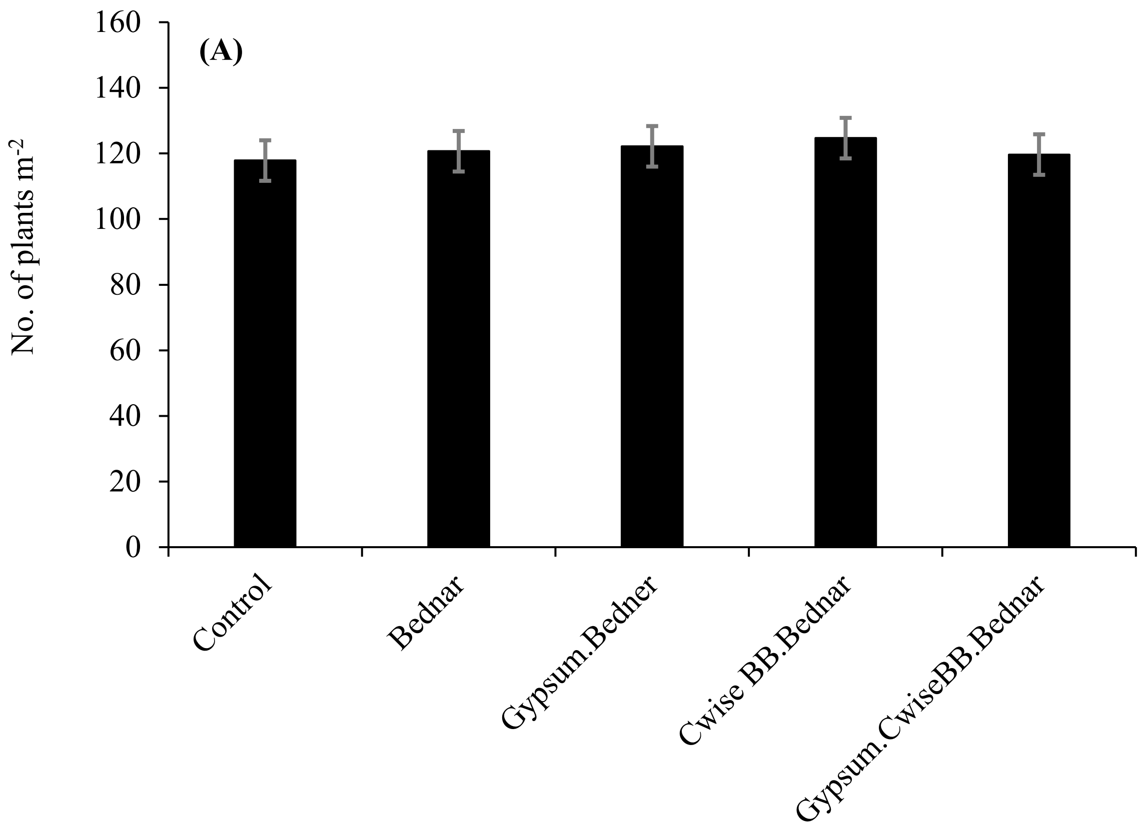
Fig. 4. (A) The 2022 average monthly and cumulative rainfall data recorded by the weather station at Kweda (KW001). **(B)** The 2023 average monthly and cumulative rainfall data recorded by the weather station at Kweda (KW001). **(C)** The 2024 average monthly and cumulative rainfall data recorded by the weather station at Kweda (KW001). Data was retrieved from the official website of the Department of Primary Industries and Regional Development (DPIRD) of the Government of Western Australia at: https://weather.agric.wa.gov.au/.

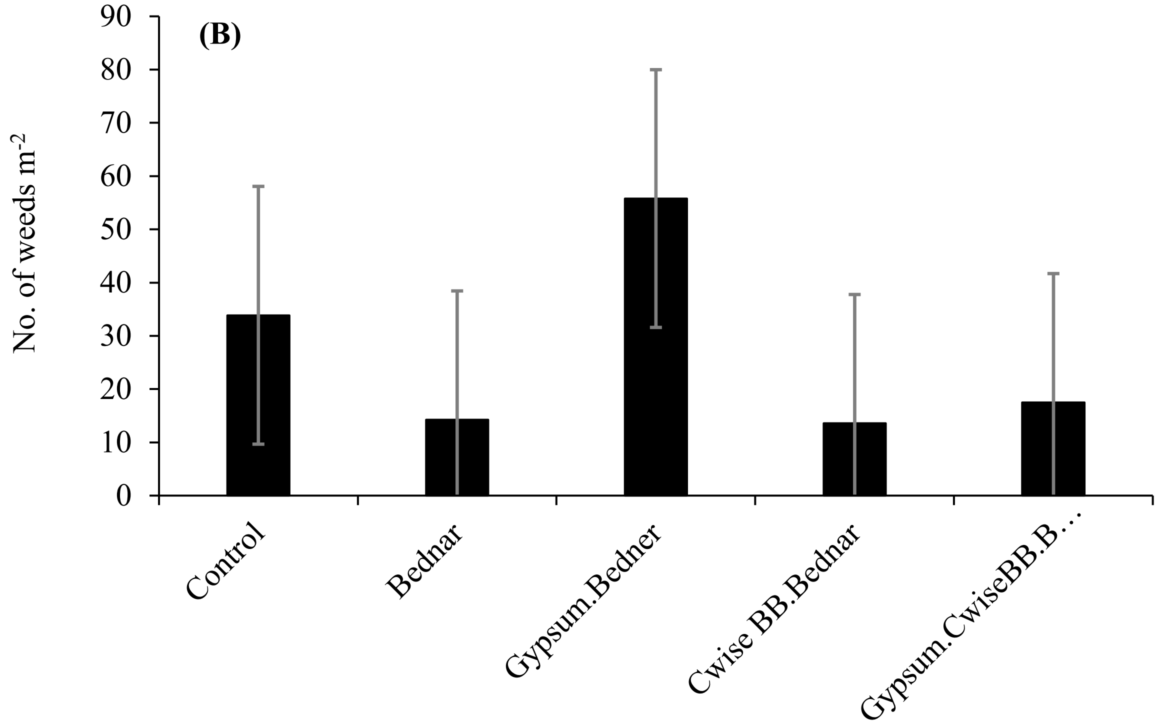
3. Results

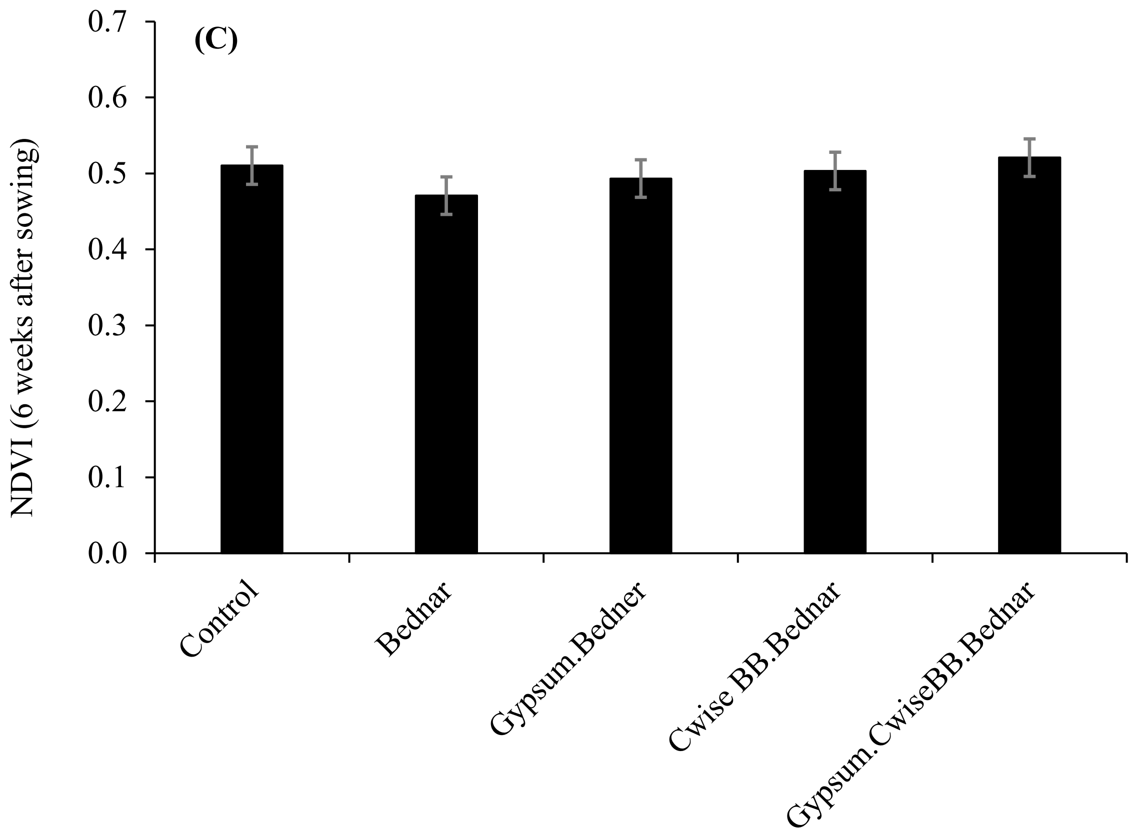
3.1. Crop data (2022)

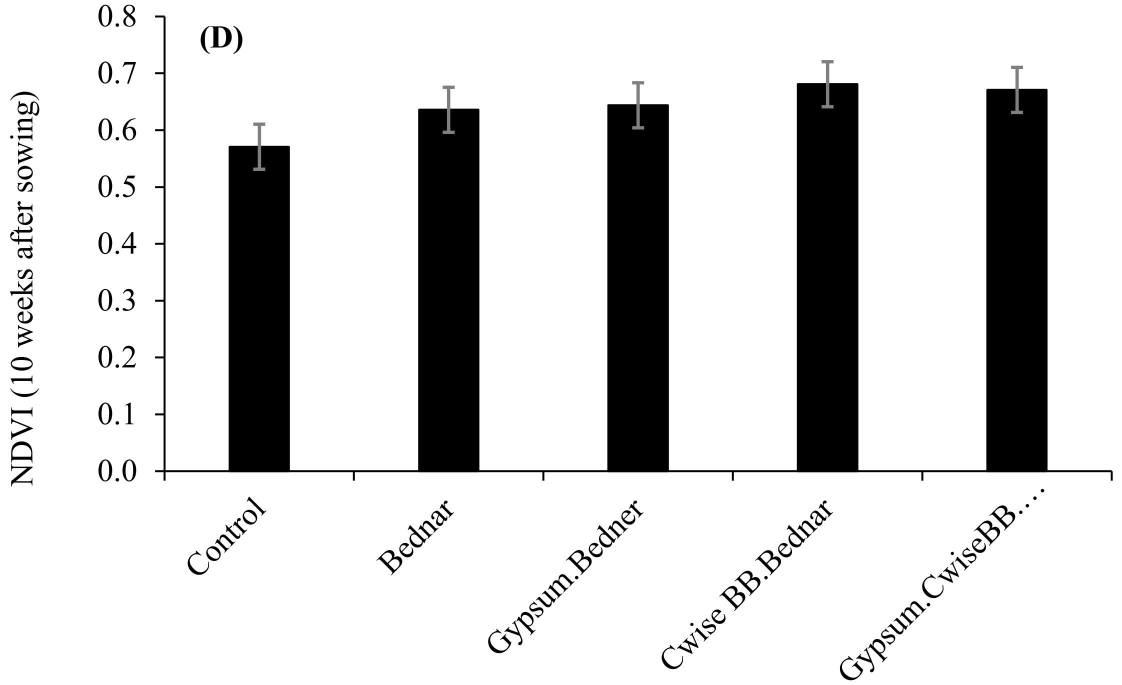
In the large plots experiment, all the other measured parameters were not statistically affected by the applied treatments except the yield (Fig. 5A-E). The large plots experiment showed an improvement between the unripped (control) and the bednar ameliorated treatments with a significant increase in yield for the gypsum and the gypsum + Cwise treatments vs control. The Cwise (humiclay) alone showed a larger yield and a reduced variability between blocks; however, it was not significantly different from the control. Overall, gypsum has been recognised as the most beneficial amendment.

Overall, no significant differences were shown for plant establishment and plant health (NDVI at 6 and 10 weeks after seeding) as shown in Fig. 5C-D. A possible explanation for this might occur from the variability of the blocks, which were found to be significantly different and included in the model for the statistical analysis.




(B)
No. of weeds m-2
90
80
70
60
50
40
30
20
10
0
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.B…


(C)
NDVI (6 weeks after sowing)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar



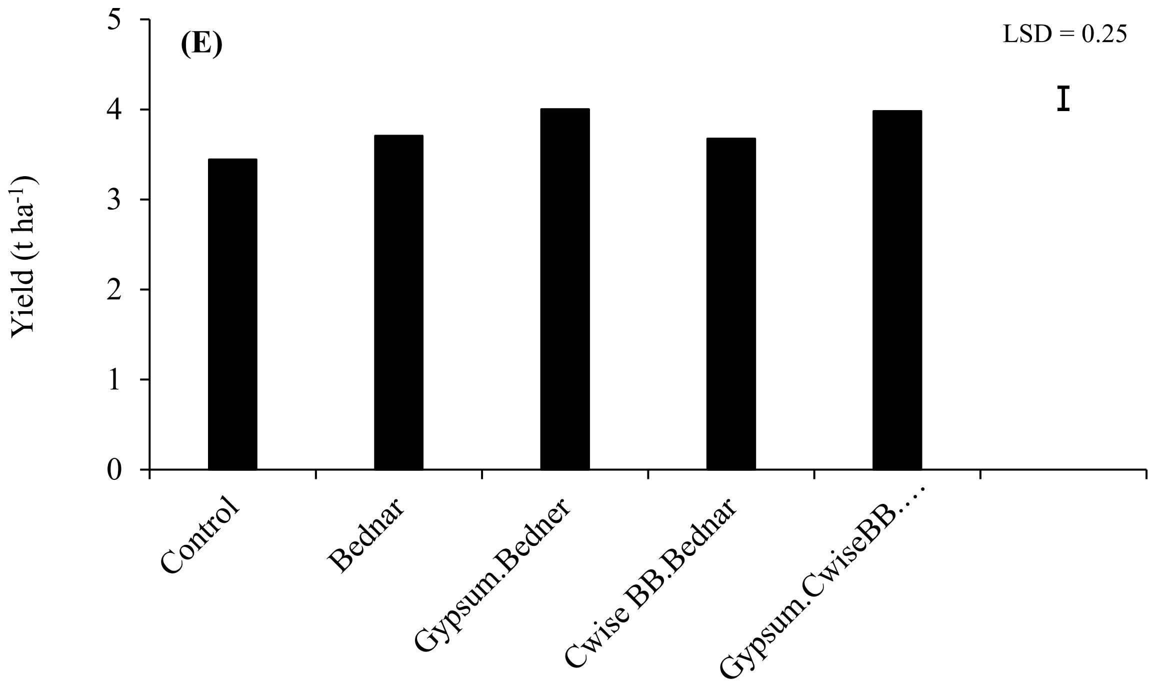
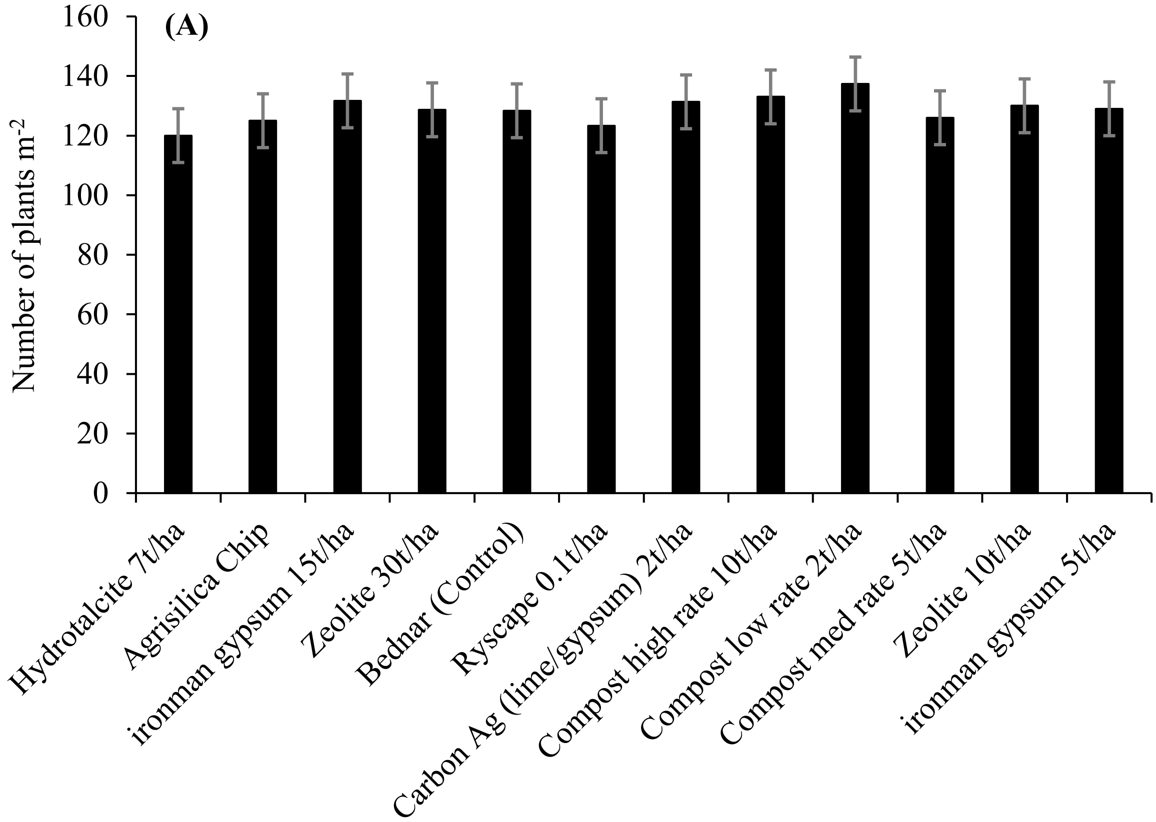
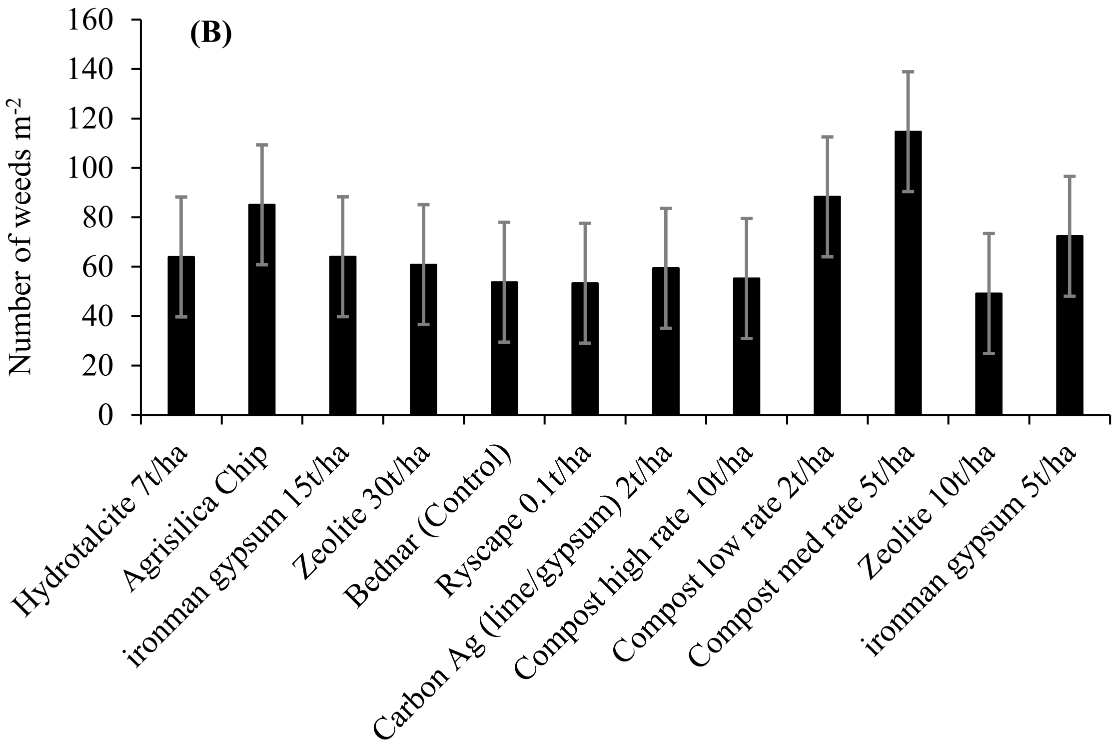


Fig. 5. Crop growth parameters, weeds density and crop yield of barley influenced by the applied soil ameliorants and treatments in the Large Plots Experiment at Kweda measured during 2022 cropping season. **(A)** Number of plants m^{-2}. **(B)** Number of weeds m^{-2}. **(C)** NDVI at 6 weeks after seeding. **(D)** NDVI at 11 weeks after seeding. **(E)** Barley yield (t/ha). Wherever the treatments effect was non-significant (P > 0.05), standard error of the mean was used as

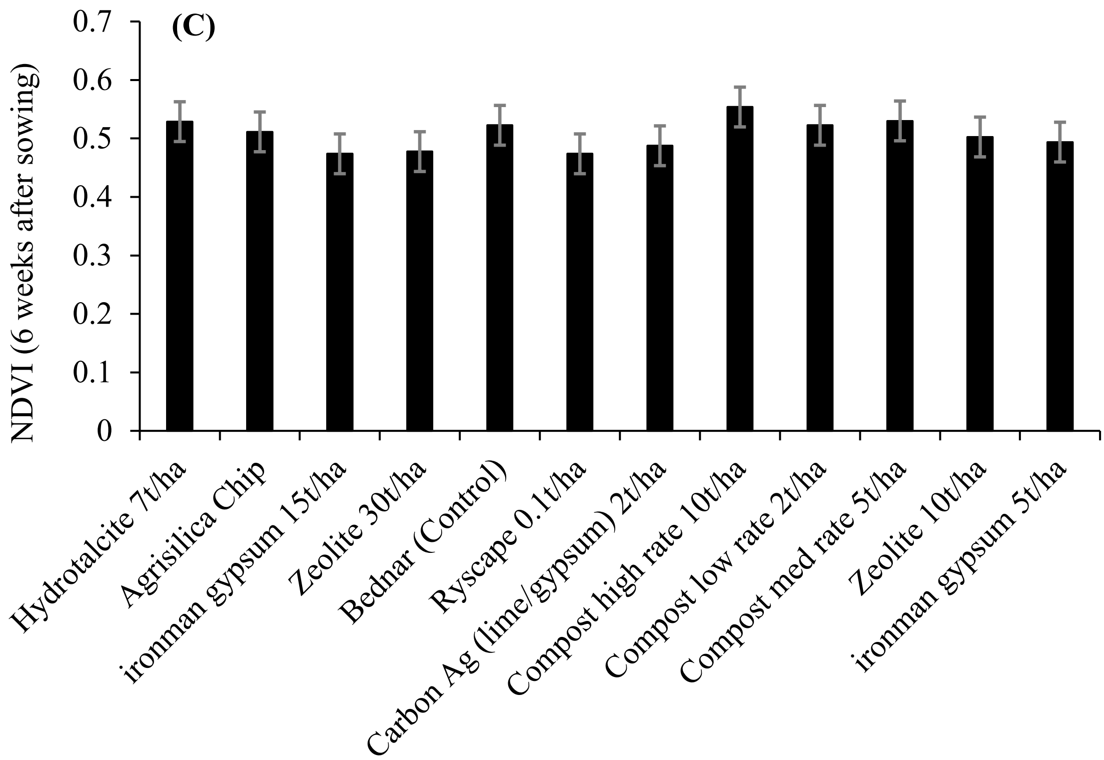
error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD ($\alpha = 95\%$) was used as a separate error bar.

The small plots experiment investigated a series of novel amendments and variable rates, all incorporated by Bednar. Hence, the Bednar treatment was considered as the control for this trial. In the small plots experiment, none of the measured crop parameters were significantly affected by any treatment relative to control (Bednar) as shown in Fig. 6A-E. As mentioned above, as a potential limitation on the results, a significant difference between the blocks was identified, which increased the variability and potentially reduced the statistical power of the analysis. Another likely cause for the lack of differences between treatments could be explained by the rainfall data, which showed to be above average for the cropping season 2022. Hence, optimal soil moisture reduced the potential benefit of the incorporated amendments.

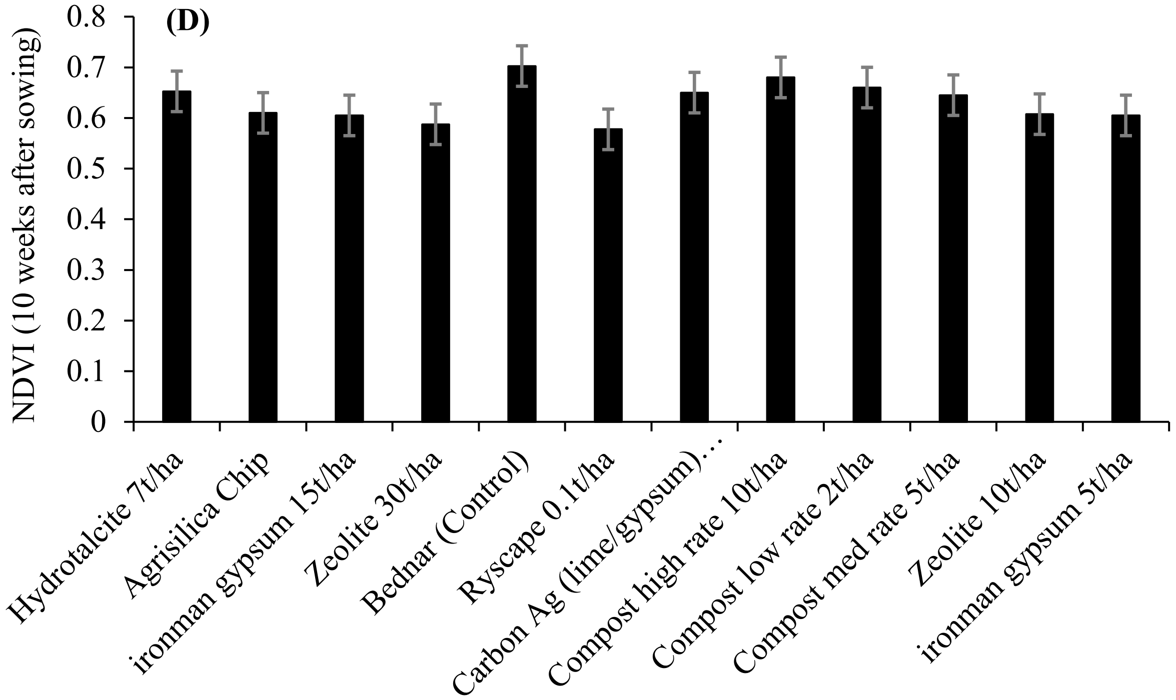




(B)
Number of weeds m-2
160
140
120
100
80
60
40
20
0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha



(C)
NDVI (6 weeks after sowing)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha



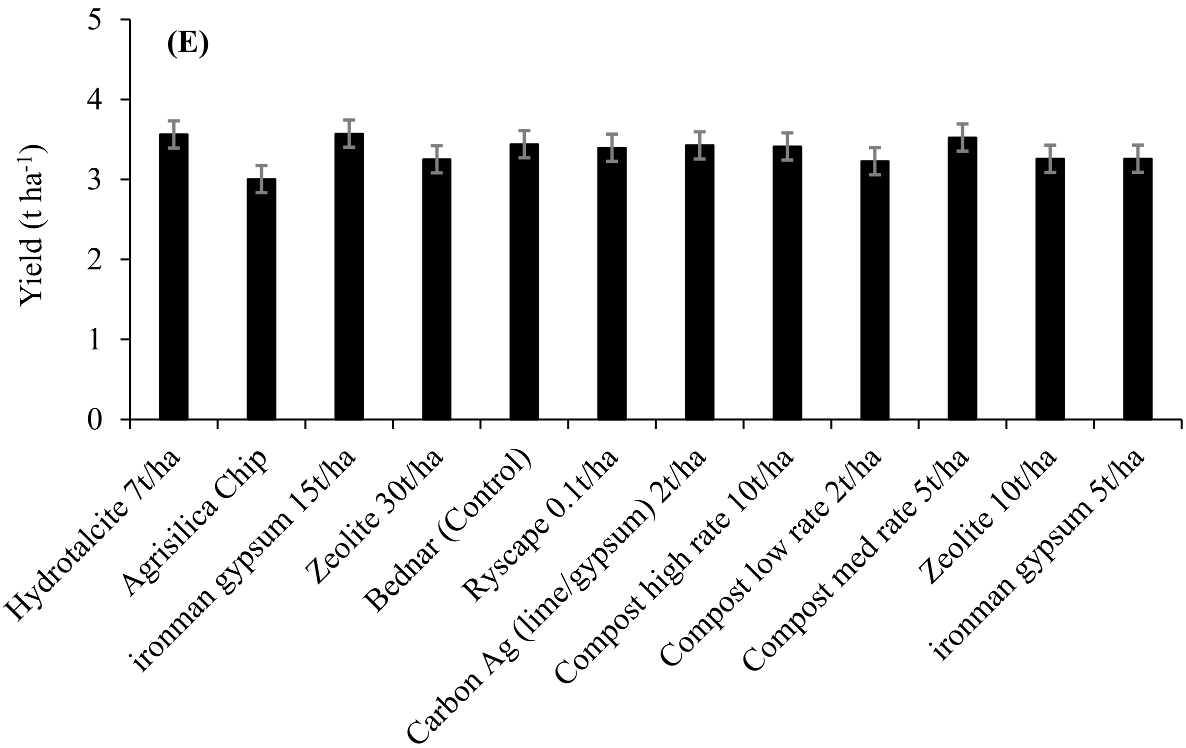
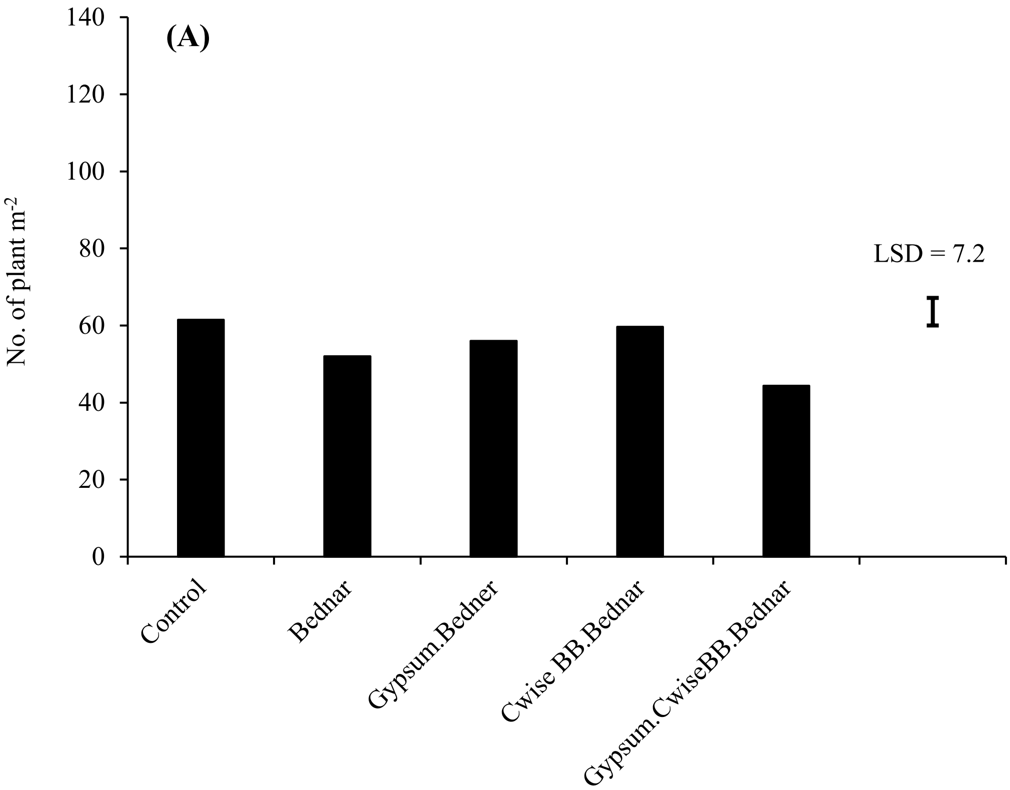


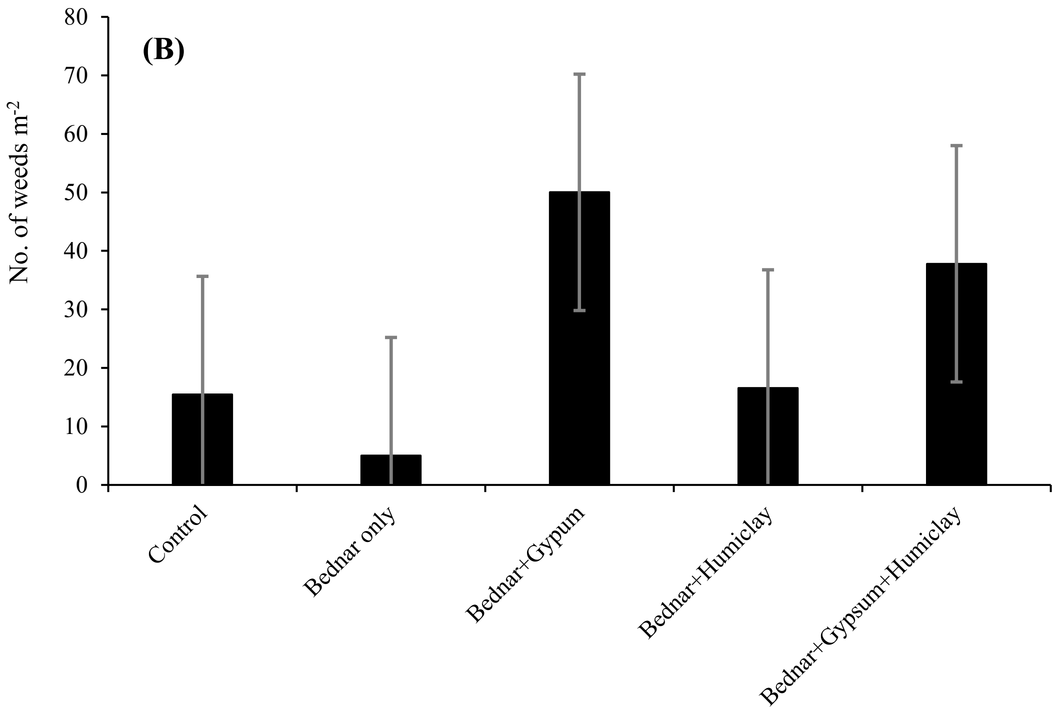
Fig. 6. Crop growth parameters, weeds density and crop yield of barley influenced by the applied soil ameliorants and treatments in the Small Plots Experiment at Kweda measured

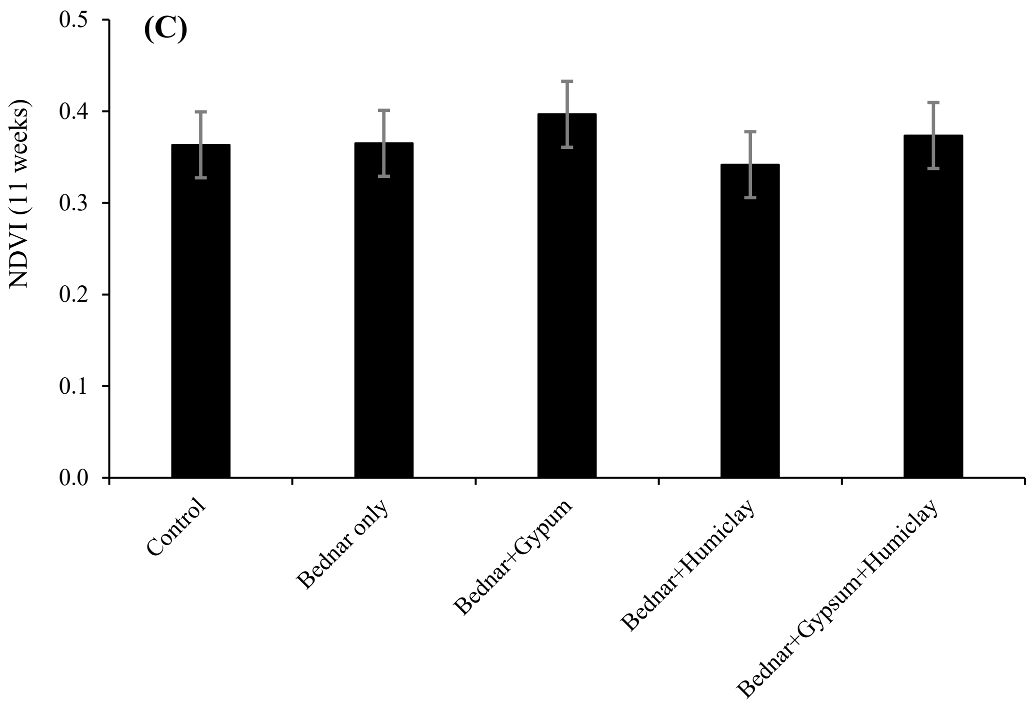
during 2022 cropping season. **(A)** Number of plants m^{-2}. **(B)** Number of weeds m^{-2}. **(C)** NDVI at 6 weeks after seeding. **(D)** NDVI at 11 weeks after seeding. **(E)** Barley yield (t/ha). Wherever the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD (α = 95%) was used as a separate error bar.

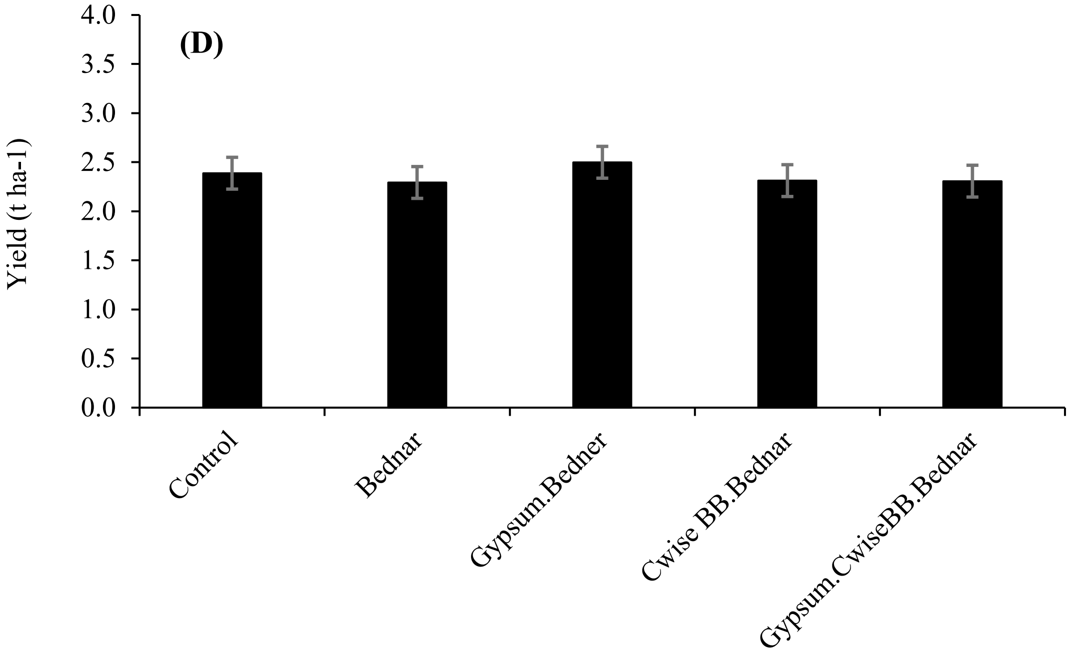
3.2. Crop Data 2023

Target density of Lupins has been reported as 40-45 plants m^{-2} in Western Australia (Shackley et al., 2023). All treatments in the large plots experiment produced within or above the targeted range in 2023 (Fig. 7A). NDVI and weeds density recorded respectively at 11 weeks after seeding was found statistically similar between all the studied treatments (Fig. 7B). The non-significant difference could be partially attributed to the significant variations between the blocks which was included as a source of variation in the model. Yield and protein content were not significantly affected by the studied treatments. Yield ranged from 2.3 to 2.5 t ha^{-1} (Fig. 7D) while protein content ranged narrowly between 34.9 and 35.7 % (Fig. 7E).




(B)
No. of weeds m-2
80
70
60
50
40
30
20
10
0
Control
Bednar only
Bednar+Gypum
Bednar+Humiclay
Bednar+Gypsum+Humiclay


(C)
NDVI (11 weeks)
0.5
0.4
0.3
0.2
0.1
0.0
Control
Bednar only
Bednar+Gypum
Bednar+Humiclay
Bednar+Gypsum+Humiclay



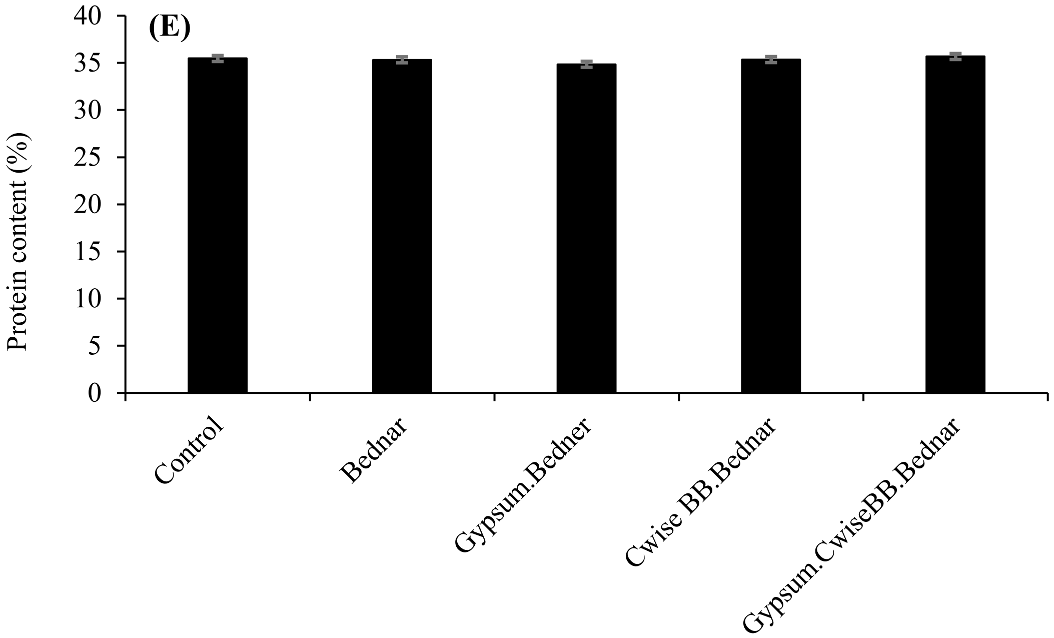
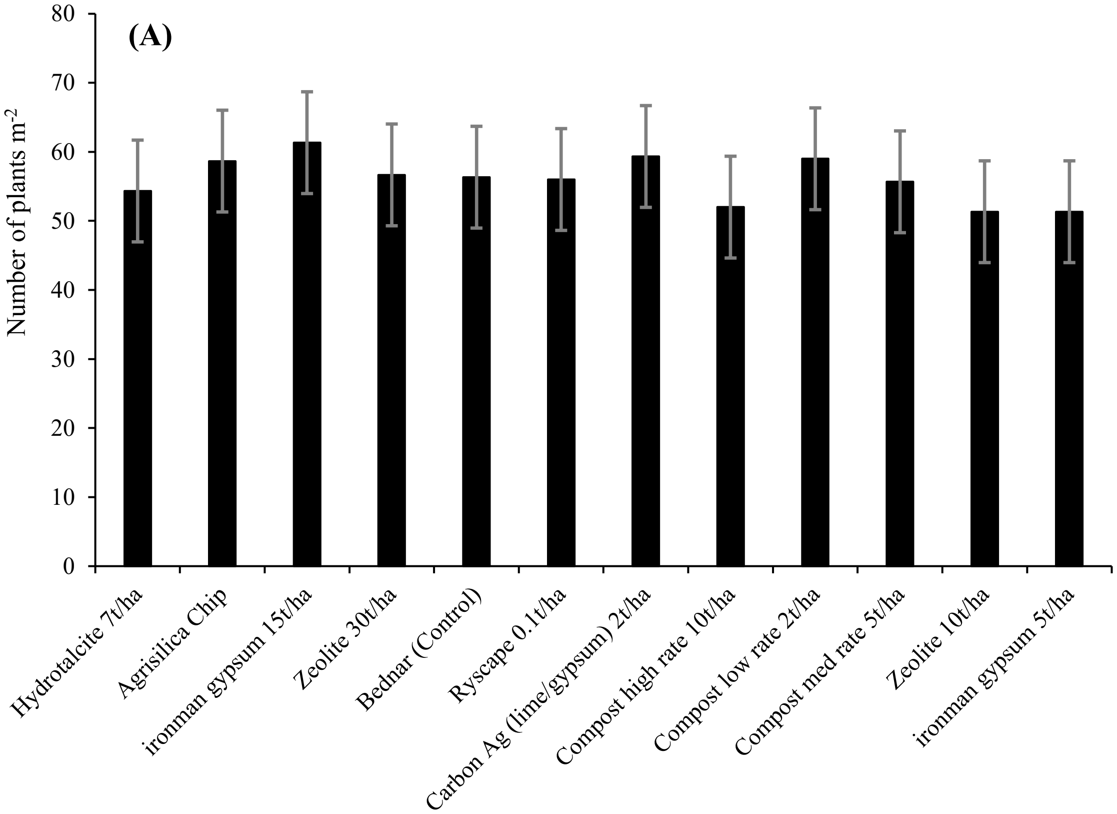
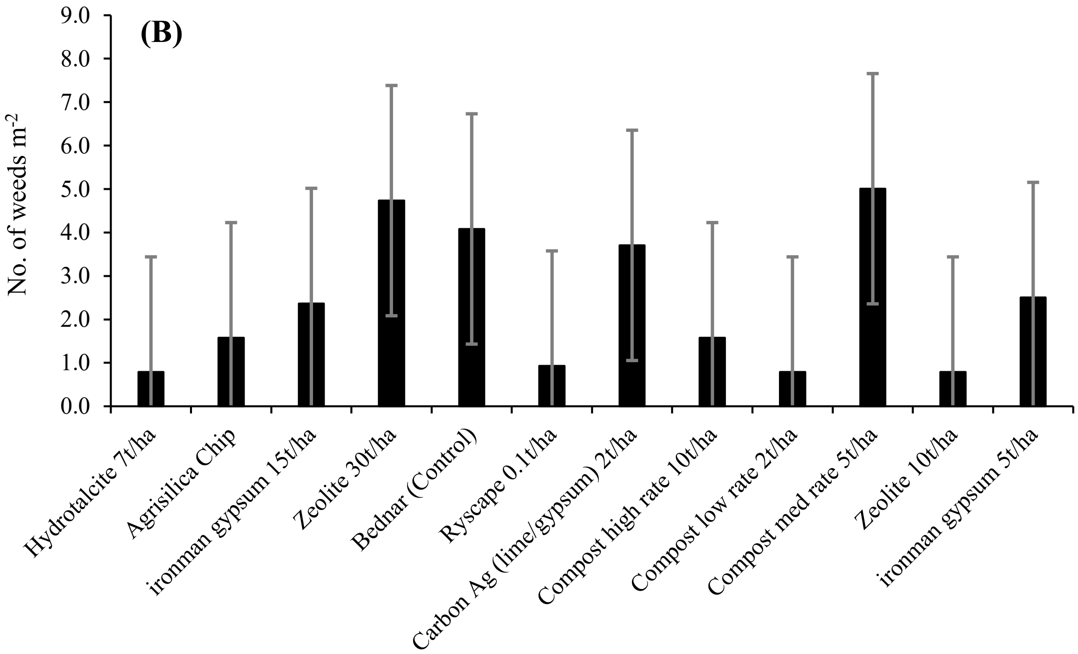


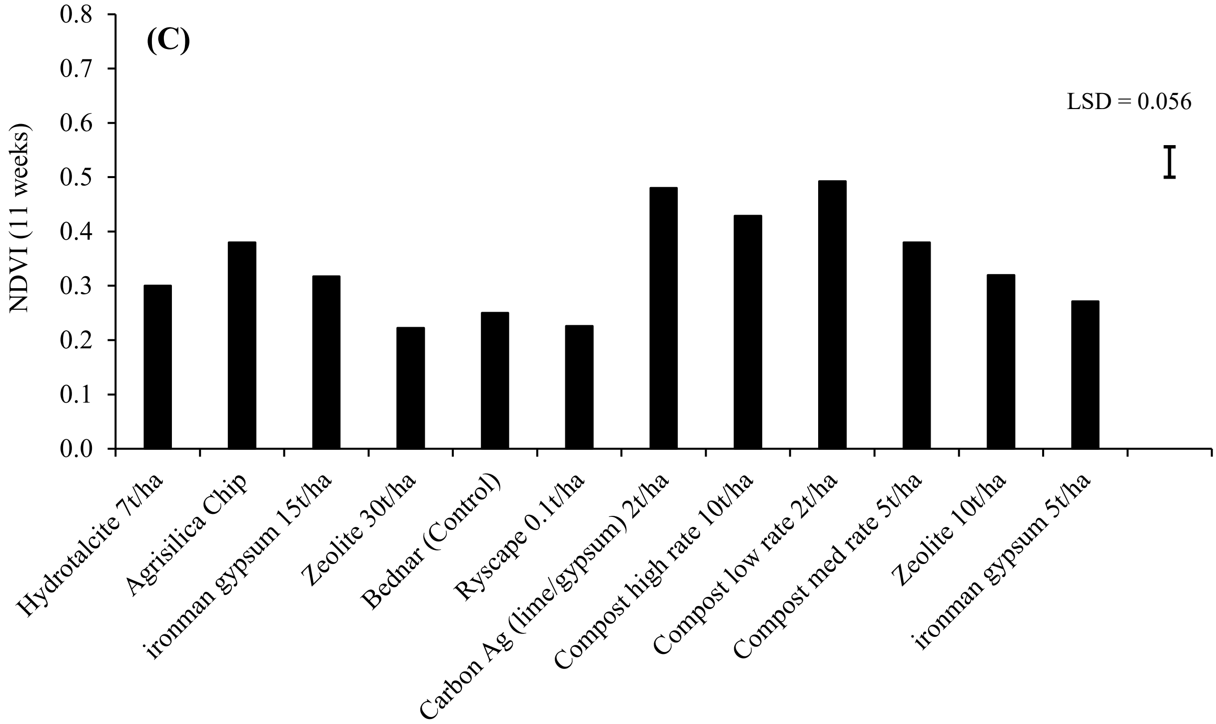
Fig. 7. Influence of soil treatments and ameliorants on various growth and developmental parameters of Lupin crop in the large plots experiment in 2023. **(A)** Number of plants m^{-2}. **(B)** No. of weeds m^{-2}. **(C)** Hand-based NDVI recorded at 11 weeks after seeding. **(D)** Yield (t/ha) of Lupin. **(E)** Protein content (%) of Lupin at harvest. Wherever the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD value ($\alpha = 95\%$) was used as a single error bar.

Plant density recorded at 9 weeks after seeding in the small plots experiment in 2023 was above the target range (40-45 plants m-2) with no statistical differences between the treatments (Fig. 8A). Weeds density was also not influenced by the treatments studied (Fig. 8B). 1-5 weeds/m^2 were recorded 9 weeks after seeding (Fig. 8B). Lupins in different treatments were found with significantly different NDVI at 11 weeks after seeding (Fig. 8C). Low rate of compost (2 t/ha) was found with the greatest NDVI of 0.49 (>2 times of Zeolite @ 30 t/ha, 2 times of control, 1.8 times of ironman gypsum @ 5 t/ha, 1.6 times of hydrotalcite, 1.6 times of ironman gypsum @ 15 t/ha, 1.3 times of Agrisilica chip), as shown in fig. 8C. However, NDVI recorded in all three compost treatments was statistically similar.

Compost is known for improving crop growth via enhancement of soil properties. For the instance, Duong (2013) has reported a significant increase in the availability and mobility of Nitrogen and Phosphorus in soil along with increase in the soil cation exchange capacity. Similarly, Ngo and Cavagnaro (2018) have reported an increase in the wheat and tomato biomass in compost treated soil over control. The authors partially attributed the increase in biomass to enhanced P availability regardless of the soil moisture conditions (wet or dry). This implies that compost might have enhanced nutrients availability to Lupins despite the dry conditions which might not be the case with other soil amendments. Surprisingly, crop yield was not influenced by the treatments despite the different NDVI. This might be either because of poor correlation between the NDVI and yield or the differential growth pattern of the crop in different treatments after 11th week (when NDVI was recorded) perhaps due to rainfall in August and September. There is a possibility that NDVI might have differed later in the growing season.


(A)
Number of plants m-2
80
70
60
50
40
30
20
10
0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha


(B)
No. of weeds m-2
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha



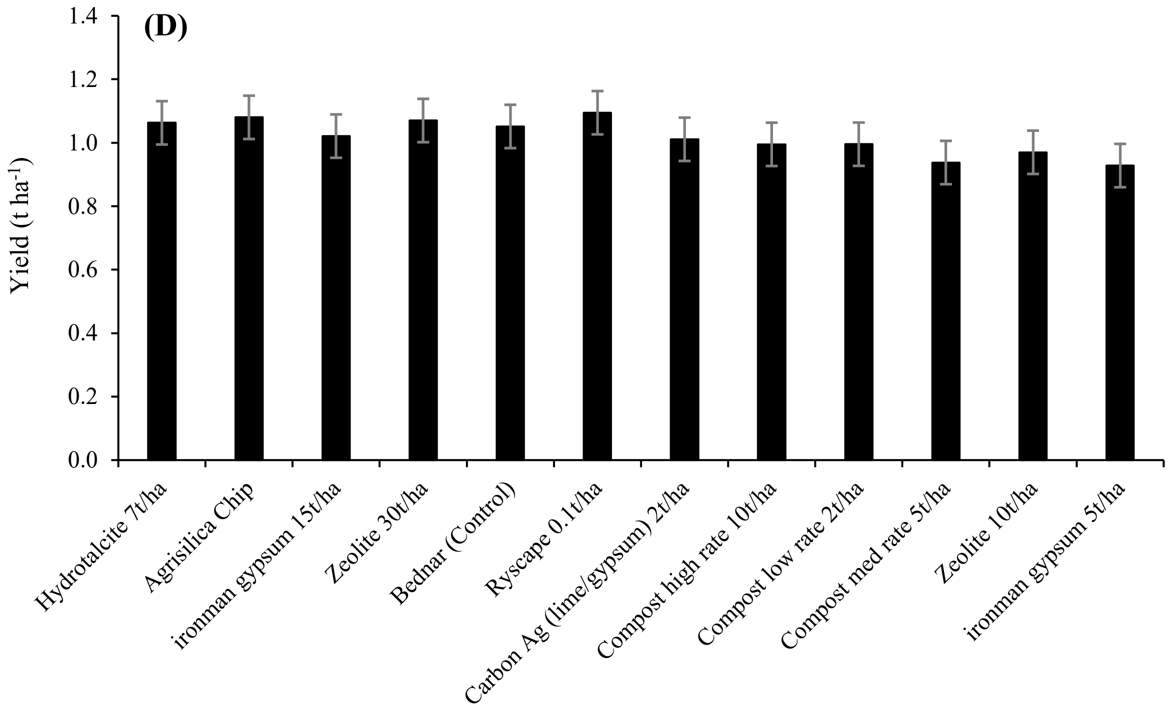
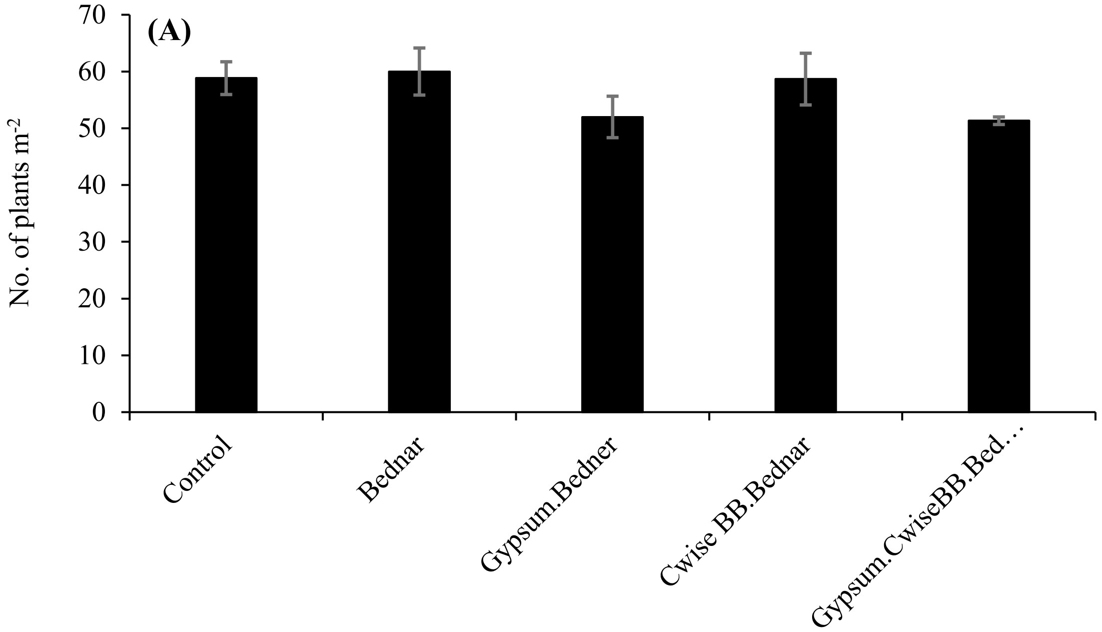
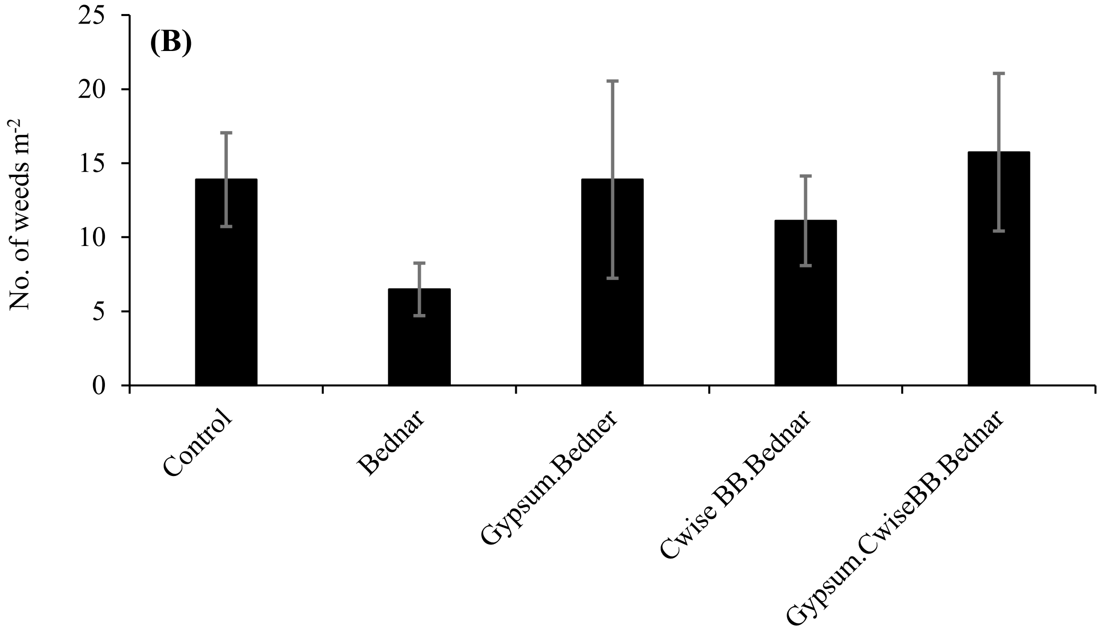


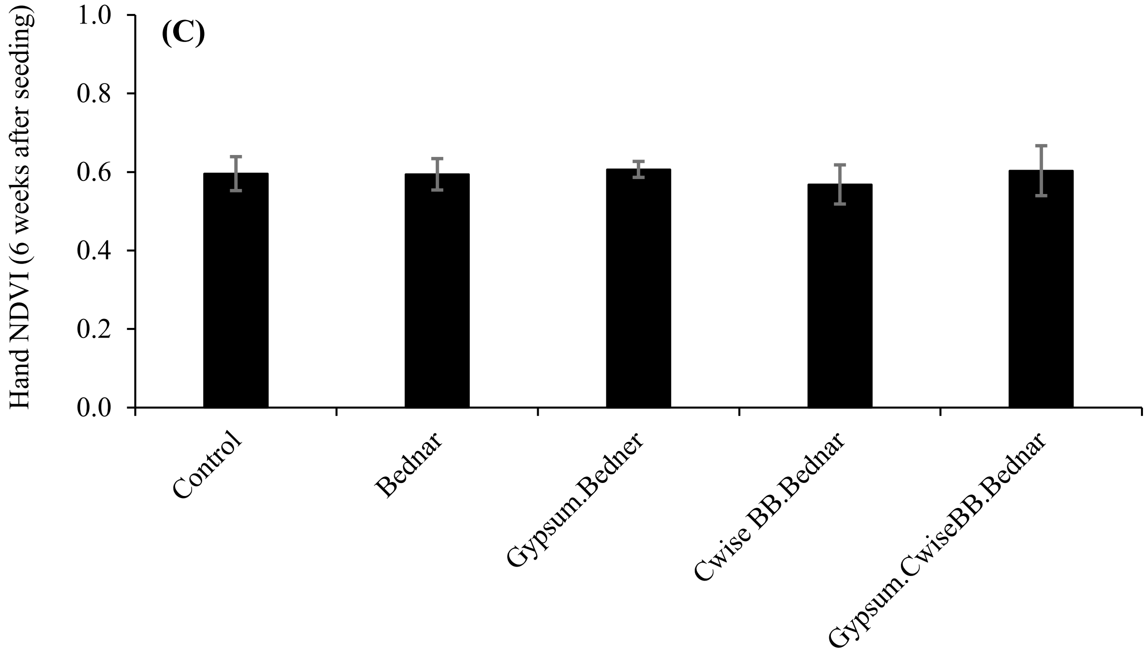
Fig. 8. Influence of the soil treatments and ameliorants on various growth and developmental parameters of Lupin crop in the small plots experiment in 2023. **(A)** Number of plants m^{-2}. **(B)** No. of weeds m^{-2}. **(C)** Hand-based NDVI recorded at 11 weeks after seeding. **(D)** Yield (t/ha) of Lupin. Wherever the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD value ($\alpha = 95\%$) was used as a single error bar.

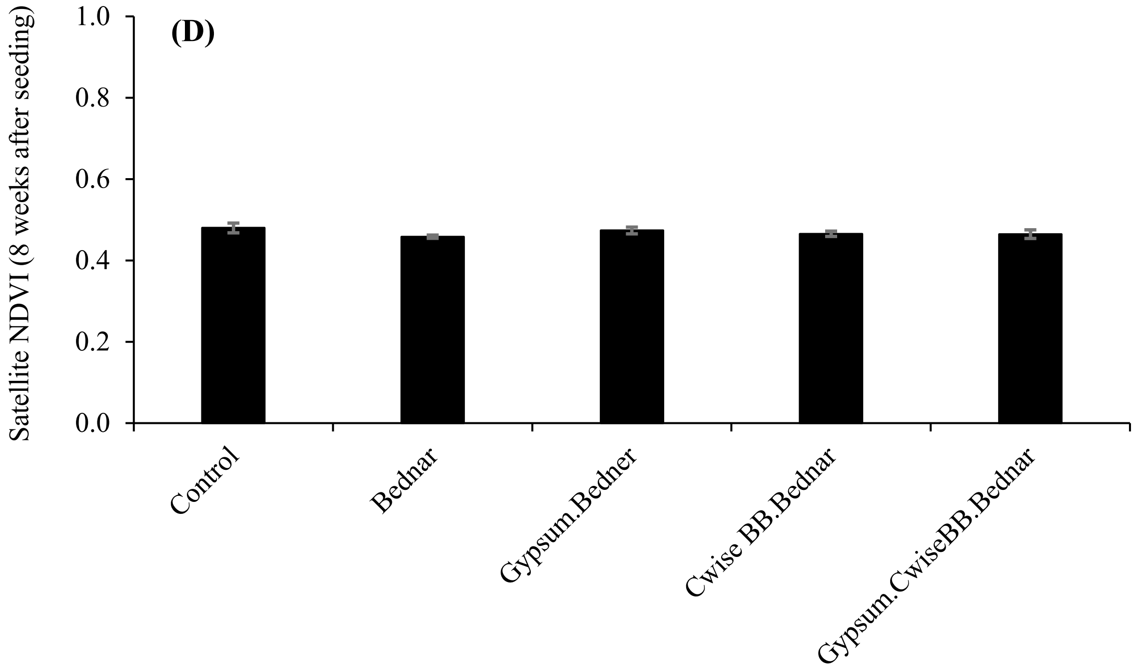
3.3. Crop Data 2024

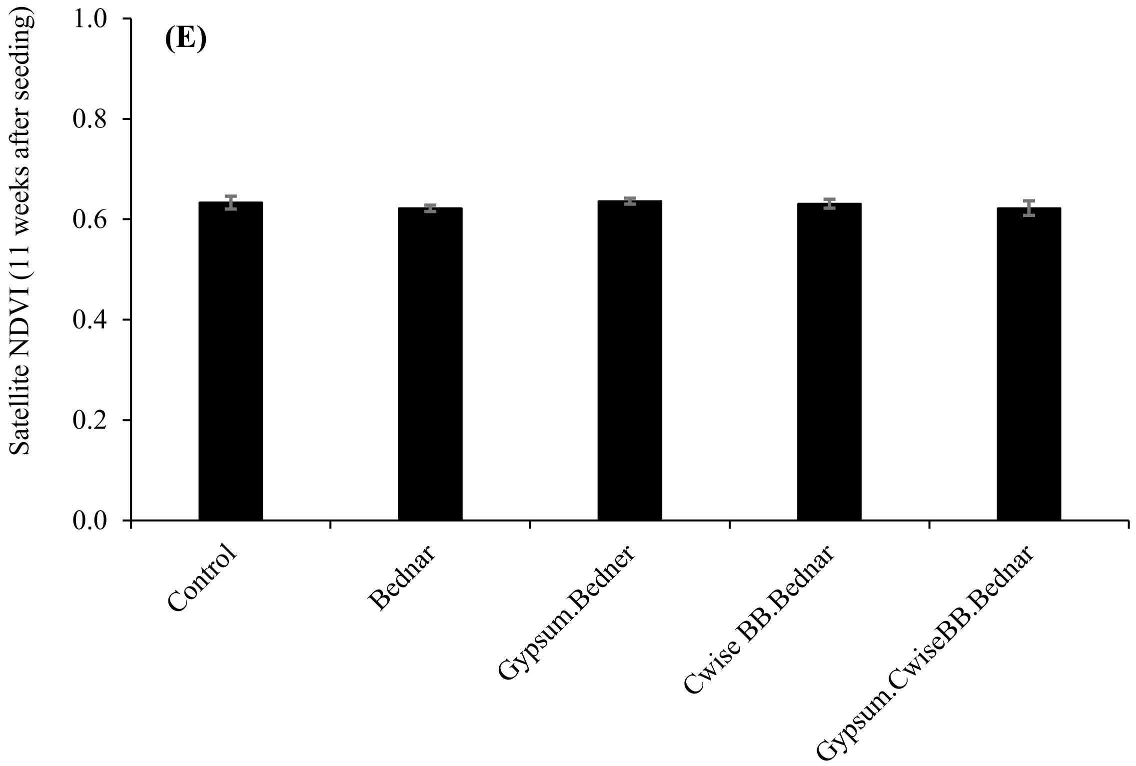
None of the recorded crop parameters (plants count, weeds count, NDVI, Yield, Protein content) have been recorded with a significant difference between the treatments in either of the experiments in 2024 (Fig. 9A-H and Fig. 10A-G).

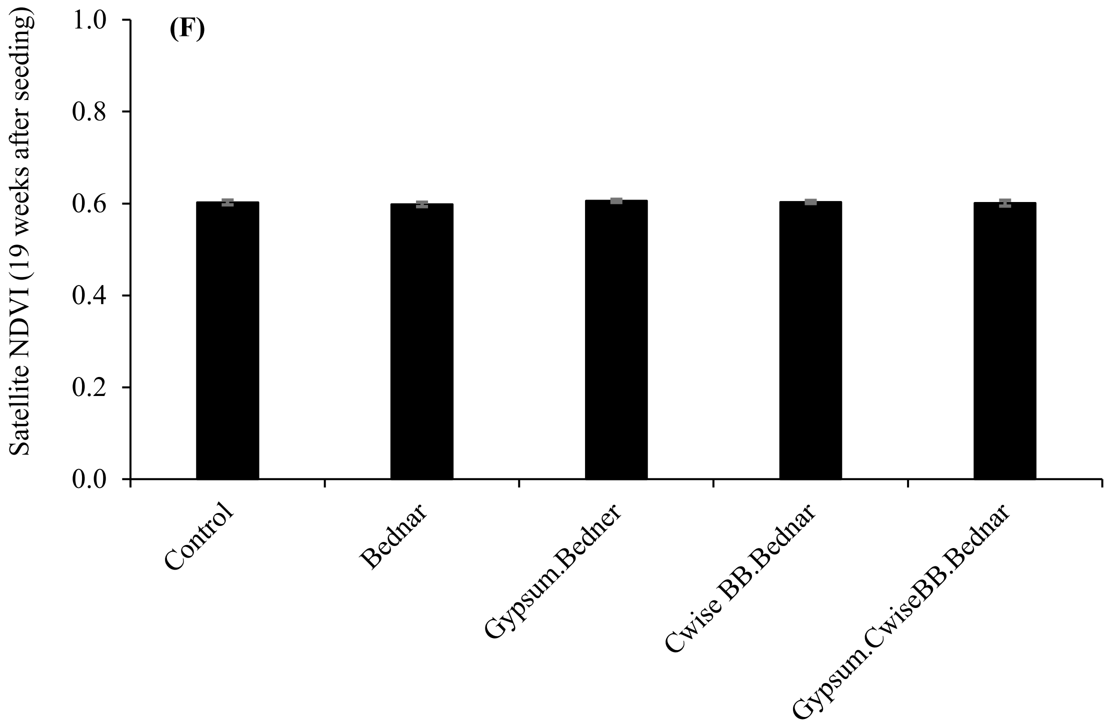


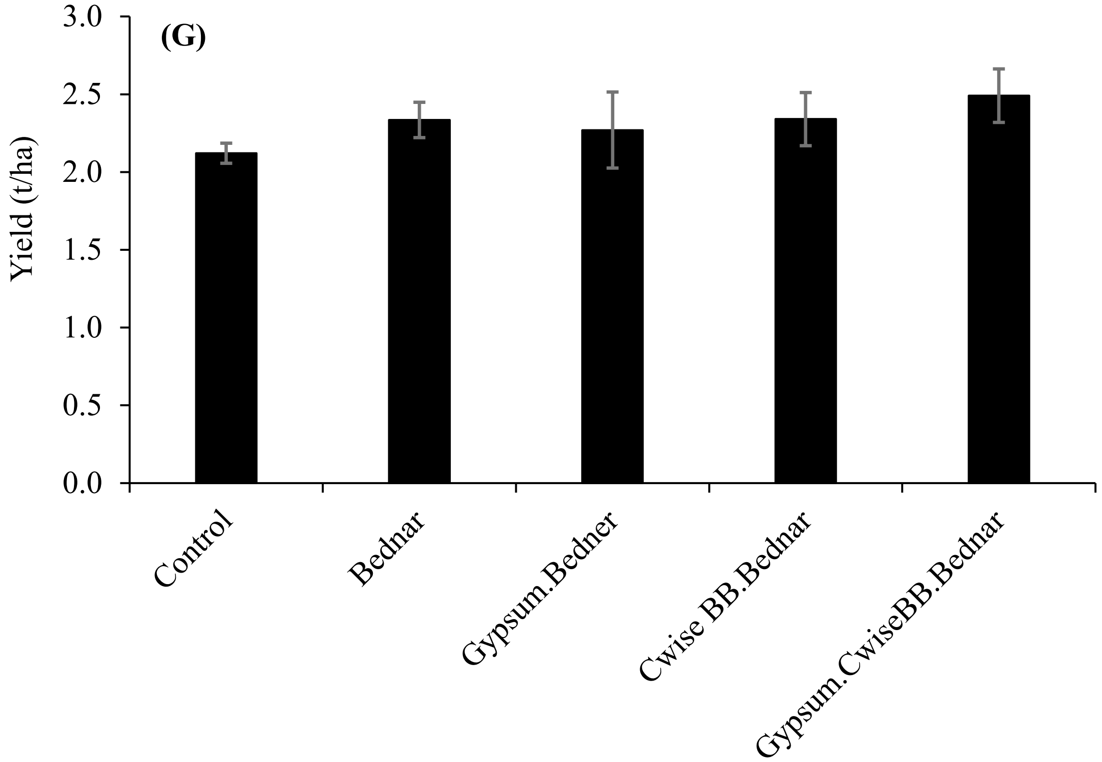



Hand NDVI (6 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
(C)
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


Satellite NDVI (8 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
(D)
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(E)
Satellite NDVI (11 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(F)
Satellite NDVI (19 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar



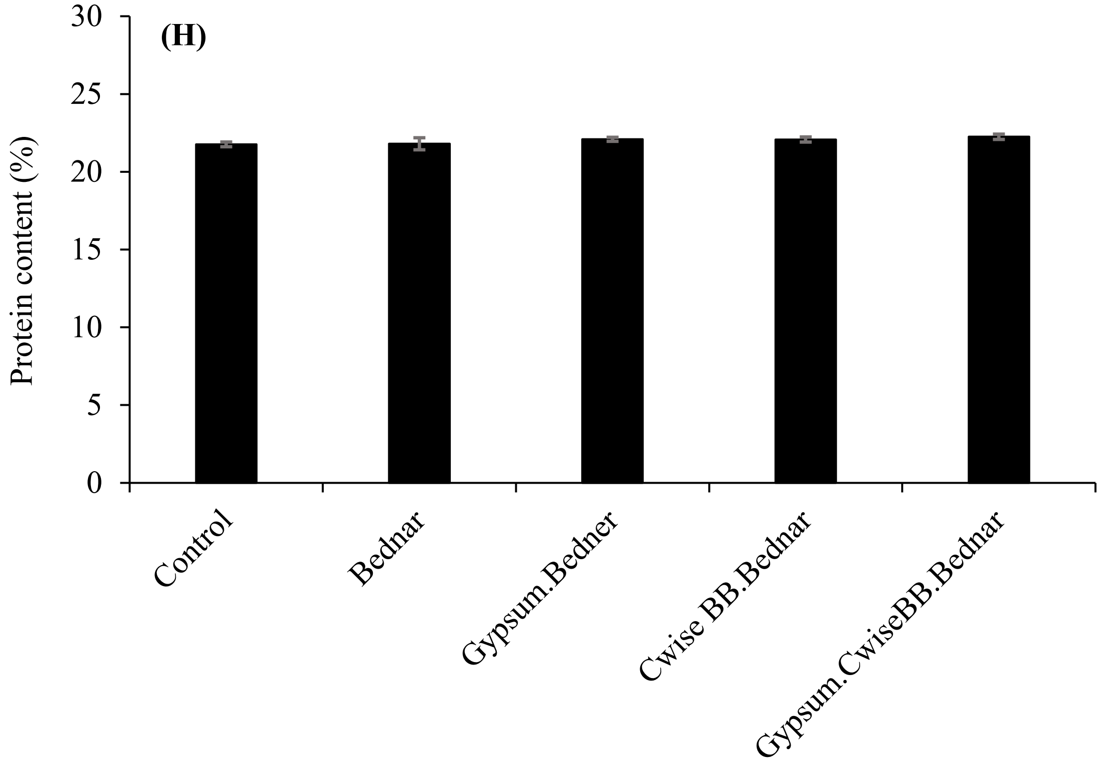
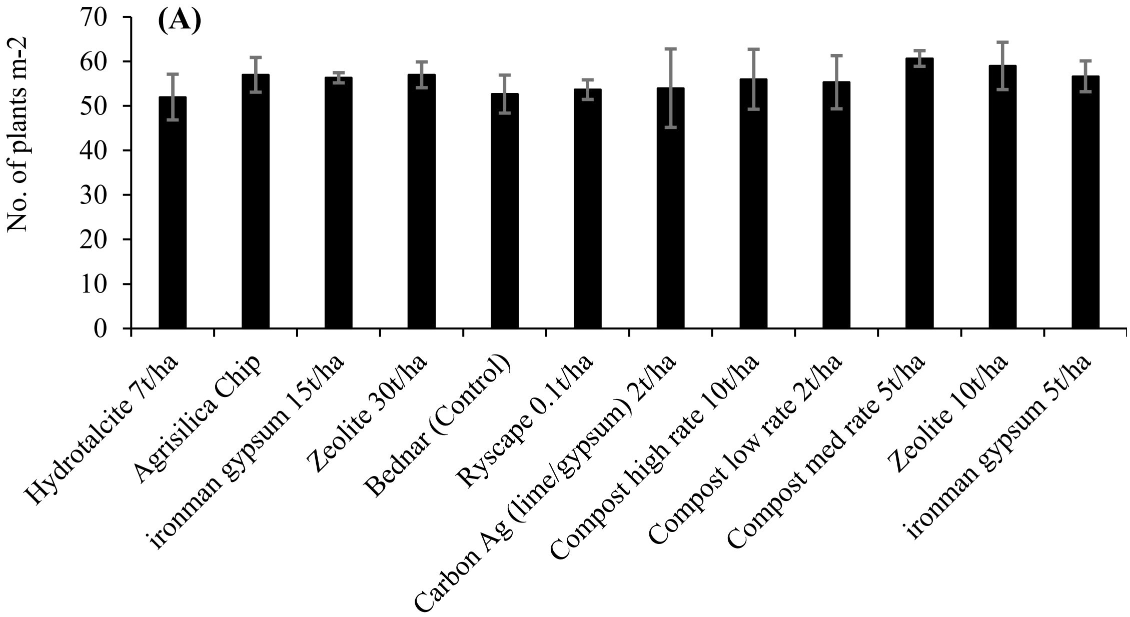
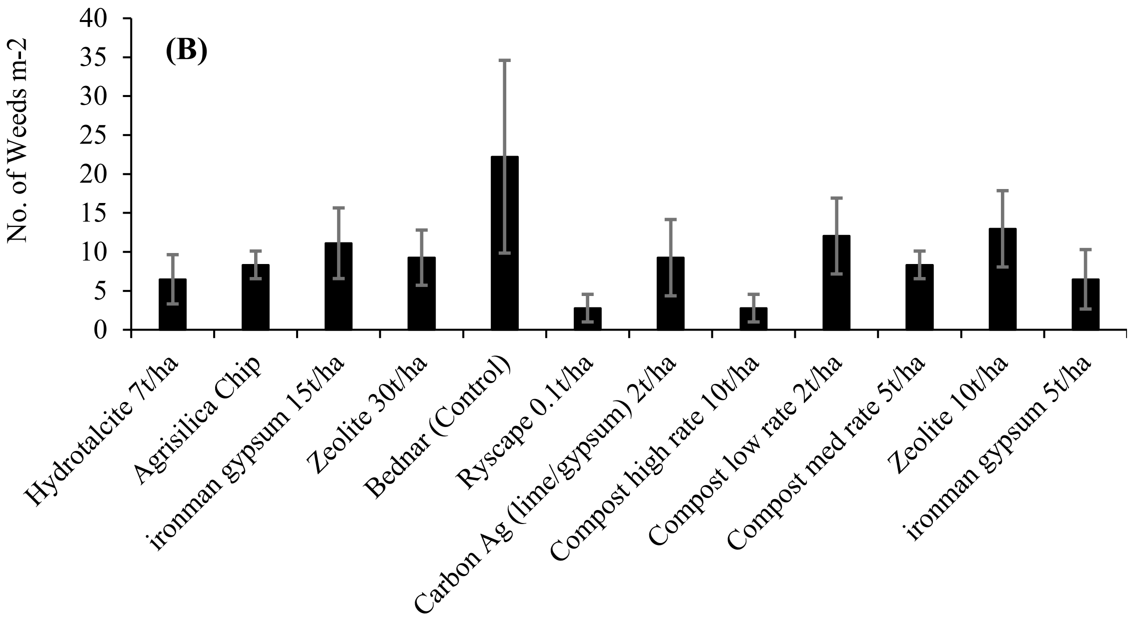
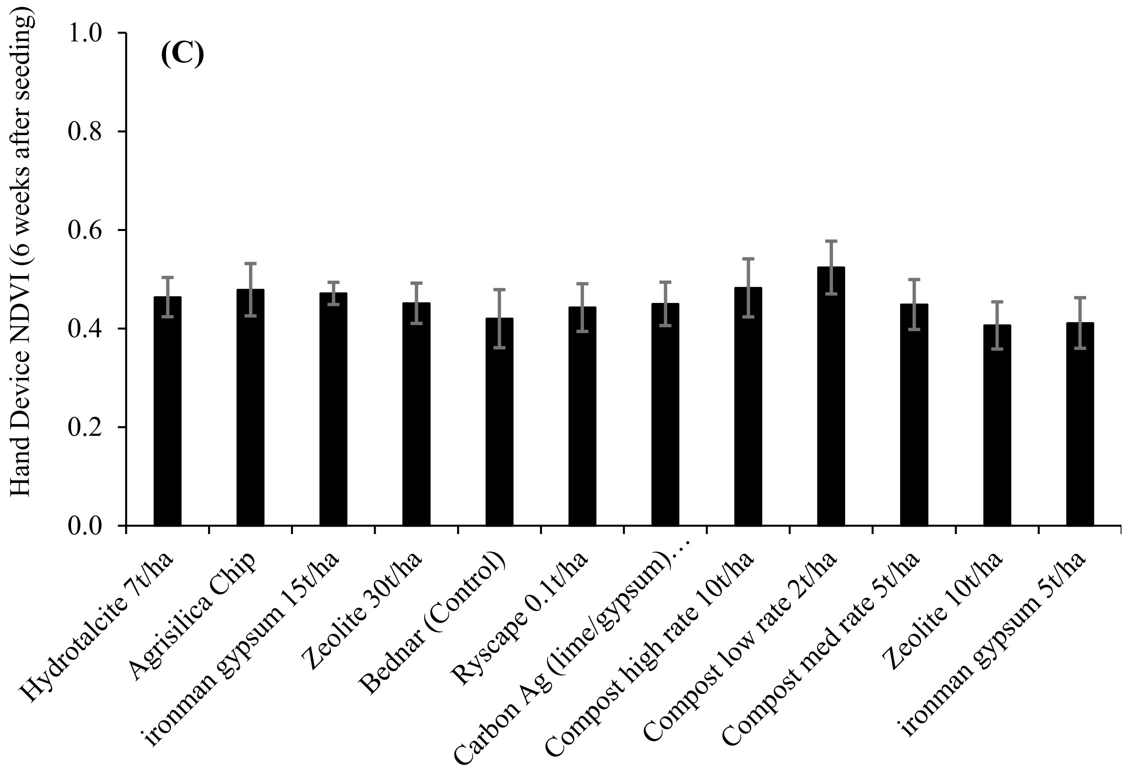


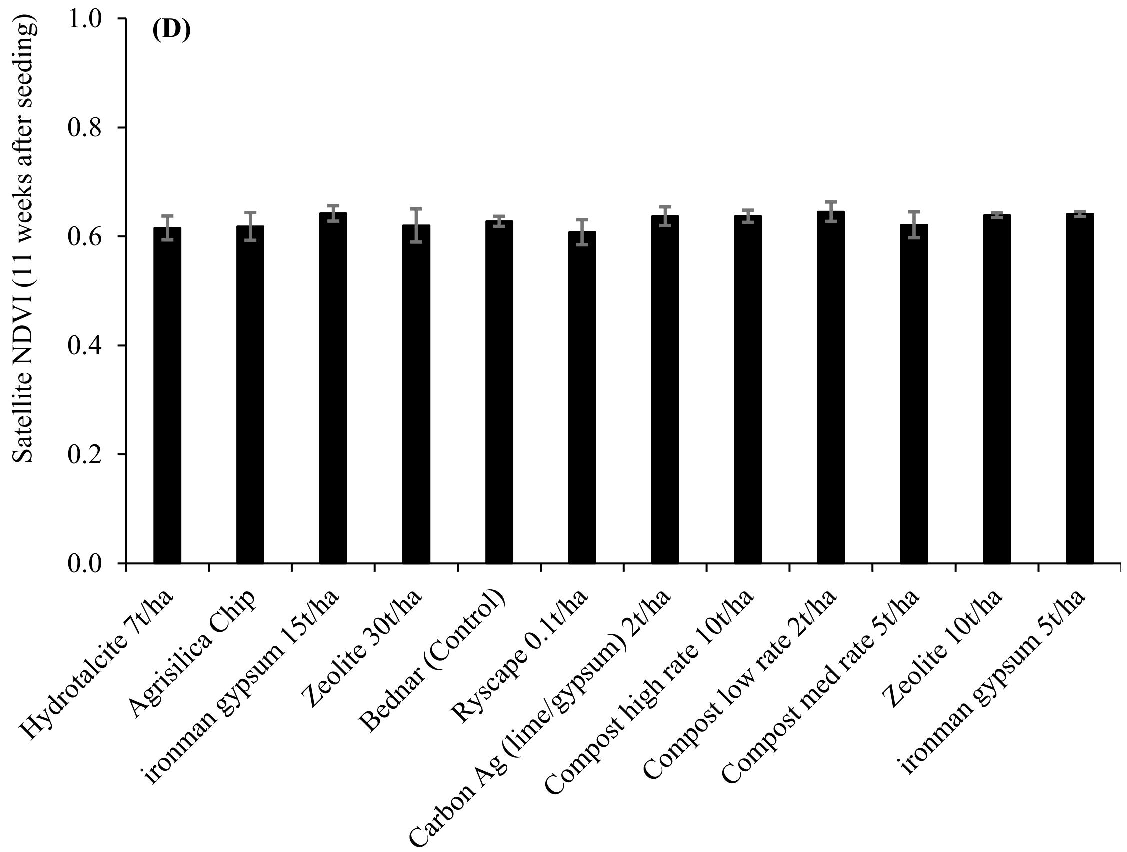
Fig. 9. Influence of the soil treatments and ameliorants on various growth and developmental parameters of Canola crop in the large plots experiment in 2024. **(A)** Number of plants m^{-2}. **(B)** No. of weeds m^{-2}. **(C)** Hand-based NDVI recorded at 6 weeks after seeding. **(D)** Satellite-based NDVI recorded 8 weeks after seeding. **(E)** Satellite-based NDVI recorded 11 weeks after seeding. **(F)** Satellite-based NDVI recorded 19 weeks after seeding. **(G)** Canola yield (t/ha). **(H)**

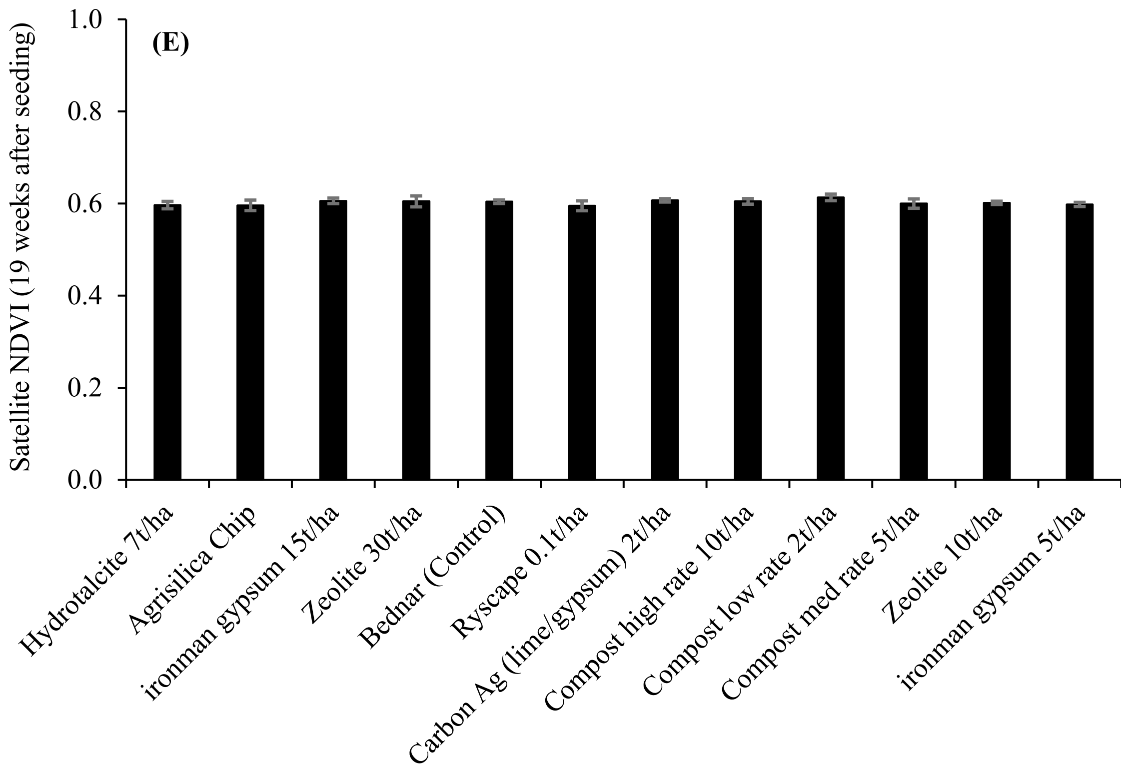
Protein content of the canola seed. Wherever the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD value ($\alpha = 95\%$) was used as a single error bar.

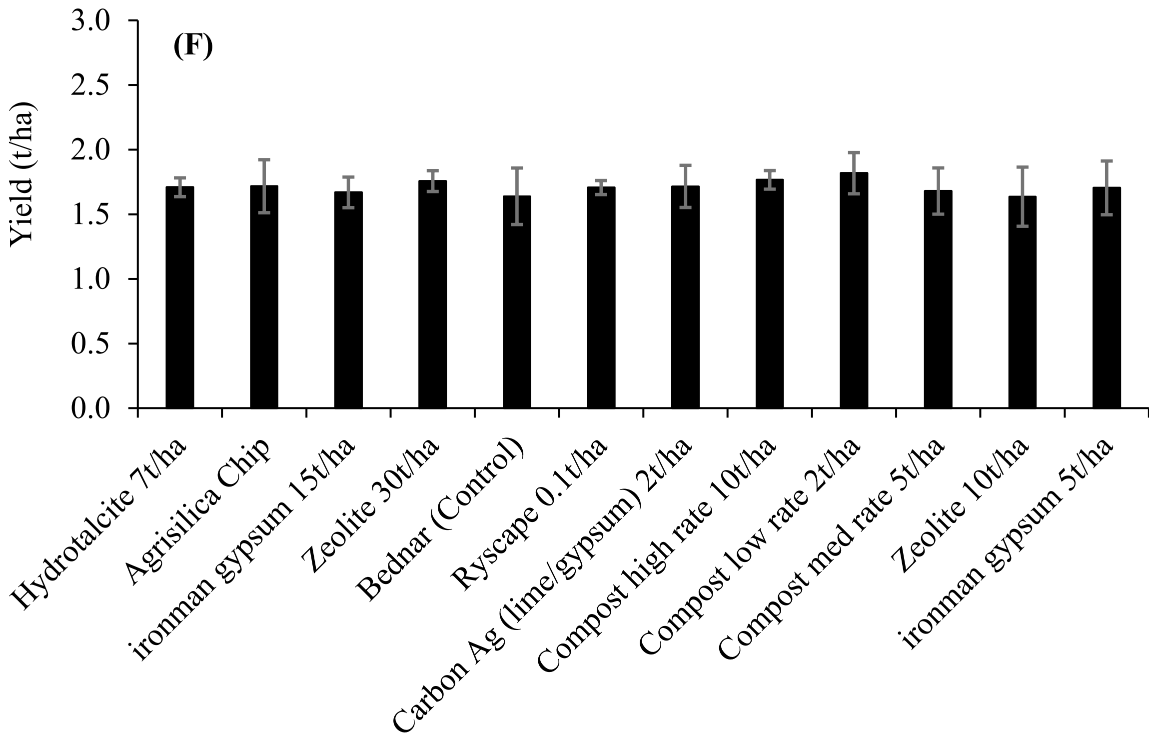





(C)
Hand Device NDVI (6 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum)…
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha


(D)
Satellite NDVI (11 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha


(E)
Satellite NDVI (19 weeks after seeding)
1.0
0.8
0.6
0.4
0.2
0.0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha


(F)
Yield (t/ha)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Bednar (Control)
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha

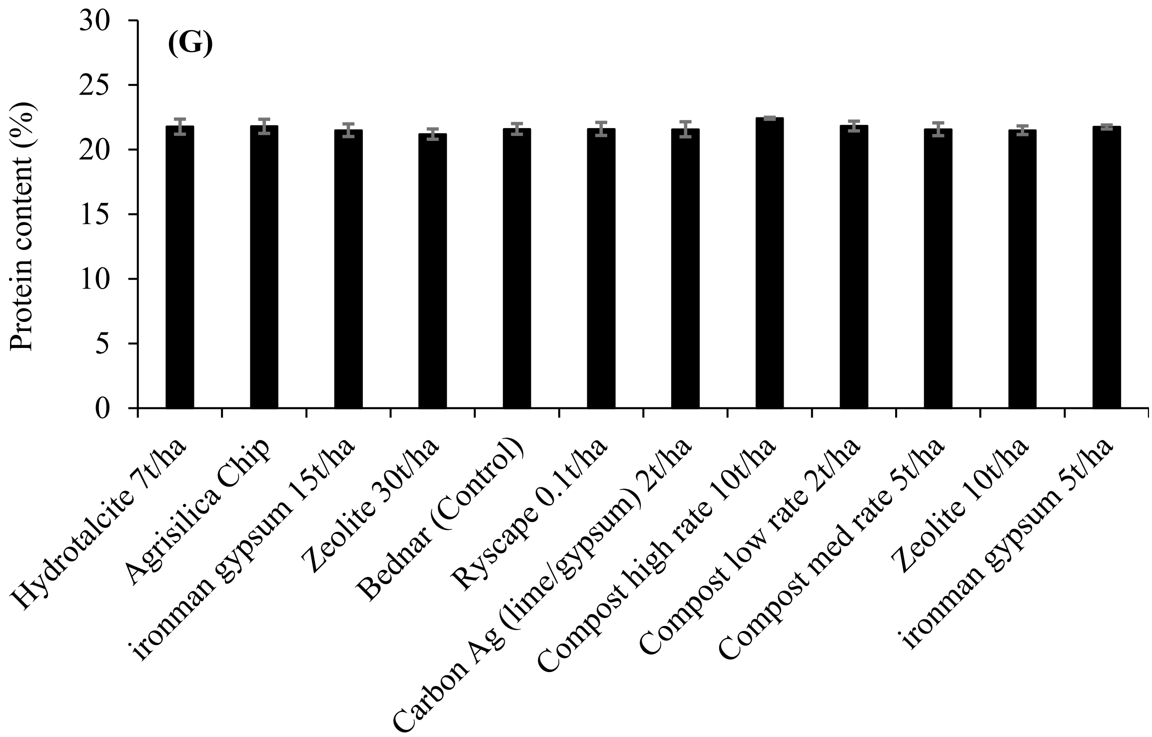


Fig. 10. Influence of the soil treatments and ameliorants on various growth and developmental parameters of Canola crop in the large plots experiment in 2024. **(A)** Number of plants m^{-2}. **(B)** No. of weeds m^{-2}. **(C)** Hand-based NDVI recorded at 6 weeks after seeding. **(D)** Satellite-based NDVI recorded 11 weeks after seeding. **(E)** Satellite-based NDVI recorded 19 weeks after seeding. **(F)** Canola yield (t/ha). **(G)** Protein content of the canola seed. Wherever the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD value ($\alpha = 95\%$) was used as a single error bar.

3.4. Soil Data (2022-2024)

Soil samples were collected before the start of experiment each year. In 2022, samples were collected from 0-10 and 10-30 cm profiles of only 4 replicates of control as a baseline sampling. In 2023, samples were collected only from the three treatments of the large plots experiment, i.e., from the control, bednar treated plots and the plots treated with Gypsum+Bedner. In April-2024, samples were collected from all the treatments and all replicates of both the large plots and small plots experiments.

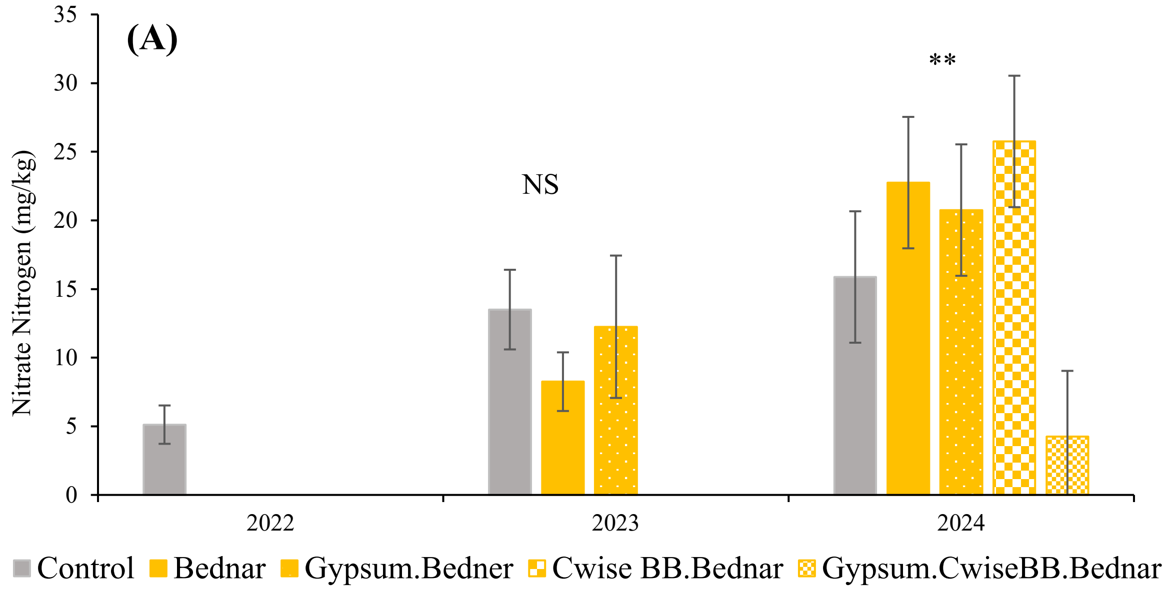
Statistical analysis of the soil data was carried out. Hence, there was no treatment comparison in 2022, only the mean value of the 4 replications of the control was calculated with standard error of the mean. For 2023 and 2024 data, a one-way ANOVA was performed using Block (rep) and Treatment as a Source of Variation in the analysis. Wherever, data was found to be significantly affected by the treatments in either 2023 or 2024 ($P \leq 0.05$), a standard error of the population mean for the experiment/year has been inserted as error bar on the data bars to compare the means in the figures. Where data was not significantly affected in any of the years ($P > 0.05$), the data have been represented in the tables rather than figures. Table 5-6 show such data of the large plots trial while Table 7-8 show such data of the small plots trial. Table 5 and 7 show non-significant data of the 0-10 cm profile from the large and small plots experiments respectively while able 6 and 8 show non-significant data of the 10-30 cm profile from the large and small plots experiments respectively.

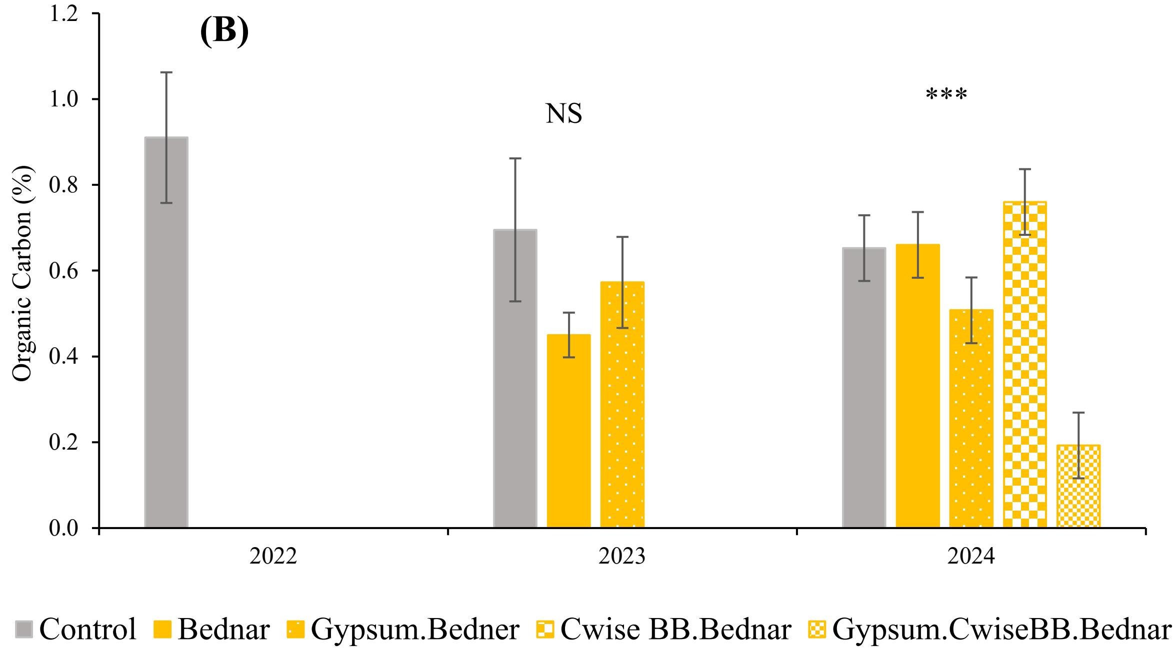
Soil data of the large plots experiment show that soil physio-chemical properties were different between the applied treatments mainly in the top 10 cm while remained similar between the treatments in the 10-30 cm profile (Fig. 11 and Table 5-6). Between the years, 2024 was found with more differences between the treatments in the large plots experiment relative to 2023 (Fig. 11A-I). In the large plots experiment in 2024, a reduction in the majority of soil charestiristics of the soil treated with Gypsum.CwiseBB.Bednar, such as nitrate nitrogen, organic carbon, conductivity, DTPA Manganese, DTPA Zinc, exchangeable Calcium and magnesium, was found relative to control (Fig. 11A-I). However, the soil treated with Cwise BB.Bednar was found with a significantly greater nitrate nitrogen and DTPA Copper as found in 2024 relative to control (Fig. 11A and E).

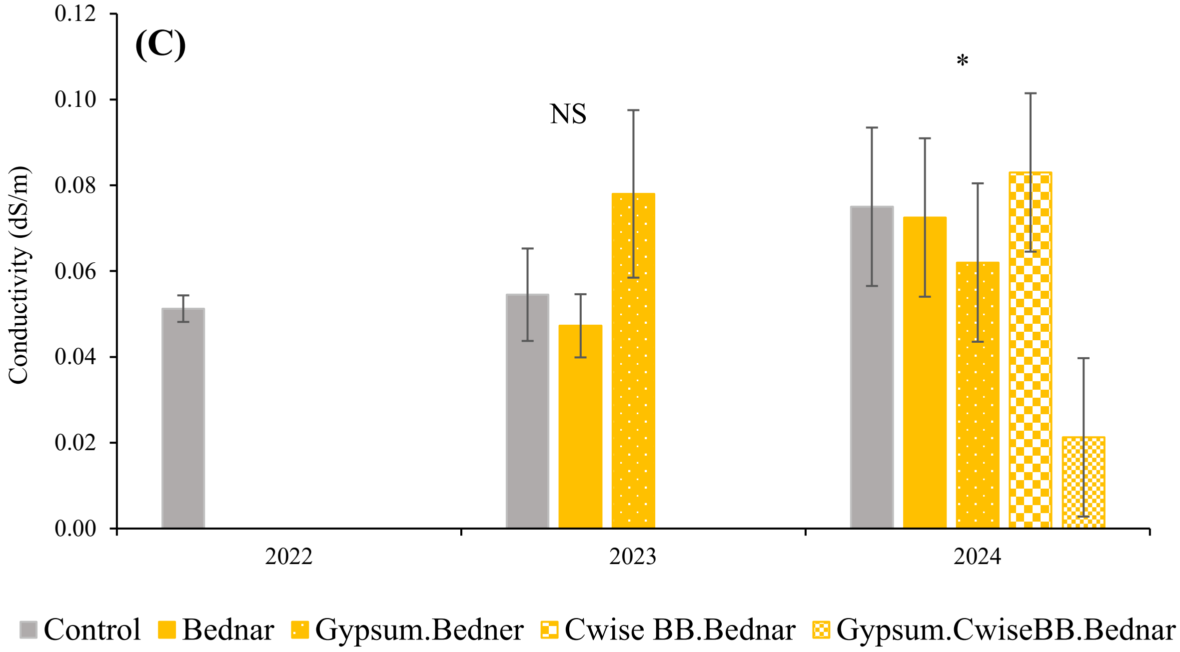
Contrasting to the large plots trial, changes in the physio-chemical attributes of soil were detected in both the topsoil (0-10 cm) and sub-soil (10-30 cm) (Fig. 12 and 13). Compost treated soil was found with a significantly greater value of phosphorus and potassium Colwell (mg/kg), DPTA Copper, DTPA Zinc, exchangeable Calcium, exchangeable Magnesium, exchangeable Potassium, exchangeable Sodium and Boron Hot $CaCl_2$ in the top 10 cm soil in the small plots trial (Fig. 12). This is consistent with the greater NDVI recorded by in the compost treatments (Fig. 8C). However, compost treatment did not stand out in the 10-30 cm soil profile (Fig. 13).

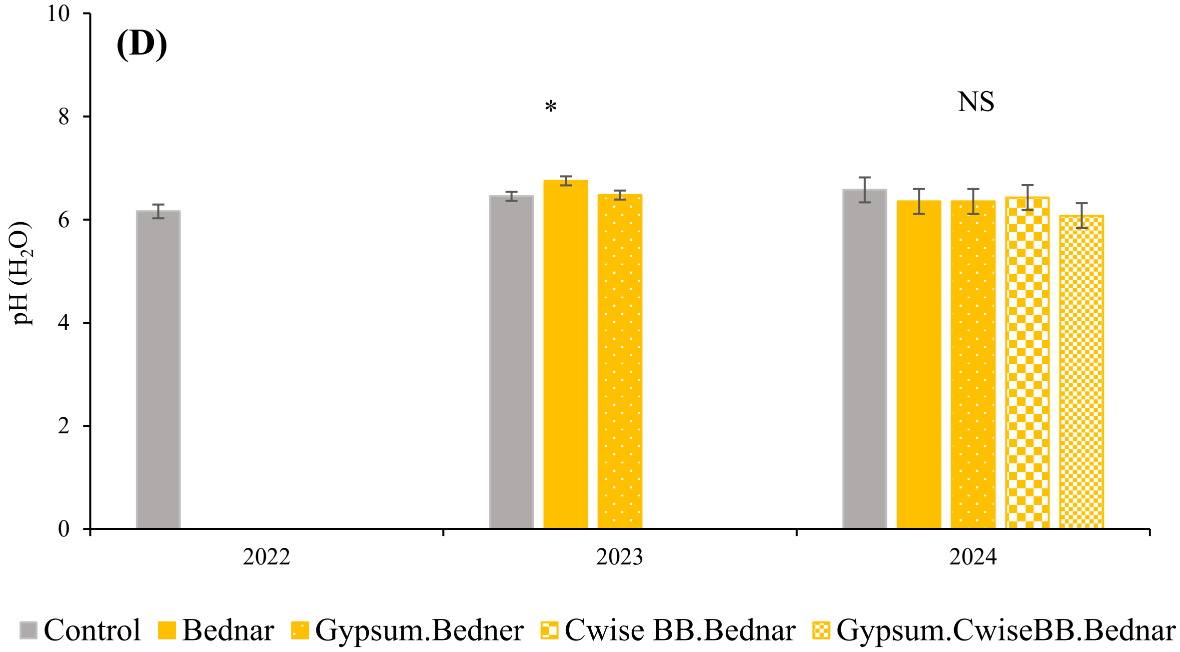
In both the experiments at Kweda site (large plots experiment and small plots experiment), differences were observed between the treatments in terms of the soil properties. For instance, the soil treated with Cwise Humiclay Compost + Bednar (large plots) was found with a significantly greater nitrate nitrogen and DTPA Copper in the top 10 cm soil as found in 2024 relative to control. Similarly, the Compost treated soil (small plots) was found with a significantly greater value of phosphorus and potassium Colwell (mg/kg), DPTA Copper, DTPA Zinc, exchangeable Calcium, exchangeable Magnesium, exchangeable Potassium, exchangeable Sodium and Boron Hot CaCl2 in the top 10 cm soil in the small plots trial. However, these changes in the soil properties did not reflect in the yield and no significant differences were observed in the yields of different treatments in 2024.

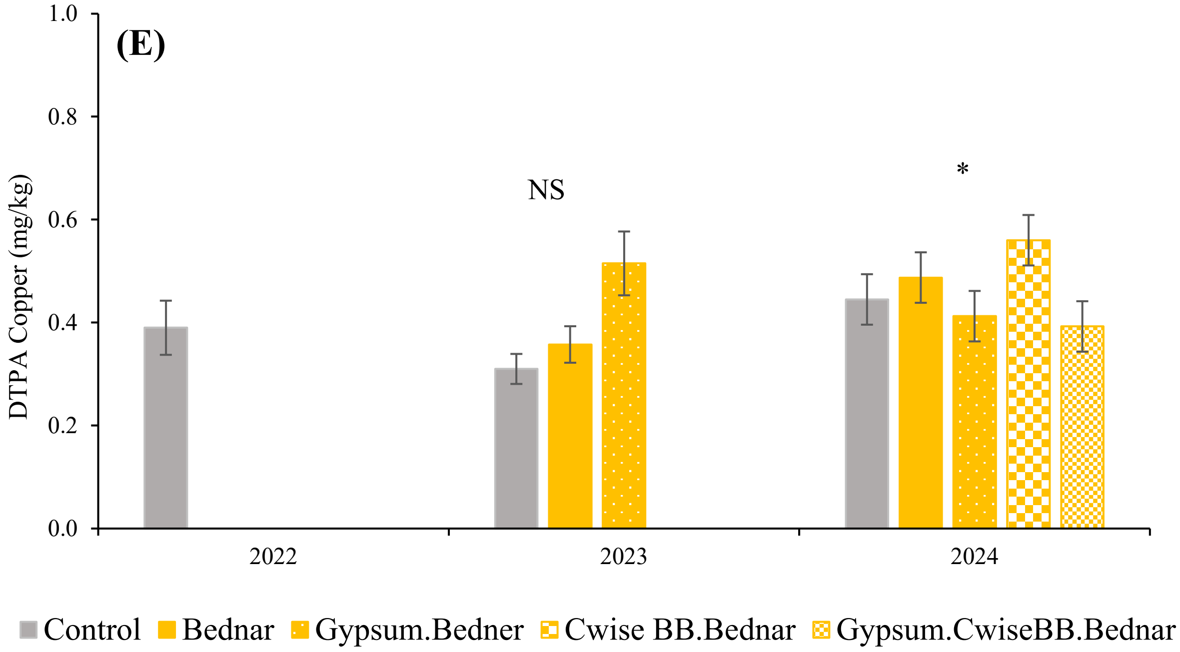
Another batch of samples has been collected from 0-10, 10-30 and 30-45 cm depth in March-2025. Samples have been sent for comprehensive analysis to the CSBP laboratory in Bibra Lake, WA and results are being awaited. In addition, samples for the Predictor B analysis (Soil DNA testing for nematodes by SARDI) have been collected from 0-10 and 10-30 cm depths of the selected treatments of the large plots experiment (Control, Bednar, Gypsum+Cwise+Bednar and small plots experiment (compost low rate, compost medium rate and compost high rate). Samples have already been sent to Katherine Linsell at SARDI, expected to be delivered by 10th of April.

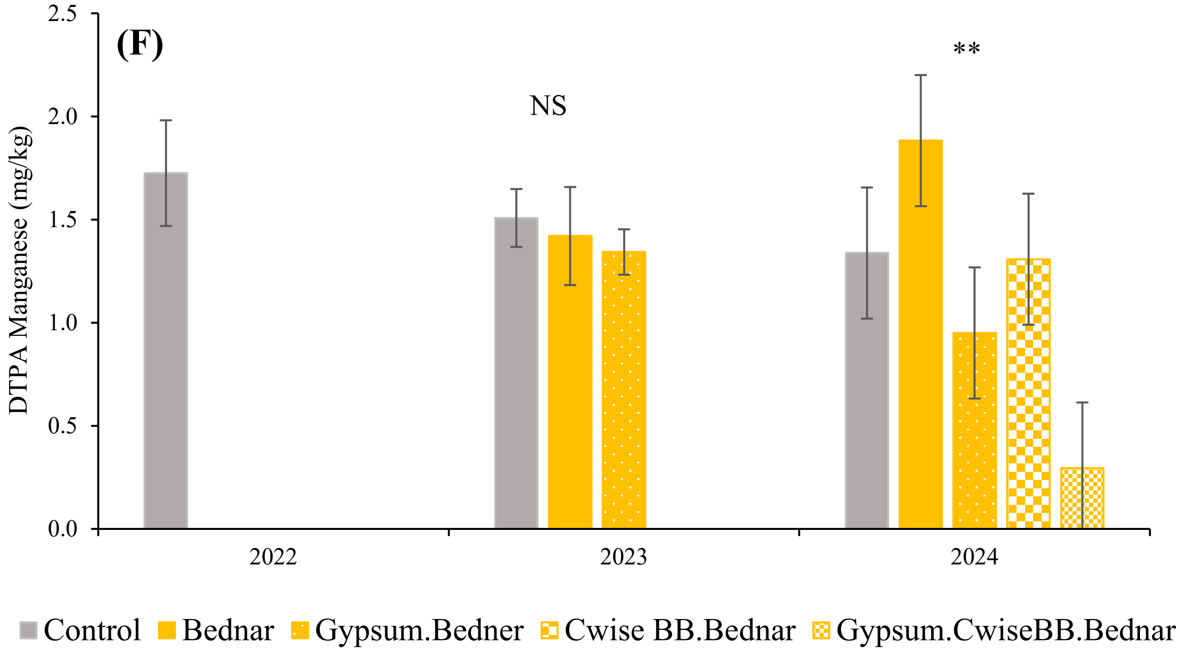

(A)
Nitrate Nitrogen (mg/kg)
35
30
25
20
15
10
5
0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar

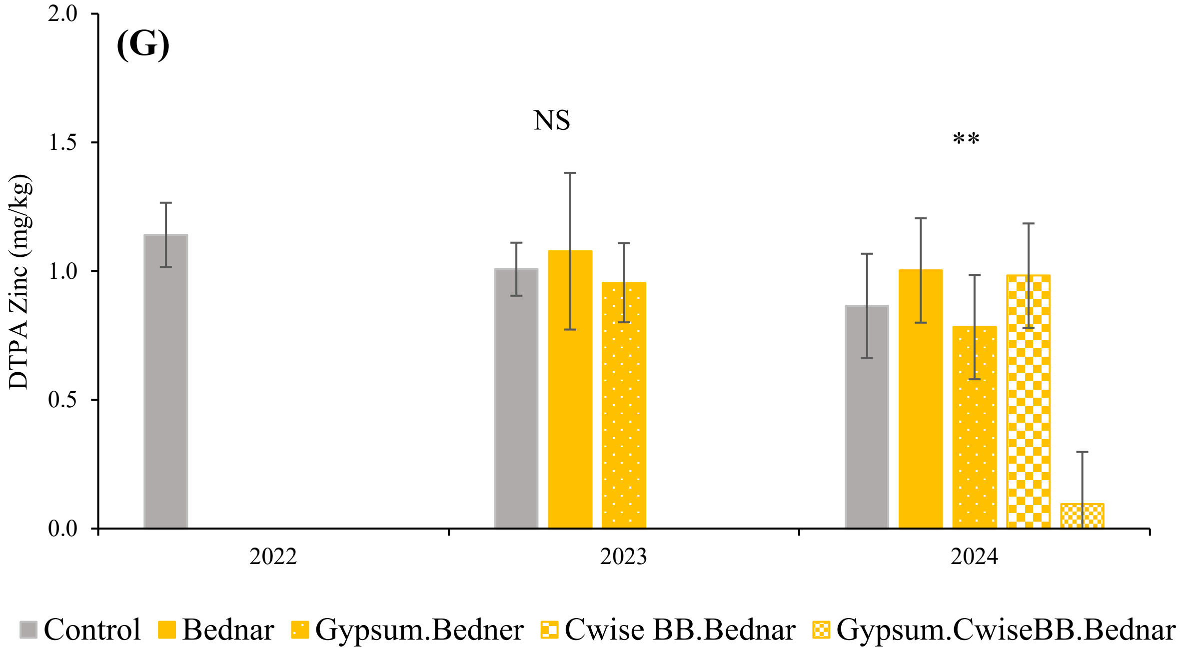

(B)
Organic Carbon (%)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
NS
***
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar

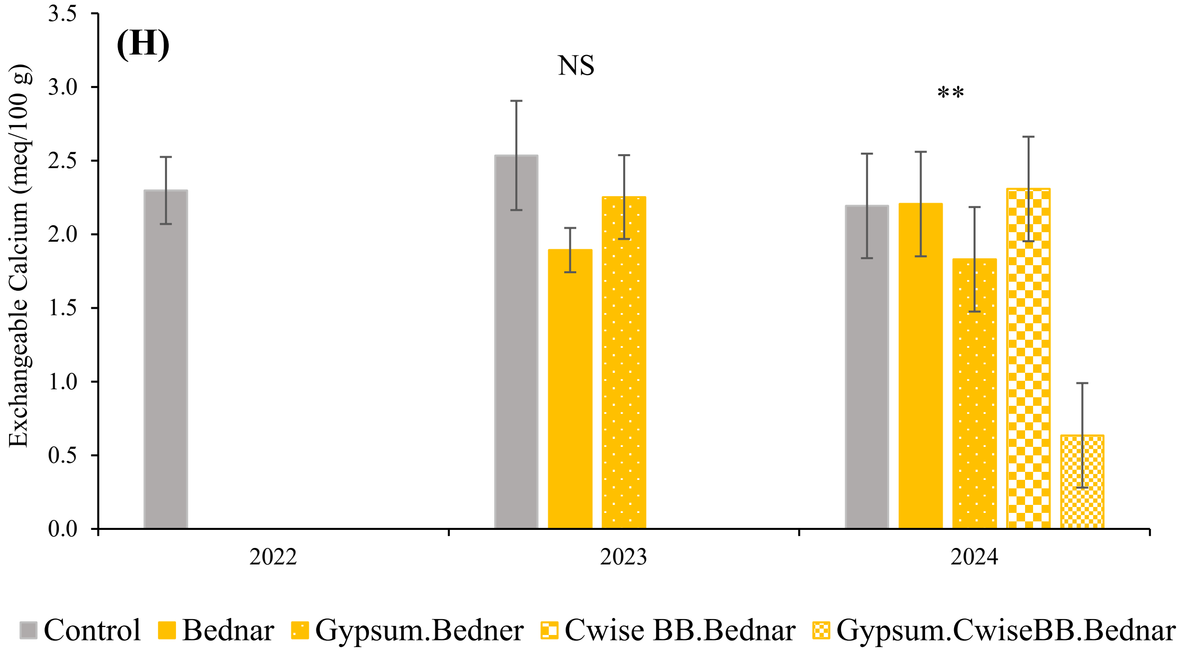

(C)
Conductivity (dS/m)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
NS
*
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(D)
pH (H2O)
10
8
6
4
2
0
*
NS
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(E)
DTPA Copper (mg/kg)
1.0
0.8
0.6
0.4
0.2
0.0
NS
*
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(F)
DTPA Manganese (mg/kg)
2.5
2.0
1.5
1.0
0.5
0.0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(G)
DTPA Zinc (mg/kg)
2.0
1.5
1.0
0.5
0.0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(H)
Exchangeable Calcium (meq/100 g)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar

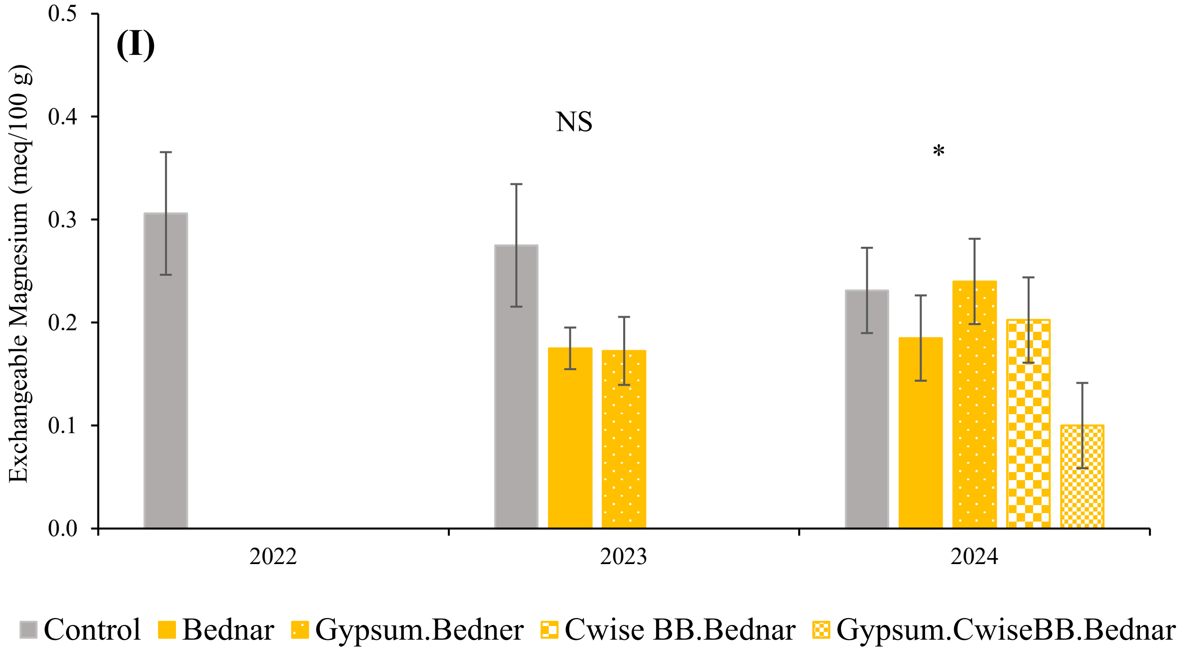


Fig. 11. Soil physio-chemical properties and nutrients in 0-10 cm profile in the large plots experiment during different years (2022-2024). **(A)** Nitrate Nitrogen (mg/kg). **(B)** Organic Carbon (%). **(C)** Conductivity (dS/m). **(D)** pH (H_2O). **(E)** DTPA Copper (mg/kg). **(F)** DTPA Manganese (mg/kg). **(G)** DTPA Zinc (mg/kg). **(H)** Exchangeable Calcium (meq/100 g). **(I)** Exchangeable Magnesium (meq/100 g). NS = $P > 0.1$, † = $P < 0.1$, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$. Error bar is either the standard error of the treatment mean (n = 4) when $P > 0.05$ or the standard error of the population mean across the treatments when $P \leq 0.05$. Standard error of the population mean was calculated by using the following formula: Square Root of (2 × Mean Square of Error ÷ 4).

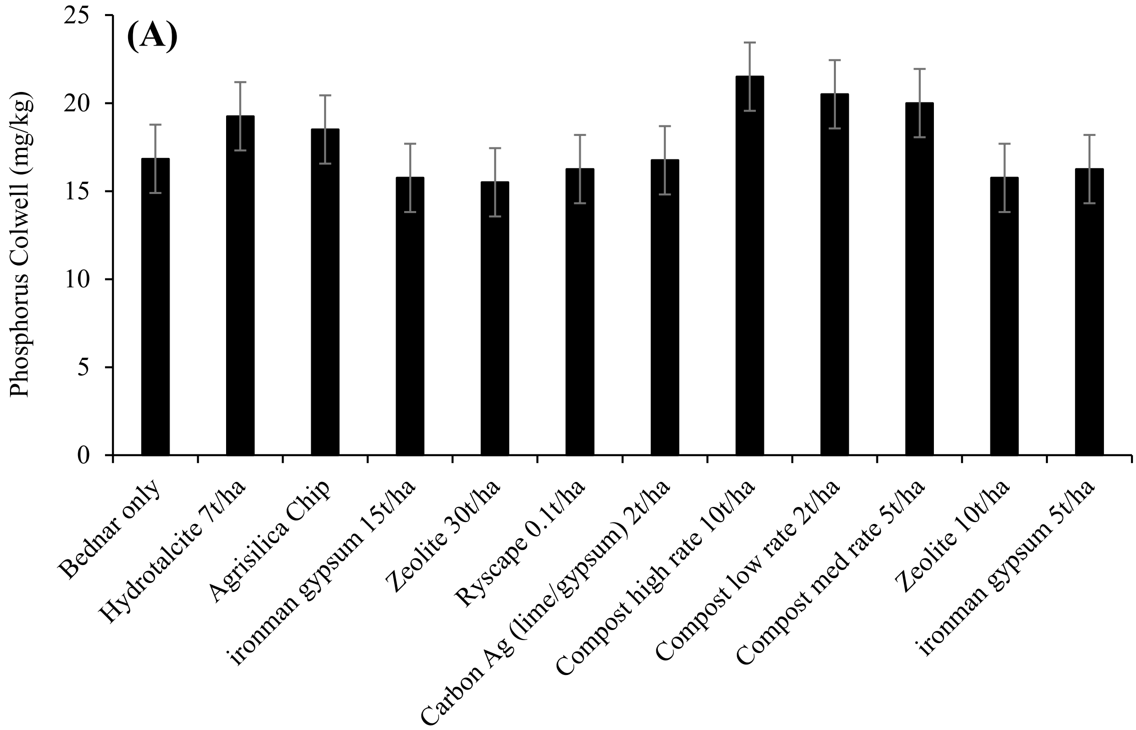
Table. 5. Soil properties (0-10 cm) measured in different soil treatments in the Large Plots Experiment at Kweda during different years. Samples were taken each year before seeding. Data is the mean of four replications ± standard error of the treatment mean (n = 4).

Soil properties	Year	Control	Bednar	Gypsum.Bedner	Cwise BB.Bednar	Gypsum.CwiseBB.Bednar
Ammonium Nitrogen (mg/kg)	2022	2.51 ± 0.28	No data	No data	No data	No data
	2023	0.95 ± 0.03	1.95 ± 0.61	0.98 ± 0.03	No data	No data
	2024	3.46 ± 0.42	1.78 ± 0.3	1.33 ± 0.27	1.85 ± 0.44	0.93 ± 0.03
Phosphorus Colwell (mg/kg)	2022	14.75 ± 0.81	No data	No data	No data	No data
	2023	14.5 ± 0.96	14.5 ± 0.87	13.5 ± 1.55	No data	No data
	2024	14.88 ± 2.66	13.25 ± 2.32	12.75 ± 1.44	14.75 ± 2.06	16.5 ± 2.47
Potassium Colwell (mg/kg)	2022	16.75 ± 3.82	No data	No data	No data	No data
	2023	10.48 ± 5.63	19.74 ± 7.79	10.98 ± 5.8	No data	No data
	2024	30.63 ± 3.35	29.75 ± 3.73	29.5 ± 4.35	27 ± 5.02	21.75 ± 5.92
Sulfur (mg/kg)	2022	5.98 ± 0.46	No data	No data	No data	No data
	2023	3.7 ± 1.81	6.83 ± 4.35	14.88 ± 4.05	No data	No data
	2024	16.38 ± 8	18 ± 8.33	12.33 ± 3.97	19.73 ± 8.75	3.48 ± 1.04
pH Level (CaCl2)	2022	5.69 ± 0.11	No data	No data	No data	No data
	2023	5.85 ± 0.06	6.13 ± 0.13	5.9 ± 0.09	No data	No data
	2024	5.85 ± 0.2	5.7 ± 0.15	5.68 ± 0.1	5.85 ± 0.21	5.13 ± 0.23
DTPA Iron (mg/kg)	2022	17.8 ± 6.52	No data	No data	No data	No data
	2023	10.65 ± 1.59	9.38 ± 0.5	9.13 ± 1.22	No data	No data
	2024	26.03 ± 11.2	27.18 ± 13.02	17.58 ± 4.91	17.23 ± 3.72	20.4 ± 5.89
Exc. Aluminium (meq/100 g)	2022	0.16 ± 0.02	No data	No data	No data	No data
	2023	0.05 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	No data	No data
	2024	0.06 ± 0.02	0.06 ± 0	0.04 ± 0.01	0.05 ± 0.01	0.1 ± 0.03
Exc. Potassium (meq/100 g)	2022	0.04 ± 0.01	No data	No data	No data	No data
	2023	0.05 ± 0.01	0.06 ± 0.02	0.05 ± 0.01	No data	No data
	2024	0.07 ± 0.01	0.06 ± 0.01	0.08 ± 0.01	0.05 ± 0	0.05 ± 0.01
Exc. Sodium (meq/100 g)	2022	0.06 ± 0.01	No data	No data	No data	No data
	2023	0.05 ± 0.01	0.02 ± 0	0.05 ± 0.01	No data	No data
	2024	0.06 ± 0.03	0.05 ± 0.02	0.05 ± 0.02	0.06 ± 0.02	0.02 ± 0
Aluminium CaCl2	2022	1 ± 0	No data	No data	No data	No data
	2023	No data	No data	No data	No data	No data
	2024	0.61 ± 0.2	0.57 ± 0.16	0.44 ± 0.04	0.33 ± 0.07	0.86 ± 0.08
Boron Hot CaCl2 (mg/kg)	2022	0.26 ± 0.03	No data	No data	No data	No data
	2023	0.23 ± 0.03	0.19 ± 0.03	0.18 ± 0.02	No data	No data
	2024	0.22 ± 0.03	0.21 ± 0.02	0.18 ± 0.02	0.22 ± 0.02	0.21 ± 0.03
PBI	2022	7.15 ± 1.2	No data	No data	No data	No data
	2023	3.93 ± 1.39	5.75 ± 1.43	7.8 ± 2.64	No data	No data
	2024	8.23 ± 0.35	11.7 ± 0.31	7.45 ± 0.91	8.45 ± 1.53	22.4 ± 8.93

Table. 6. Soil properties (10-30 cm) measured in different soil treatments of the large plots experiment at Kweda during different years. Samples were taken each year before seeding. Data is the mean of four replications ± standard error of the treatment mean (n = 4).

Soil properties	**Year**	**Control**	**Bednar**	**Gypsum.Bedner**	**Cwise BB.Bednar**	**Gypsum.Cwise BB.Bednar**
Ammonium Nitrogen (mg/kg)	2022	1.14 ± 0.1	No data	No data	No data	No data
	2023	0.9 ± 0	0.93 ± 0.03	0.9 ± 0	No data	No data
	2024	0.9 ± 0	0.93 ± 0.03	0.9 ± 0	0.93 ± 0.03	0.9 ± 0
Nitrate Nitrogen (mg/kg)	2022	2.5 ± 0.14	No data	No data	No data	No data
	2023	1 ± 0	5.75 ± 3.77	2 ± 0.41	No data	No data
	2024	5.1 ± 0.63	8.5 ± 2.1	7.25 ± 1.44	6.5 ± 0.65	5.75 ± 0.85
Phosphorus Colwell (mg/kg)	2022	21.1 ± 8.49	No data	No data	No data	No data
	2023	18 ± 3.16	12.75 ± 2.29	15 ± 1.78	No data	No data
	2024	17.5 ± 2.21	17.25 ± 0.85	15.75 ± 3.09	17 ± 2.55	16.25 ± 1.75
Potassium Colwell (mg/kg)	2022	13 ± 3	No data	No data	No data	No data
	2023	0.95 ± 0	4.96 ± 4.01	0.95 ± 0	No data	No data
	2024	18.7 ± 3.68	14.75 ± 0.25	20.75 ± 5.22	18.25 ± 1.11	14.5 ± 0.5
Sulfur (mg/kg)	2022	3.33 ± 0.88	No data	No data	No data	No data
	2023	0.58 ± 0.06	3.73 ± 2.86	2.2 ± 0.67	No data	No data
	2024	2.95 ± 0.91	2.93 ± 0.78	7.58 ± 2.98	4.1 ± 1.4	4.73 ± 0.78
Organic Carbon (%)	2022	0.43 ± 0.18	No data	No data	No data	No data
	2023	0.14 ± 0.02	0.21 ± 0.03	0.19 ± 0.03	No data	No data
	2024	0.18 ± 0.01	0.31 ± 0.06	0.31 ± 0.04	0.25 ± 0.03	0.18 ± 0.02
Conductivity (dS/m)	2022	0.02 ± 0	No data	No data	No data	No data
	2023	0.01 ± 0	0.03 ± 0.02	0.02 ± 0	No data	No data
	2024	0.02 ± 0	0.03 ± 0	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0
pH Level ($CaCl_2$)	2022	4.92 ± 0.18	No data	No data	No data	No data
	2023	5.1 ± 0.09	5.28 ± 0.05	5.33 ± 0.16	No data	No data
	2024	5 ± 0.12	5 ± 0.04	4.78 ± 0.13	5.05 ± 0.09	5 ± 0.04
pH Level (H_2O)	2022	5.73 ± 0.12	No data	No data	No data	No data
	2023	6.03 ± 0.07	6.15 ± 0.06	6.08 ± 0.22	No data	No data
	2024	5.9 ± 0.11	5.93 ± 0.05	5.55 ± 0.18	5.88 ± 0.13	5.8 ± 0.04
DTPA Copper (mg/kg)	2022	0.11 ± 0.01	No data	No data	No data	No data
	2023	0.21 ± 0.02	0.34 ± 0.05	0.32 ± 0.02	No data	No data
	2024	0.32 ± 0.05	0.36 ± 0.05	0.46 ± 0.07	0.33 ± 0	0.29 ± 0.03
DTPA Iron (mg/kg)	2022	16.27 ± 3.27	No data	No data	No data	No data
	2023	19.88 ± 6.47	11.43 ± 2.07	15.33 ± 3.7	No data	No data
	2024	24.08 ± 6.32	13.83 ± 3.07	30.05 ± 18.4	14.95 ± 3.47	15.48 ± 1.39
DTPA Manganese (mg/kg)	2022	0.23 ± 0.06	No data	No data	No data	No data
	2023	0.51 ± 0.01	0.64 ± 0.06	0.57 ± 0.03	No data	No data
	2024	0.29 ± 0.07	0.33 ± 0.05	0.45 ± 0.17	0.26 ± 0.03	0.28 ± 0.03
DTPA Zinc (mg/kg)	2022	0.21 ± 0.06	No data	No data	No data	No data
	2023	5.47 ± 2	3.58 ± 2.04	2.78 ± 1.4	No data	No data

	2024	0.18 ± 0.07	0.29 ± 0.08	0.17 ± 0.03	0.21 ± 0.04	0.13 ± 0.01
Exc. Aluminium (meq/100 g)	2022	0.29 ± 0.07	No data	No data	No data	No data
	2023	0.1 ± 0.02	0.07 ± 0.01	0.07 ± 0.01	No data	No data
	2024	0.11 ± 0.02	0.08 ± 0.01	0.17 ± 0.06	0.08 ± 0.01	0.09 ± 0.01
Exc. Calcium (meq/100 g)	2022	0.47 ± 0.16	No data	No data	No data	No data
	2023	0.43 ± 0.05	0.76 ± 0.15	0.7 ± 0.09	No data	No data
	2024	0.5 ± 0.12	0.78 ± 0.2	0.68 ± 0.09	0.64 ± 0.08	0.57 ± 0.05
Exc. Magnesium (meq/100 g)	2022	0.11 ± 0.04	No data	No data	No data	No data
	2023	0.08 ± 0.02	0.1 ± 0.03	0.07 ± 0.01	No data	No data
	2024	0.09 ± 0.01	0.1 ± 0.01	0.08 ± 0.01	0.1 ± 0.02	0.08 ± 0.01
Exc. Potassium (meq/100 g)	2022	0.03 ± 0.02	No data	No data	No data	No data
	2023	0.04 ± 0	0.05 ± 0.01	0.04 ± 0	No data	No data
	2024	0.04 ± 0.01	0.04 ± 0	0.04 ± 0.01	0.04 ± 0	0.03 ± 0
Exc. Sodium (meq/100 g)	2022	0.04 ± 0.01	No data	No data	No data	No data
	2023	0.01 ± 0	0.03 ± 0.02	0.02 ± 0.01	No data	No data
	2024	0.03 ± 0.01	0.02 ± 0	0.03 ± 0.02	0.02 ± 0.01	0.03 ± 0.01
Aluminium $CaCl_2$	2022	2.93 ± 0.63	No data	No data	No data	No data
	2023	No data	No data	No data	No data	No data
	2024	1.24 ± 0.41	1.14 ± 0.18	2.17 ± 0.84	1.5 ± 0.18	1.43 ± 0.17
Boron Hot $CaCl_2$ (mg/kg)	2022	0.17 ± 0.06	No data	No data	No data	No data
	2023	0.12 ± 0.01	0.14 ± 0.01	0.17 ± 0.05	No data	No data
	2024	0.22 ± 0.02	0.18 ± 0.01	0.24 ± 0.02	0.18 ± 0.01	0.19 ± 0.02
PBI	2022	16.05 ± 6.23	No data	No data	No data	No data
	2023	7 ± 2.27	9.03 ± 3.5	7.47 ± 2.04	No data	No data
	2024	17.49 ± 6.62	8.9 ± 0.9	8.9 ± 2.63	10.25 ± 0.92	12.03 ± 1.03



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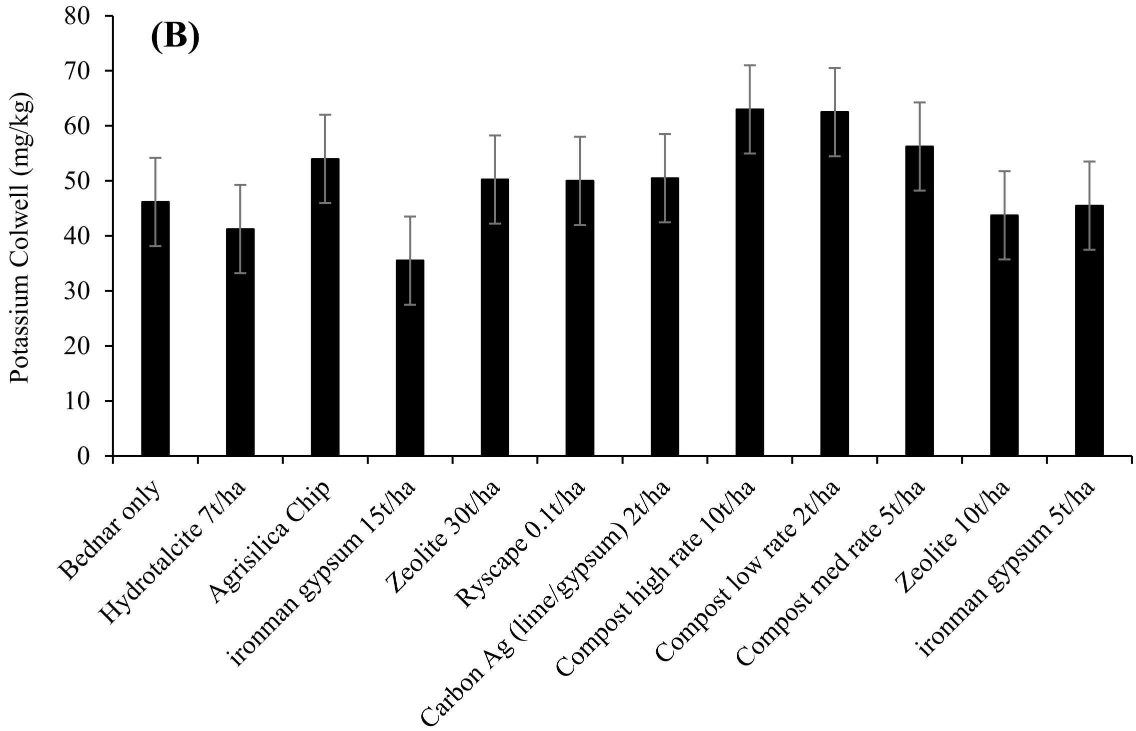

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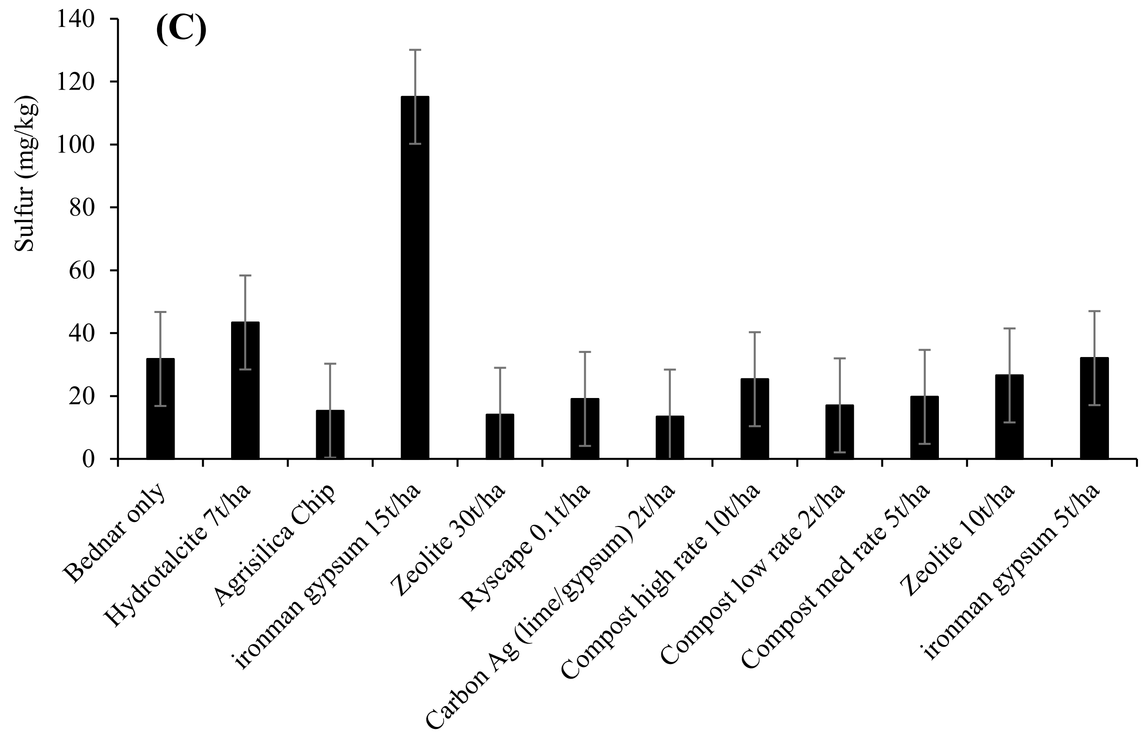

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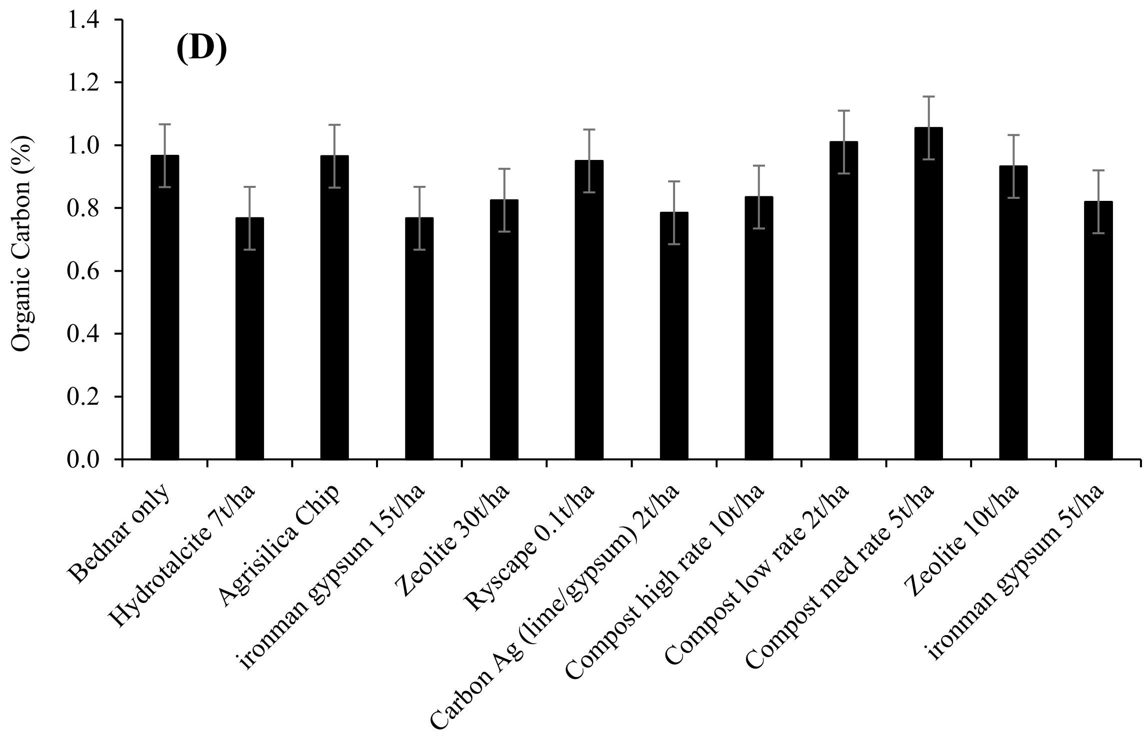

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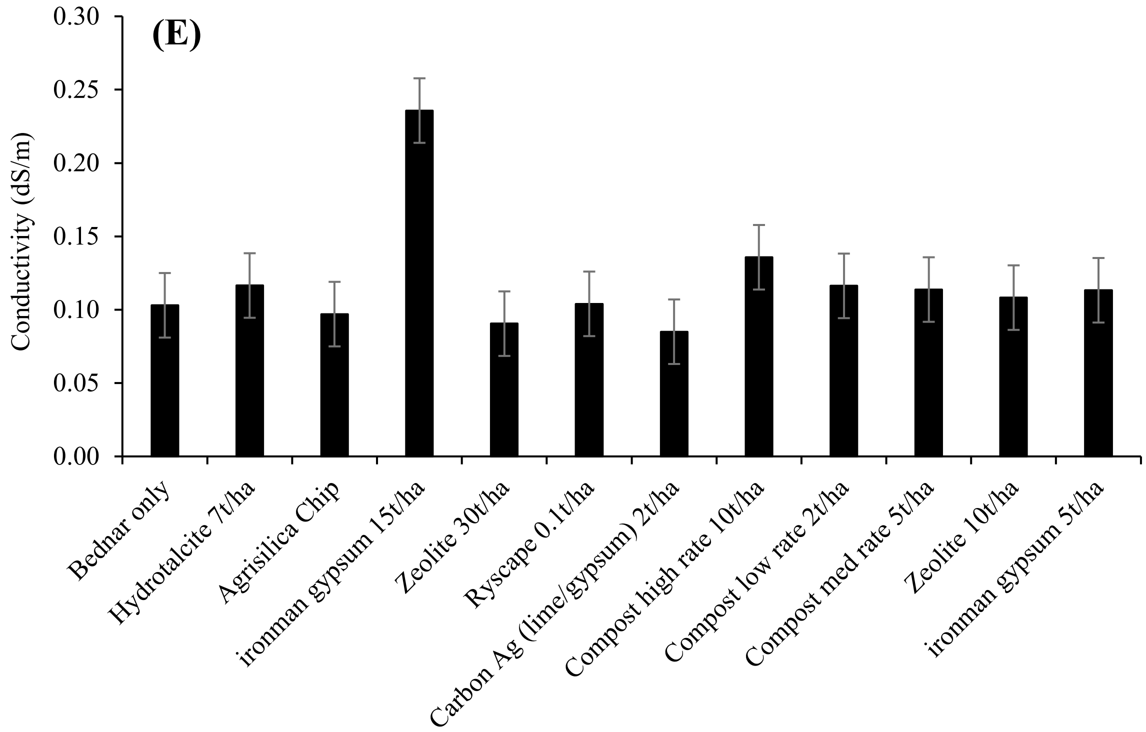

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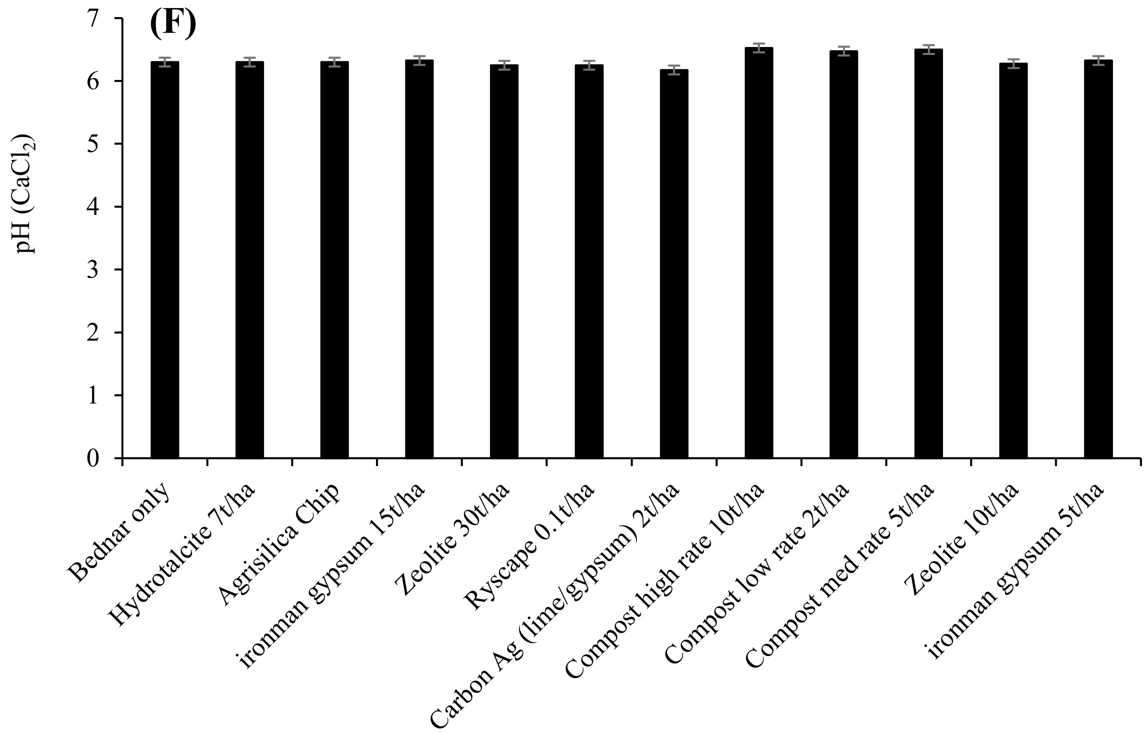

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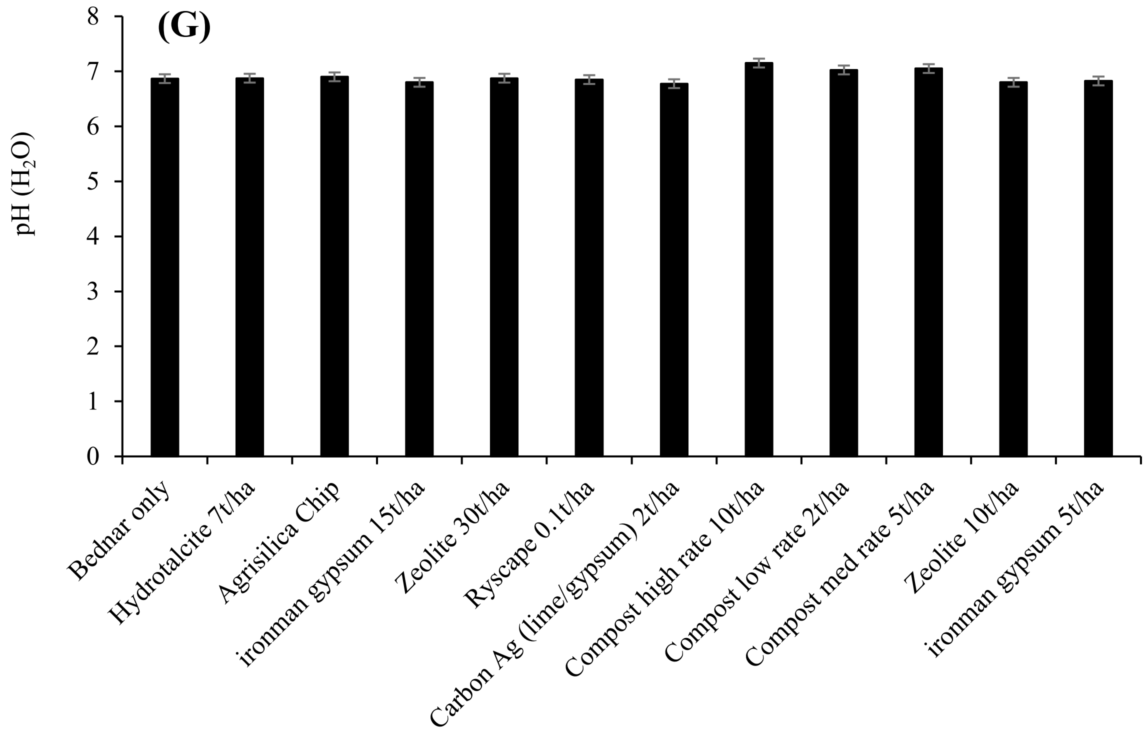

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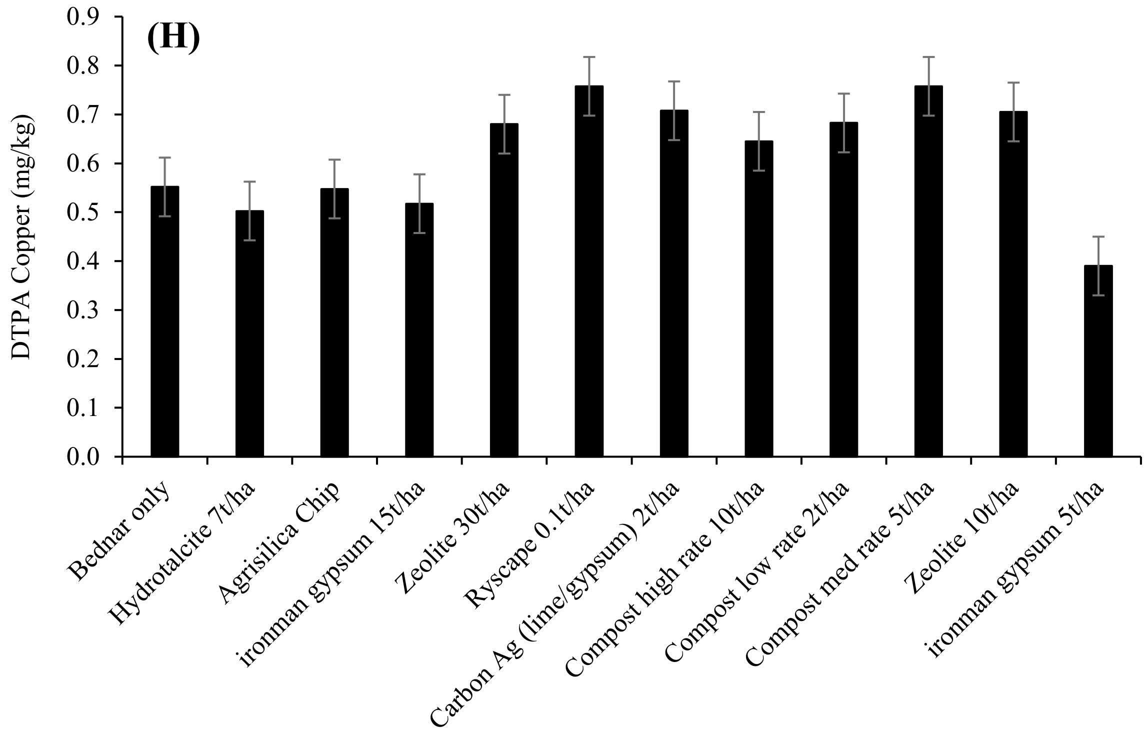

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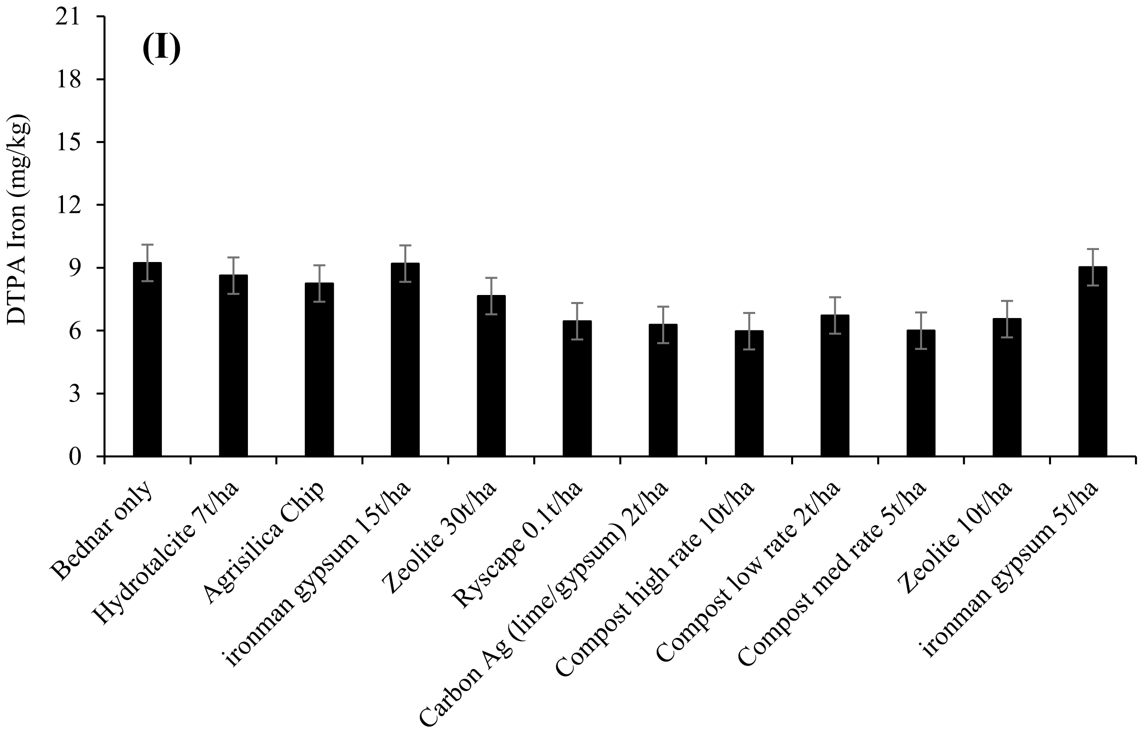

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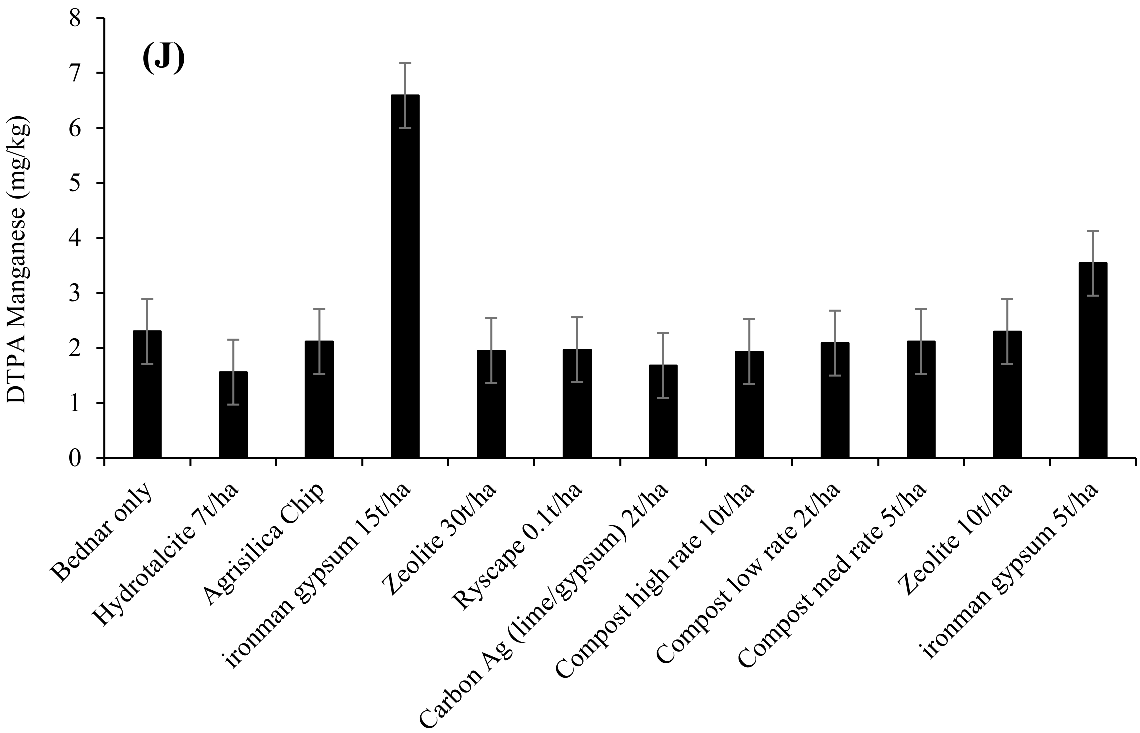

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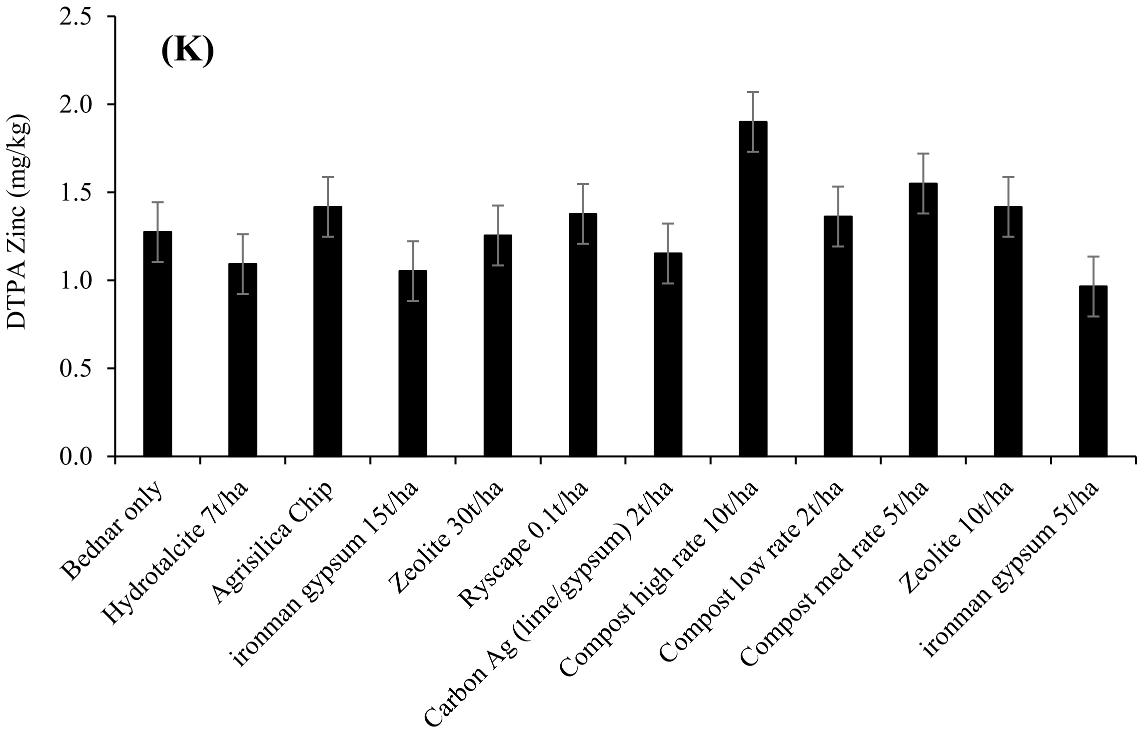

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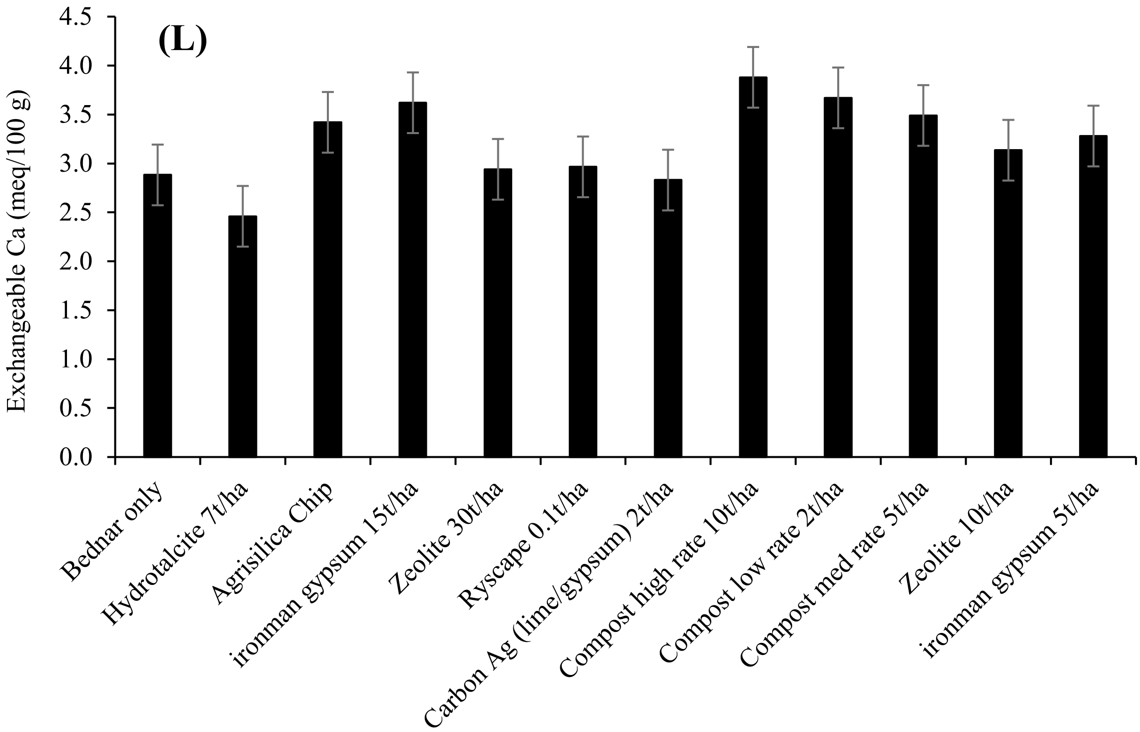

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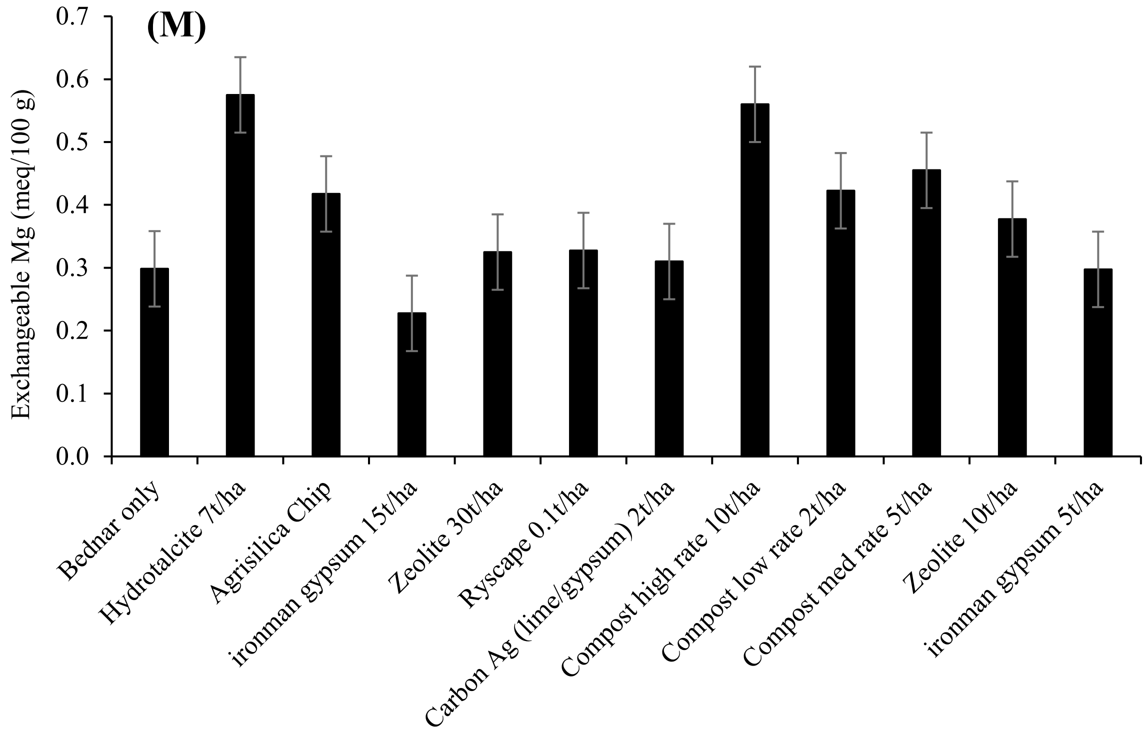

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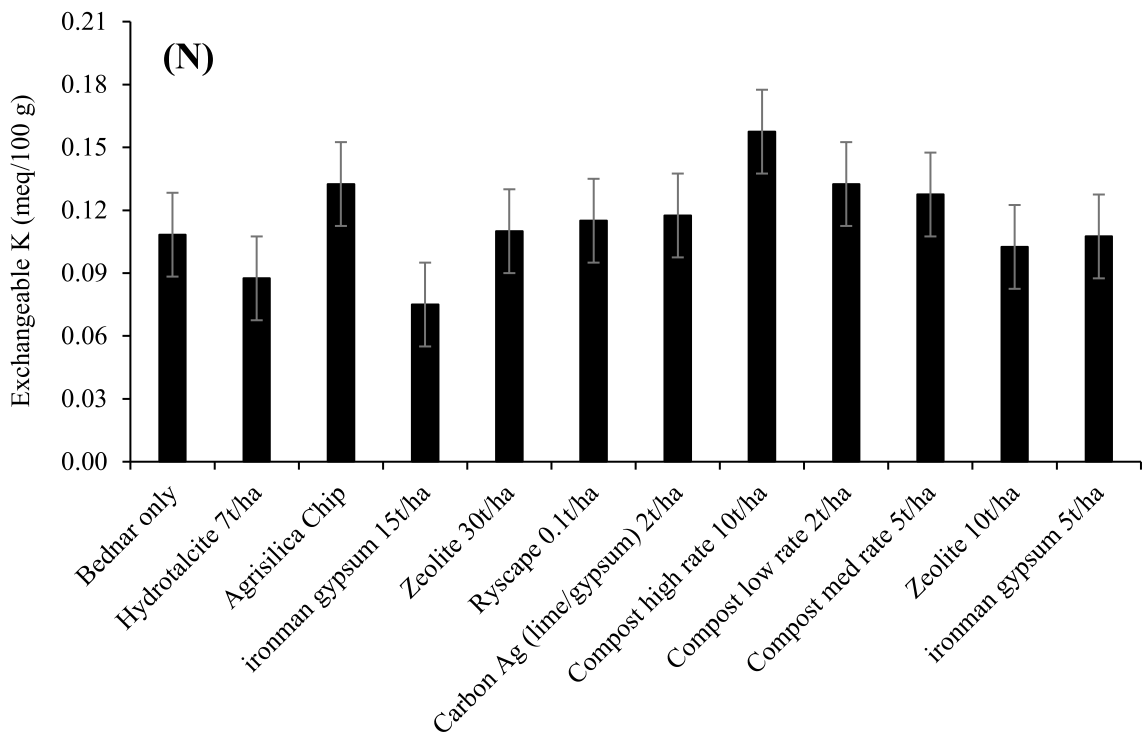
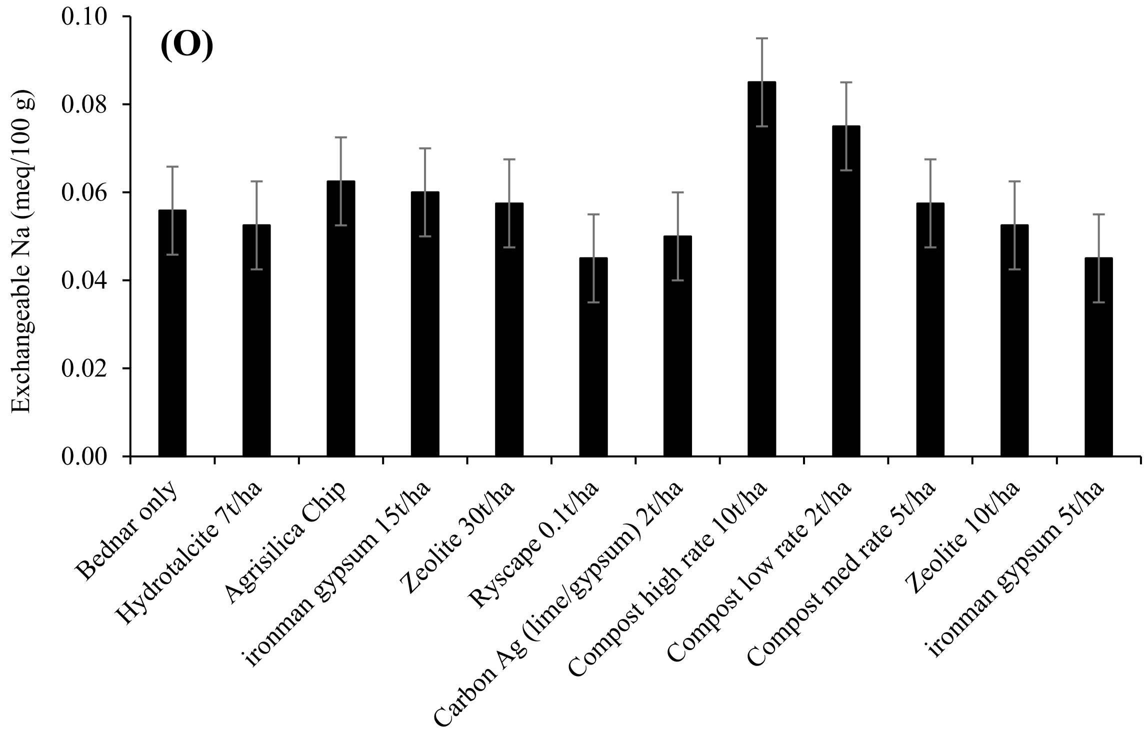


Signficance level: † (P = 0.098)



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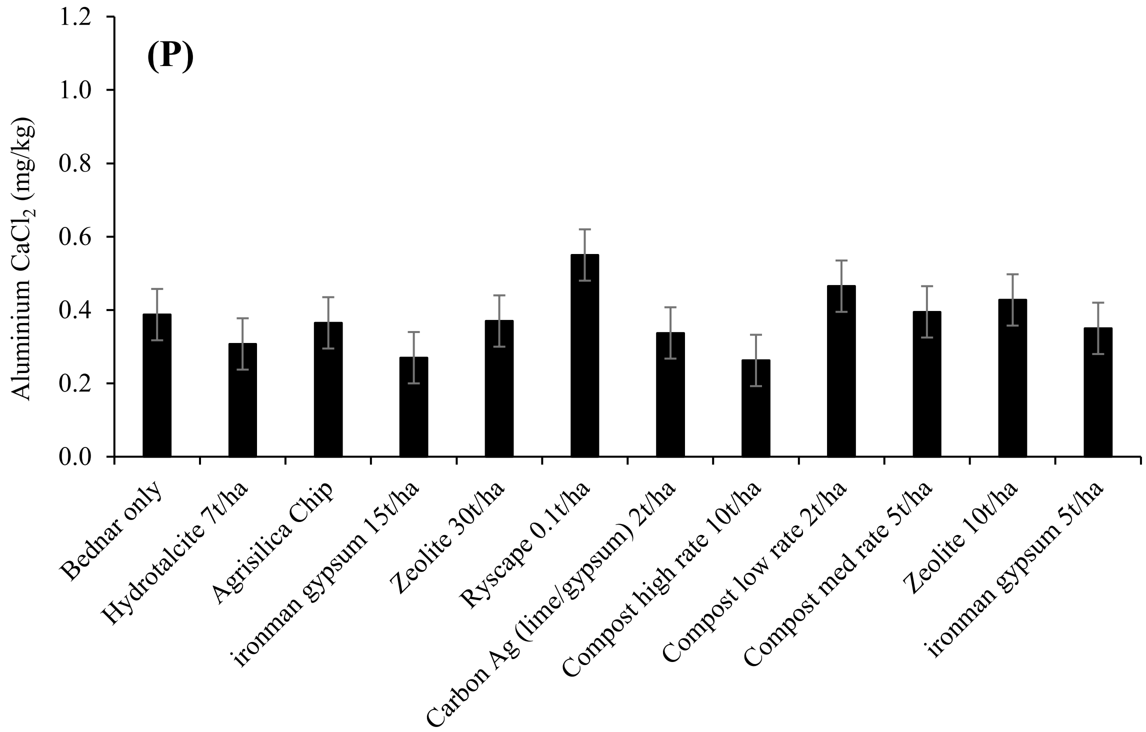
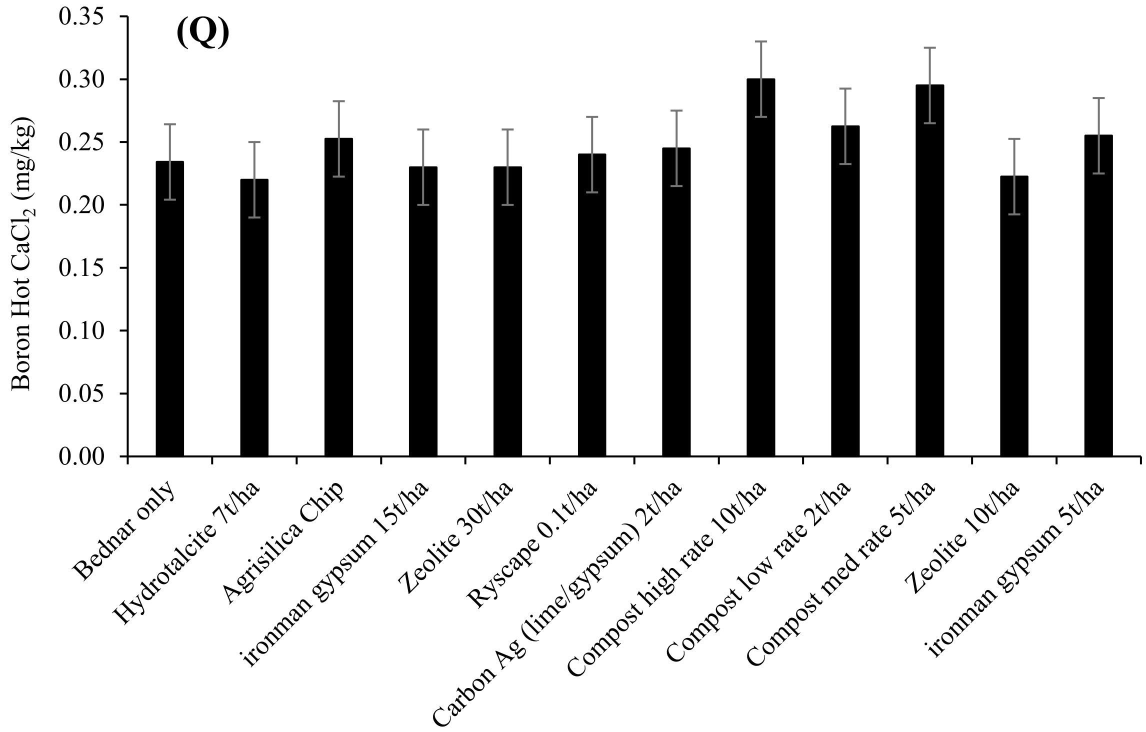
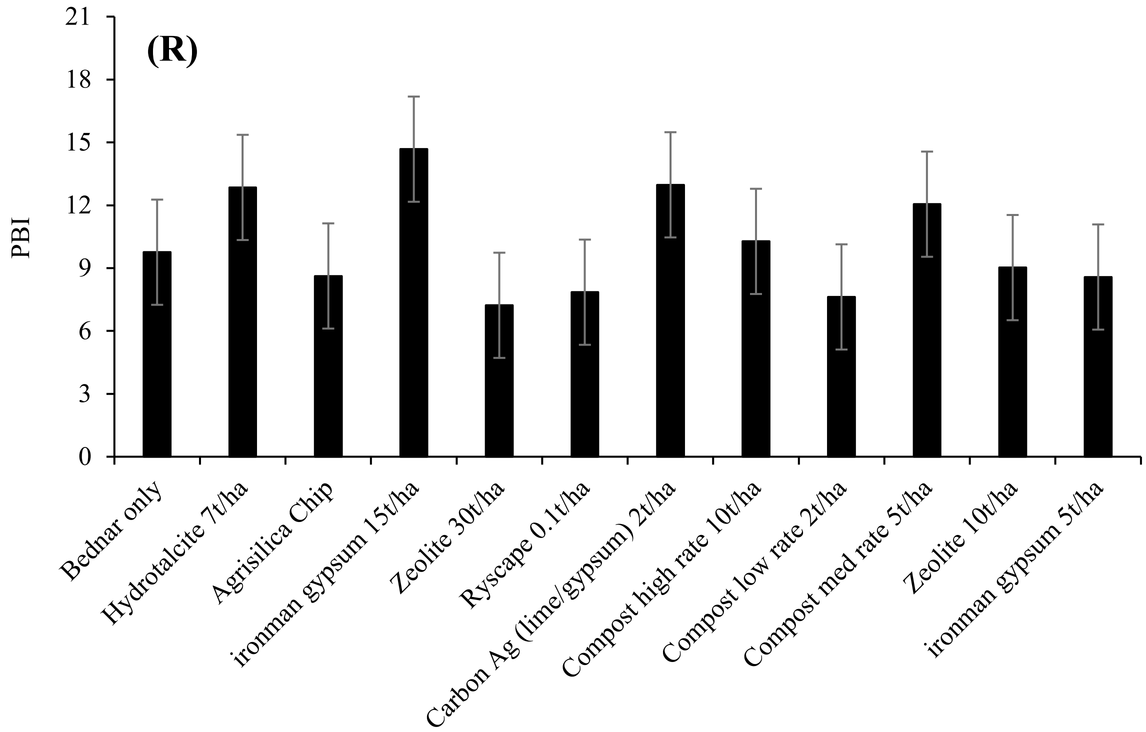


Signficance level: *



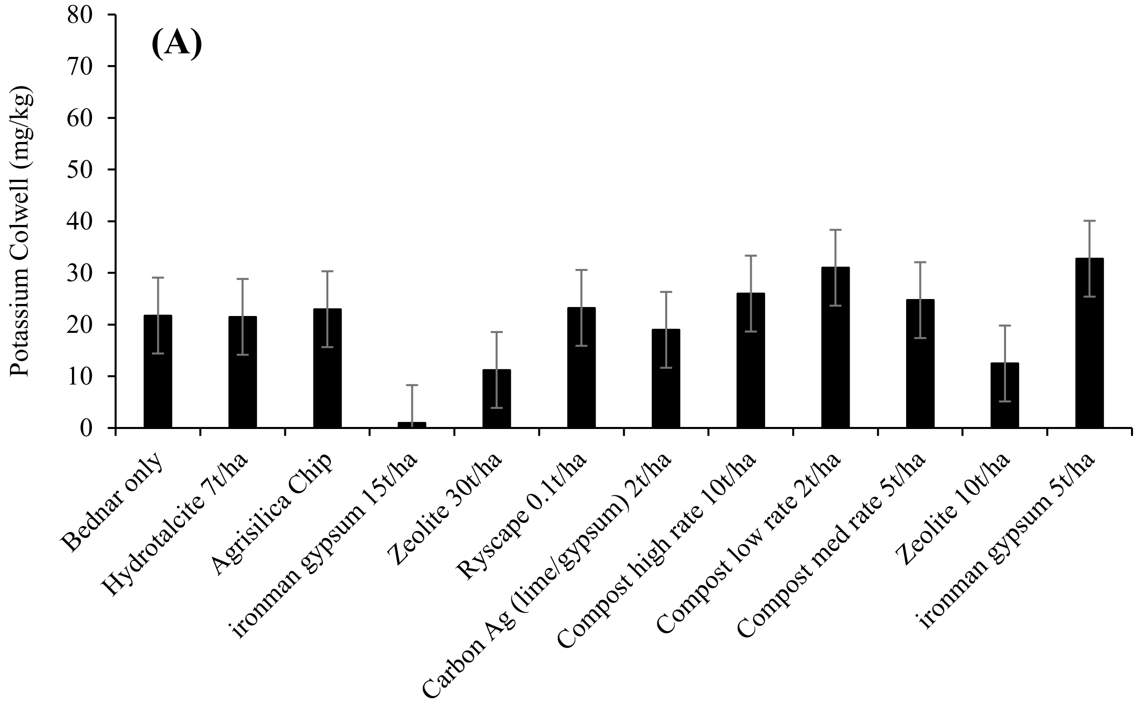
Signficance level: † (P = 0.08)



Signficance level: † (P = 0.076)

Fig. 12. Soil physio-chemical properties and nutrients in 0-10 cm profile in the small plots experiment at pre-seeding in 2024. **(A)** Phosphorus Colwell (mg/kg). **(B)** Potassium Kolwell (mg/kg). **(C)** Sulfur (mg/kg). **(D)** Organic Carbon (%). **(E)** Conductivity (dS/m). **(F)** pH ($CaCl_2$). **(G)** pH (H_2O). **(H)** DTPA Copper (mg/kg). **(I)** DTPA Iron (mg/kg). **(J)** DTPA Manganese (mg/kg). **(K)** DTPA Zinc (mg/kg). **(L)**

Exchangeable Calcium (meq/100 g). **(M)** Exchangeable Magnesium (meq/100 g). **(N)** Exchangeable Potassium (meq/100 g). **(O)** Exchangeable Sodium (meq/100 g). **(P)** Aluminium $CaCl_2$ (mg/kg). **(Q)** Boron $CaCl_2$ (mg/kg). **(R)** PBI. NS = $P > 0.1$, † = $P < 0.1$, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$. Error bar is the standard error of the population mean across the treatments. Standard error of the population mean was calculated using the following formula: Square Root of (2 × Mean Square of Error ÷ n) where n = 4.



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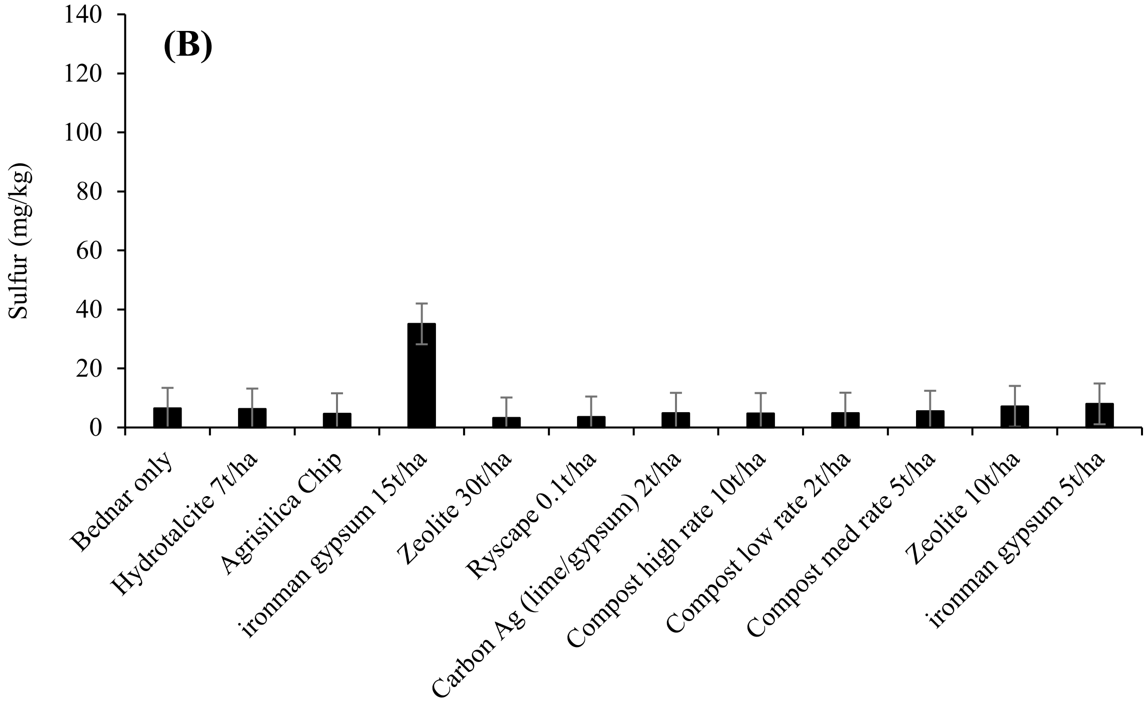

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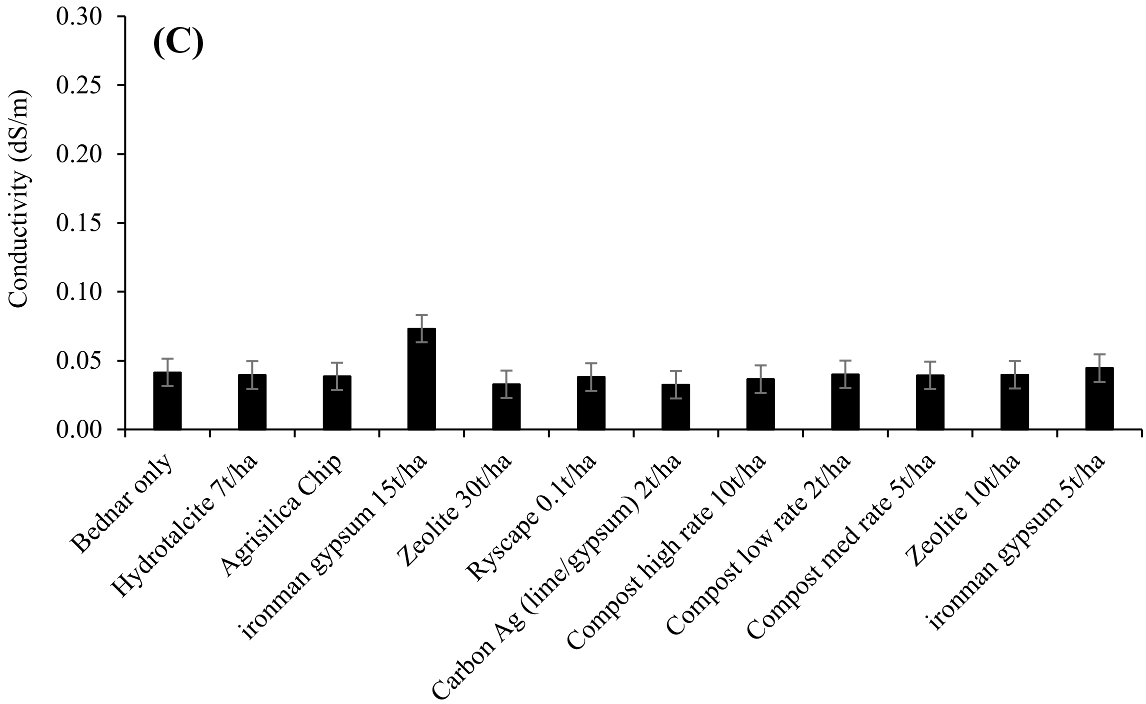

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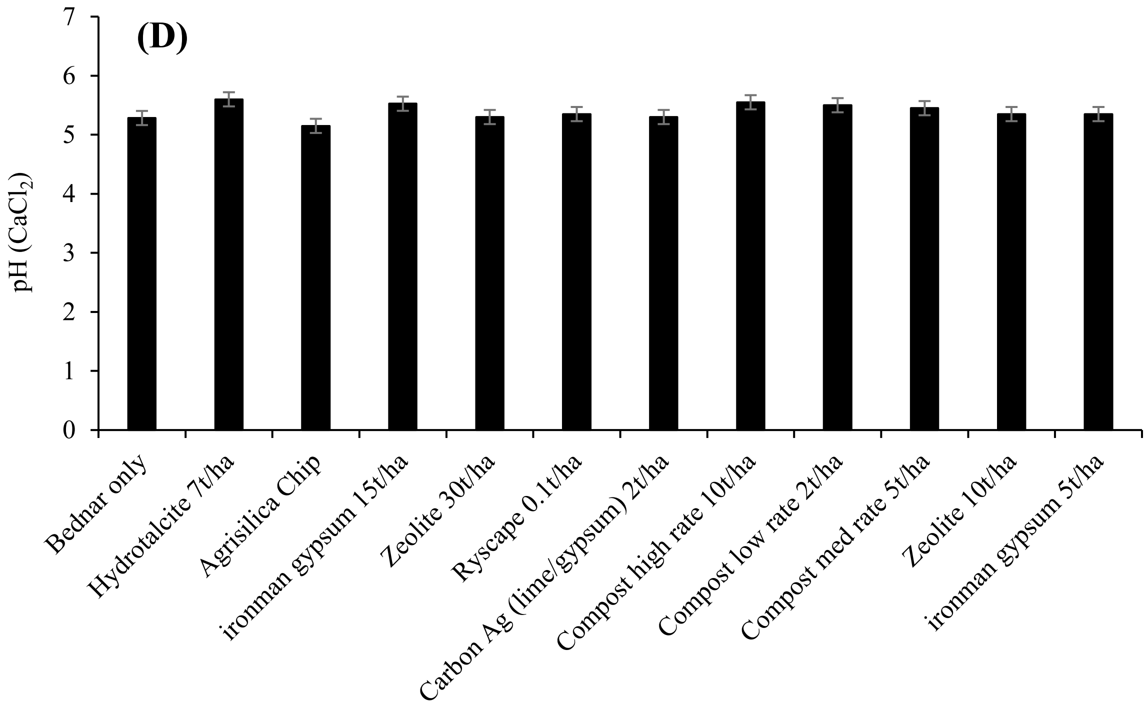

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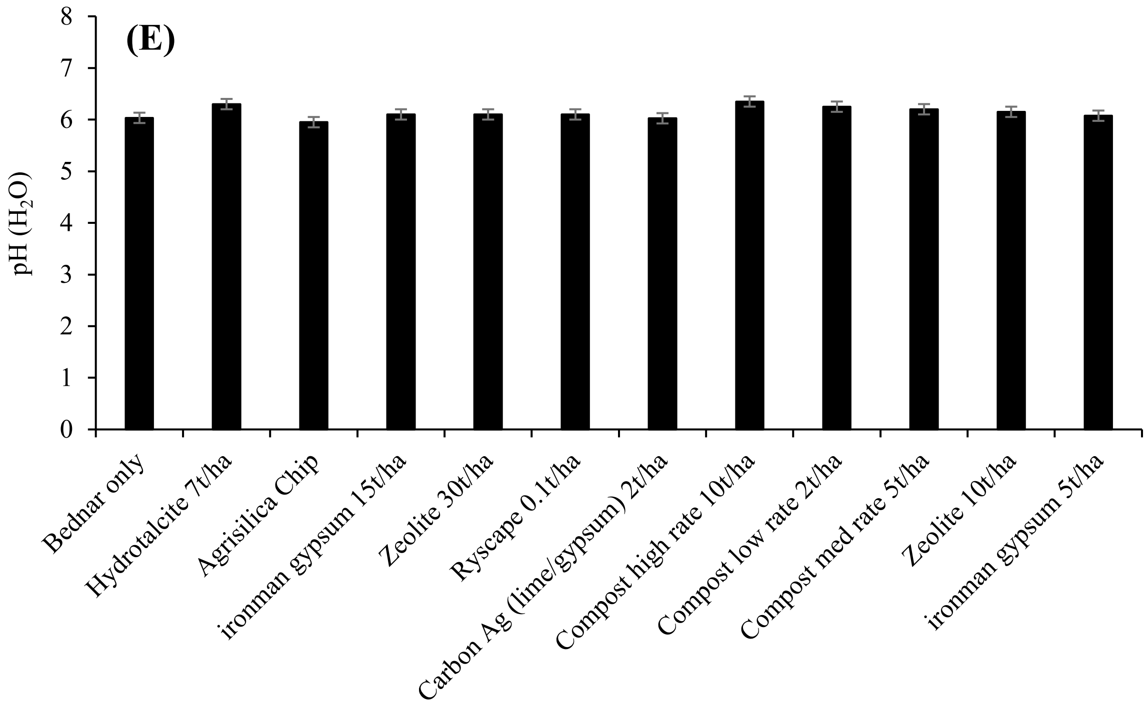

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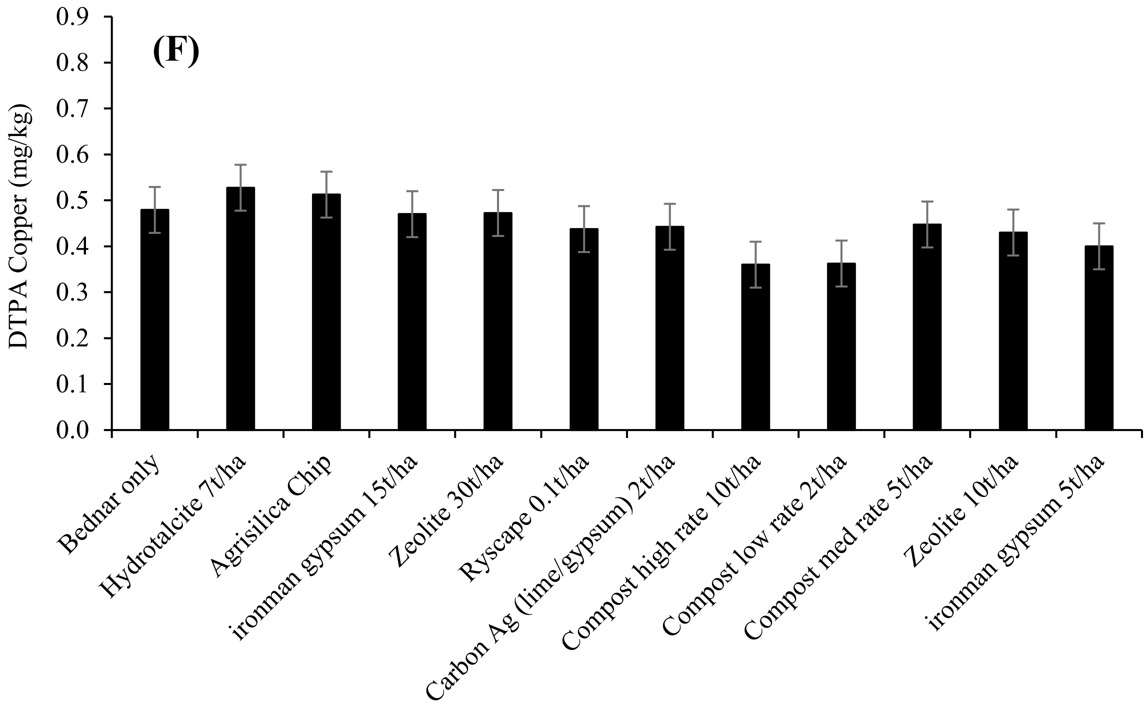

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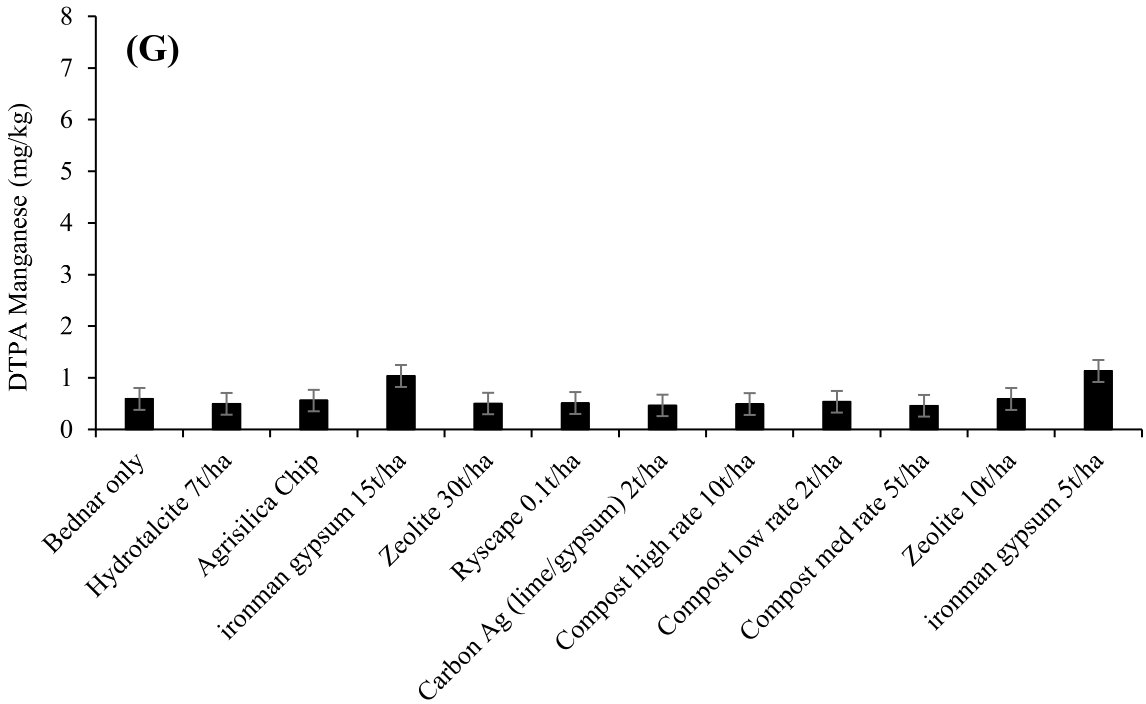

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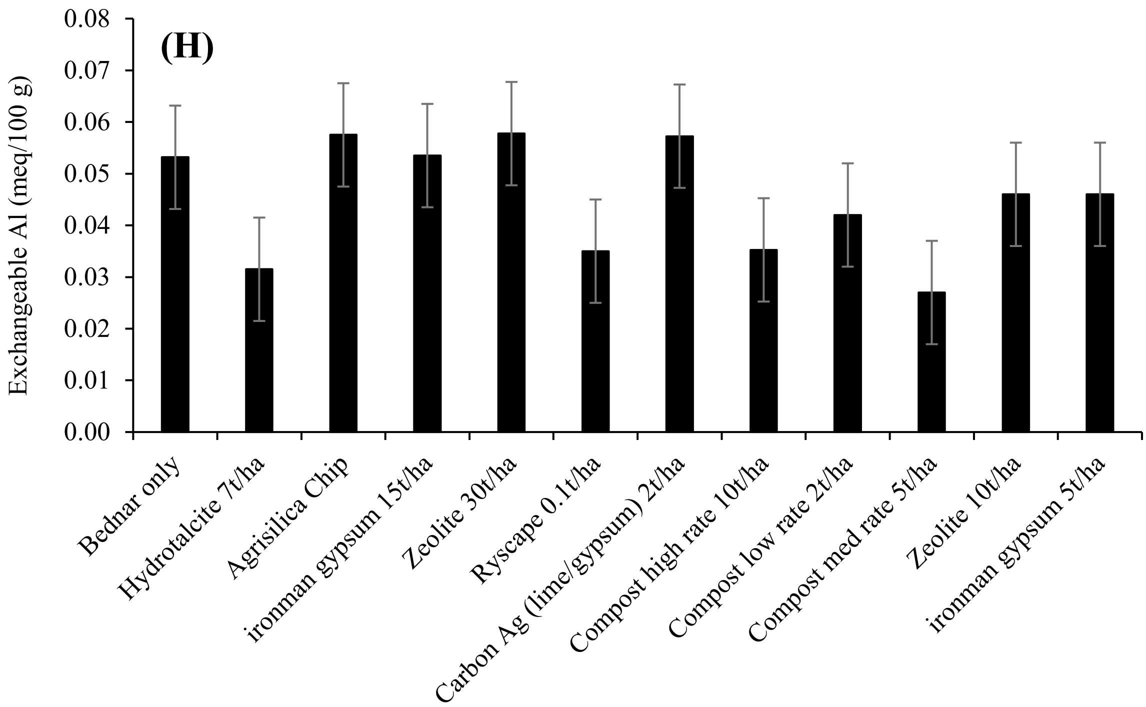

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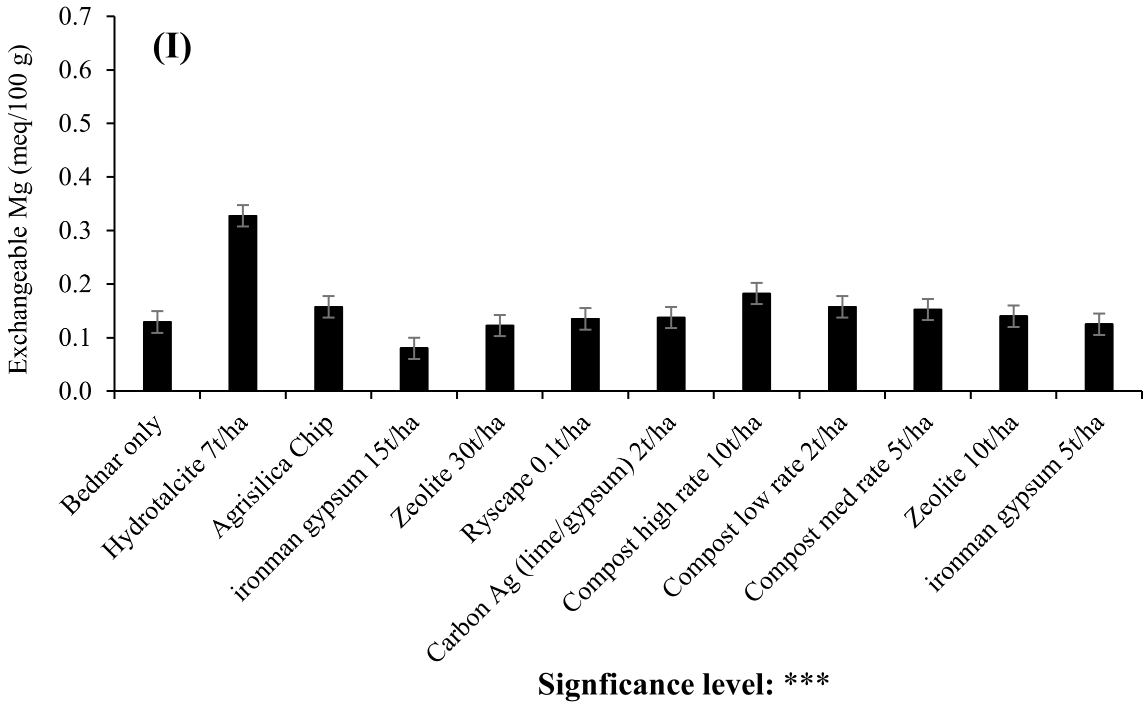


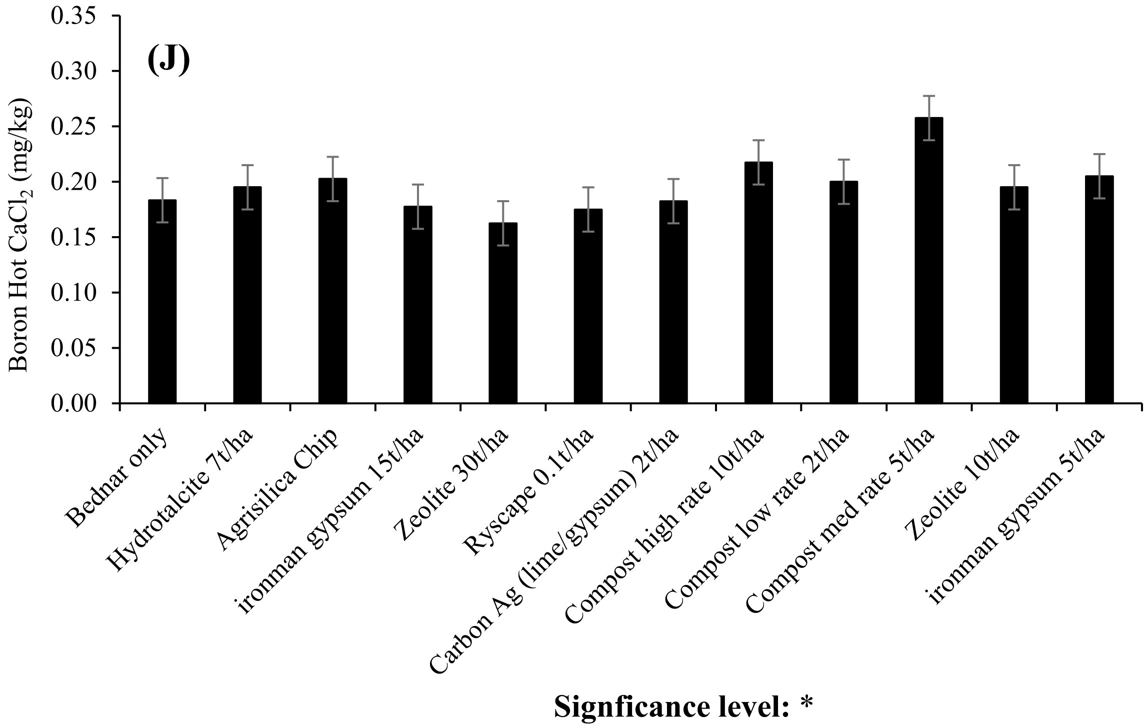


Fig. 13. Soil physio-chemical properties and nutrients in 10-30 cm profile in the small plots experiment at pre-seeding in 2024. **(A)** Potassium Kolwell (mg/kg). **(B)** Sulfur (mg/kg). **(C)** Conductivity (dS/m). **(D)** pH ($CaCl_2$). **(E)** pH (H_2O). **(F)** DTPA Copper (mg/kg). **(G)** DTPA Manganese (mg/kg). **(H)** Exchangeable Aluminium (meq/100 g). **(I)** Exchangeable Magnesium (meq/100 g). **(J)** Boron hot $CaCl_2$ (mg/kg). NS = P > 0.1, † = P < 0.1, * = P < 0.05, ** = P < 0.01, *** = P < 0.001. Standard error of the population mean was calculated using the following formula: Square Root of (2 × Mean Square of Error ÷ n) where n = 4.

Table. 7. Soil properties (0-10 cm) measured in different soil treatments in the Small Plots Experiment at Kweda at pre-seeding in 2024. Data is the mean of four replications ± standard error of the treatment mean (n = 4).

Treatments	Ammonium Nitrogen (mg/kg)	Nitrate Nitrogen (mg/kg)	Organic Carbon (%)	Exc. Aluminium (meq/100 g)	Exc. Potassium (meq/100 g)	Exc. Sodium (meq/100 g)	Boron Hot $CaCl_2$ (mg/kg)	PBI
Bednar only	12.58 ± 2.86	29.67 ± 3.79	0.97 ± 0.1	0.03 ± 0	0.11 ± 0.01	0.06 ± 0.01	0.23 ± 0.03	9.76 ± 1.42
Hydrotalcite 7t/ha	21.75 ± 14.87	26 ± 1.47	0.77 ± 0.08	0.03 ± 0	0.09 ± 0.01	0.05 ± 0	0.22 ± 0.02	12.85 ± 0.83
Agrisilica Chip	7.25 ± 0.75	31.75 ± 3.17	0.97 ± 0.19	0.04 ± 0	0.13 ± 0.04	0.06 ± 0.02	0.25 ± 0.04	8.63 ± 3.06
ironman gypsum 15t/ha	16.5 ± 6.84	26.75 ± 3.71	0.77 ± 0.09	0.03 ± 0.01	0.08 ± 0.01	0.06 ± 0.02	0.23 ± 0.02	14.68 ± 1.59
Zeolite 30t/ha	7.75 ± 1.7	27 ± 5.46	0.83 ± 0.16	0.04 ± 0.01	0.11 ± 0.02	0.06 ± 0.01	0.23 ± 0.03	7.23 ± 0.86
Ryscape 0.1t/ha	10.75 ± 3.33	25 ± 5.48	0.95 ± 0.17	0.03 ± 0	0.12 ± 0.02	0.05 ± 0.01	0.24 ± 0.04	7.85 ± 1.04
Carbon Ag (lime/gypsum) 2t/ha	6 ± 1.08	27.5 ± 6.03	0.79 ± 0.16	0.04 ± 0	0.12 ± 0.04	0.05 ± 0.02	0.25 ± 0.03	12.98 ± 2.24
Compost high rate 10t/ha	13.25 ± 5.69	37.25 ± 3.75	0.835 ± 0.06	0.03375 ± 0	0.1575 ± 0.02	0.085 ± 0.01	0.3 ± 0.02	10.275 ± 1.17
Compost low rate 2t/ha	6.75 ± 1.89	36.5 ± 6.59	1.01 ± 0.11	0.0405 ± 0.01	0.1325 ± 0.02	0.075 ± 0.02	0.2625 ± 0.03	7.625 ± 2.64
Compost med rate 5t/ha	14.75 ± 5.94	28.75 ± 4.96	1.055 ± 0.17	0.0295 ± 0.01	0.1275 ± 0.03	0.0575 ± 0.01	0.295 ± 0.04	12.05 ± 1.66
Zeolite 10t/ha	14.5 ± 3.71	24.5 ± 5.74	0.93 ± 0.17	0.05 ± 0	0.1 ± 0.02	0.05 ± 0.02	0.22 ± 0.04	9.03 ± 2.55
ironman gypsum 5t/ha	6.5 ± 1.85	27.25 ± 3.35	0.82 ± 0.12	0.03 ± 0	0.11 ± 0.02	0.05 ± 0.01	0.26 ± 0.05	8.58 ± 2.64

Table. 8. Soil properties (10-30 cm) measured in different soil treatments in the Small Plots Experiment at Kweda at pre-seeding in 2024. Data is the mean of four replications ± standard error of the treatment mean (n = 4).

	Ammonium Nitrogen (mg/kg)	Nitrate Nitrogen (mg/kg)	Phosphorus Colwell (mg/kg)	Organic Carbon (%)	DTPA Iron (mg/kg)	DTPA Zinc (mg/kg)	Exc. Calcium (meq/100 g)	Exc. Potassium (meq/100 g)	Exc. Sodium (meq/100 g)	Aluminium $CaCl_2$ (mg/kg)	PBI
Bednar only	1 ± 0.09	9.08 ± 1.66	12 ± 1.24	0.43 ± 0.06	10.03 ± 2.68	0.51 ± 0.09	1.36 ± 0.17	0.05 ± 0	0.03 ± 0	0.75 ± 0.24	9.39 ± 0.93
Hydrotalcite 7t/ha	0.9 ± 0	11.25 ± 2.02	12 ± 0.41	0.52 ± 0.06	8.28 ± 1.24	0.51 ± 0.03	1.57 ± 0.24	0.04 ± 0	0.04 ± 0.01	0.48 ± 0.04	6.9 ± 1.05
Agrisilica Chip	1.45 ± 0.52	15.25 ± 3.94	14.75 ± 1.6	0.56 ± 0.11	11.55 ± 3.42	0.53 ± 0.1	1.5 ± 0.25	0.05 ± 0.01	0.04 ± 0.01	0.68 ± 0.11	8.15 ± 1.8
ironman gypsum 15t/ha	0.93 ± 0.03	11 ± 1.29	10.5 ± 1.26	0.39 ± 0.02	9.23 ± 3.04	0.34 ± 0.06	1.41 ± 0.07	0.04 ± 0.01	0.04 ± 0.01	0.51 ± 0.05	7.78 ± 0.94
Zeolite 30t/ha	0.98 ± 0.03	11.25 ± 1.44	12 ± 1.22	0.48 ± 0.06	8.5 ± 2.28	0.44 ± 0.04	1.25 ± 0.14	0.04 ± 0.01	0.03 ± 0	0.49 ± 0.08	8.2 ± 2.04
Ryscape 0.1t/ha	0.93 ± 0.03	13 ± 2.27	10.75 ± 1.11	0.43 ± 0.08	7.25 ± 1.03	0.47 ± 0.05	1.39 ± 0.16	0.05 ± 0.01	0.03 ± 0.01	0.65 ± 0.1	6.75 ± 1.56
Carbon Ag (lime/gypsum) 2t/ha	0.9 ± 0	10 ± 1.47	11.25 ± 1.93	0.37 ± 0.05	8.03 ± 2.34	0.41 ± 0.06	1.42 ± 0.11	0.06 ± 0.01	0.03 ± 0.01	0.73 ± 0.22	9.68 ± 1.39
Compost high rate 10t/ha	0.9 ± 0	11.75 ± 2.56	12.25 ± 0.63	0.47 ± 0.06	8 ± 0.96	0.62 ± 0.16	1.45 ± 0.17	0.06 ± 0	0.03 ± 0.01	0.44 ± 0.05	6.93 ± 0.93
Compost low rate 2t/ha	0.93 ± 0.03	12.5 ± 1.44	12.25 ± 1.65	0.45 ± 0.04	8.25 ± 1.97	0.46 ± 0.04	1.55 ± 0.1	0.05 ± 0.01	0.03 ± 0.01	0.51 ± 0.06	9.03 ± 1.89
Compost med rate 5t/ha	0.93 ± 0.03	13 ± 1.58	14.25 ± 1.44	0.47 ± 0.05	8.83 ± 2.61	0.47 ± 0.07	1.33 ± 0.16	0.05 ± 0.01	0.03 ± 0.01	0.51 ± 0.1	8.88 ± 0.83
Zeolite 10t/ha	2.43 ± 1.53	13 ± 2.74	11.5 ± 0.87	0.58 ± 0.16	7.15 ± 1.9	0.43 ± 0.12	1.29 ± 0.3	0.04 ± 0.01	0.03 ± 0.01	0.7 ± 0.1	7.73 ± 1.01
ironman gypsum 5t/ha	1.48 ± 0.51	12.25 ± 1.11	13 ± 3.39	0.43 ± 0.04	11.75 ± 5.74	0.38 ± 0.03	1.24 ± 0.11	0.05 ± 0.01	0.03 ± 0.01	0.49 ± 0.13	8.58 ± 1.78

3.5. In depth analysis of the major soil nutrients (2022-2025)

Soil samples were collected before the start of experiment each year. In 2022, samples were collected from 0-10 and 10-30 cm profiles of only 4 replicates of control as a baseline sampling. In 2023, samples were collected only from the three treatments of the large plots experiment, i.e., from the control, bednar treated plots and the plots treated with Gypsum+Bedner. At pre-seeding in April-2024 and March-2025, samples were collected from all the treatments and all replicates of both the large plots and small plots experiments and samples were tested for the major nutrients along with other analysis.

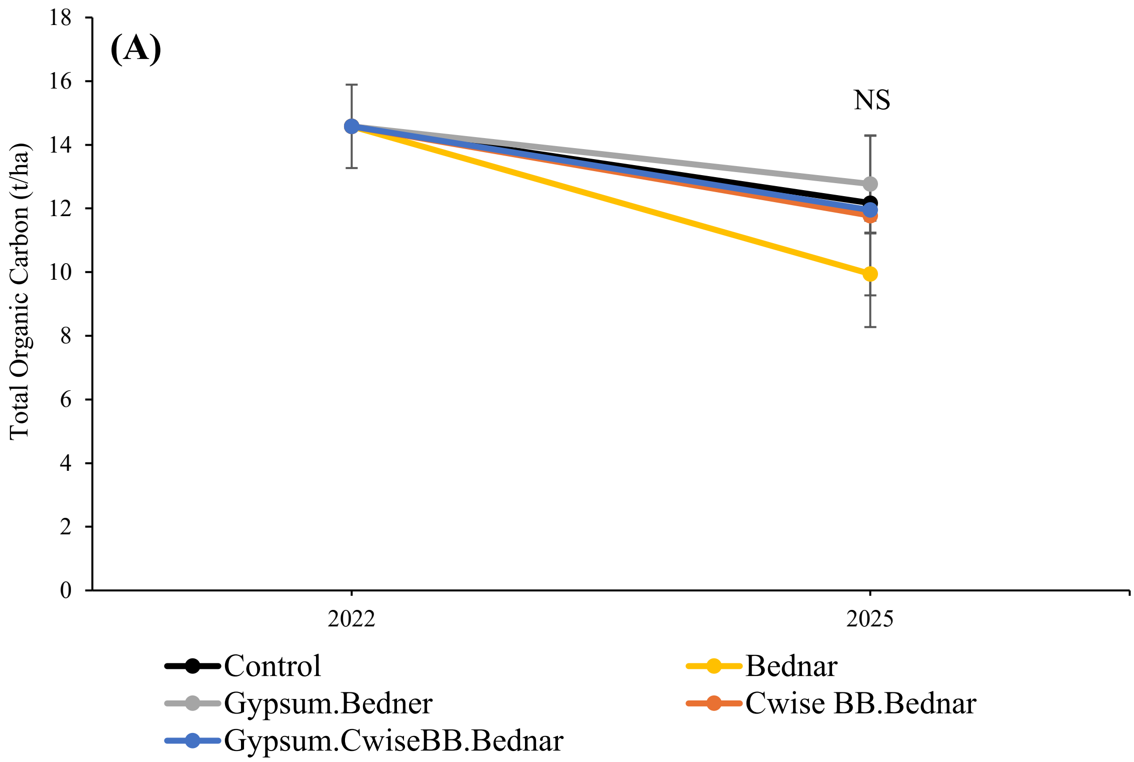
Statistical analysis of the soil data from 2023-2025 was carried out using one-way ANOVA while taking Block (rep) and Treatment as a Source of Variation. Hence, there was no treatment comparison in 2022, only the mean value of the 4 replications of the control was calculated with standard error of the mean. Wherever, data was found to be significantly affected by the treatments ($P \leq 0.05$), a comparison of means was carried out using LSD test ($\alpha = 0.05$). While the rest of the soil results have already been presented and discussed above in the **Section 3.4,** here the significant changes in the major soil nutrients from 2022 to 2025 are discussed.

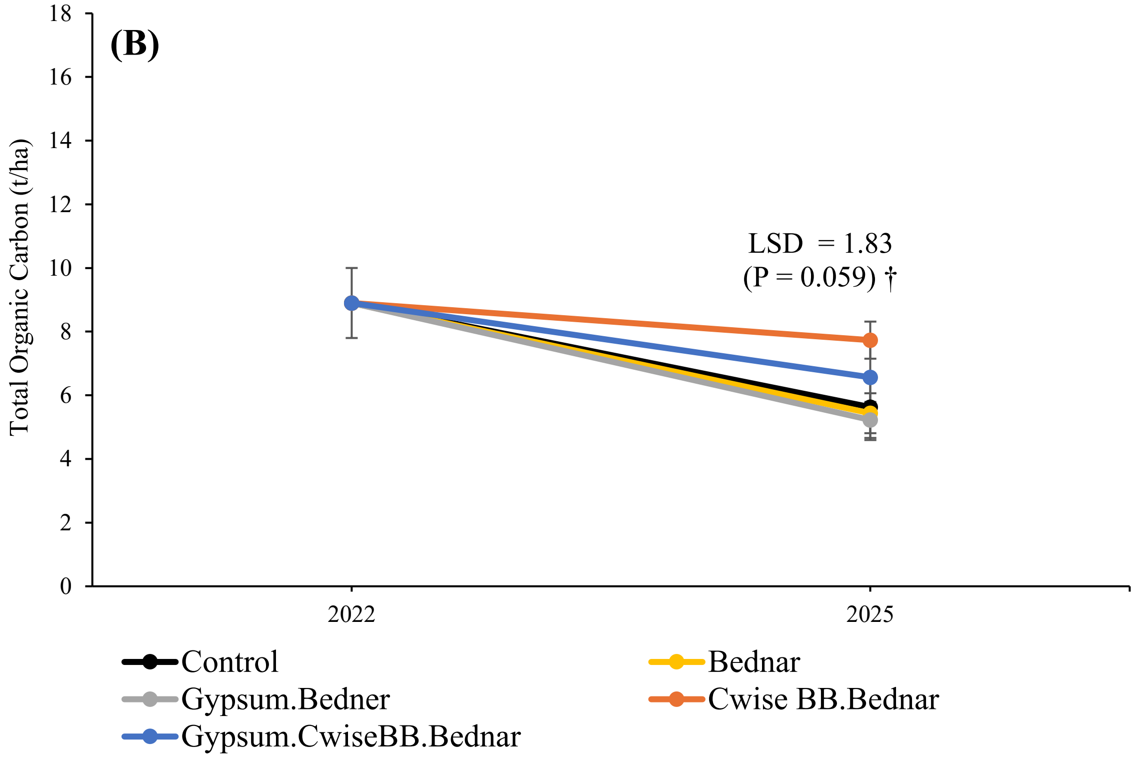
3.5.1. Total Organic Carbon (TOC) – Large Plots Experiment

In the large plots experiment, the total organic carbon (TOC) has declined from 2022 to 2025 in the 0-10 and 10-30 cm layers across the treatments with considerably greater decline in the Bednar treatment in the top 10 cm profile (Fig. 14A-B). On the other hand, TOC increased over the mentioned period down the profile (30-45 cm) with a slight more increase in Bednar and Control relative to other treatments (Fig. 14C).

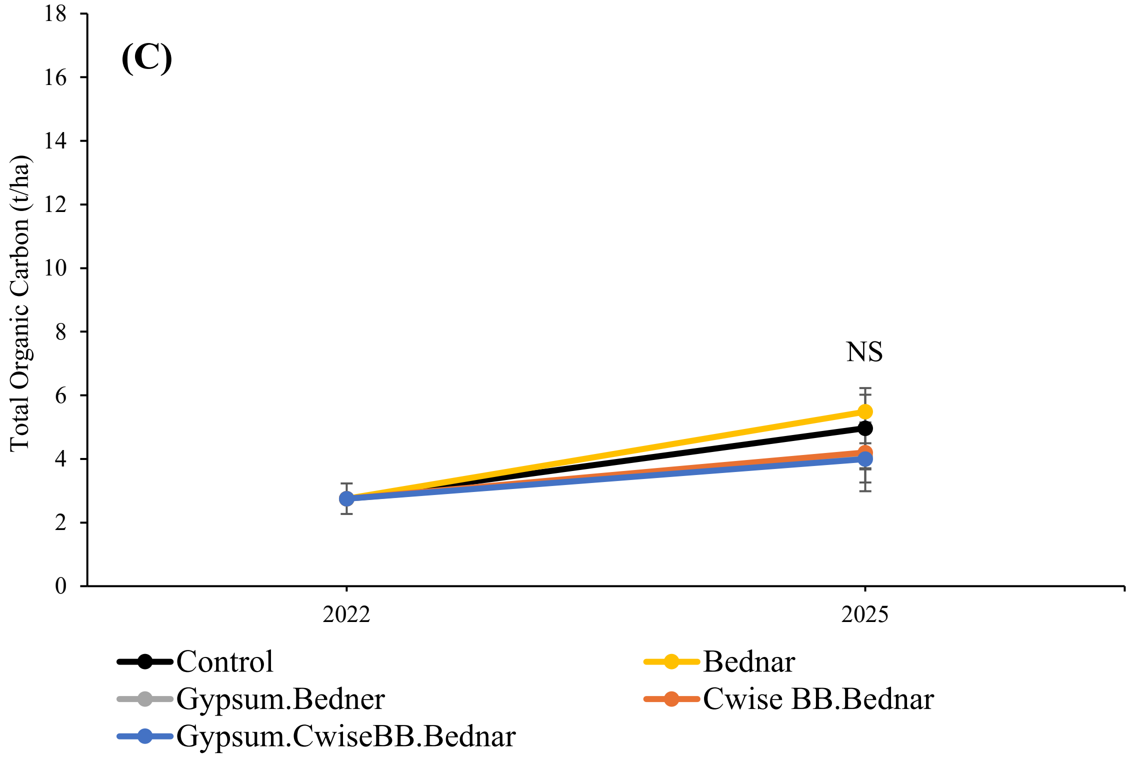
Following those trends from 2022-2025, treatments were found with marginally significant differences (90 % level of confidence with $P = 0.59$) only in the 10-30 cm profile (Fig. 14A), but treatmets were not different than control in the 0-10 and 30-45 cm profiles of soil (Fig. 14B-C). In the 10-30 cm profile, only the soil treated with the Cwise compost + Bednar seems to have greater TOC over control (90% level of confidence) (Fig. 14B). Treatments were not different in their bulk densities in the 10-30 cm profile (Fig. 14E) but were significantly different in the % of Organic C with Cwise compost + Bednar having greater Organic C than the other treatments including control (Fig. 14D). Therefore, the greater TOC of Cwise compost + Bednar treatment in the 10-30 cm profile could only be attributed to the % of organic C, with no role of the bulk density.

These results suggest that the organic amendment such as compost alone in the given conditions (low rainfall and sandy duplex soil) may not be sufficient to significantly improve the soil TOC, however, if applied in combination with the soil manipulation such as deep ripping through Bednar, could provide better results. One of the posssible reasons could be better mixing of compost in the deep ripped bednar treated soil than the compost on un-ripped soil. Another reason might be the dependency of the organic amendments such as compost on the soil water and combining it with deep ripping might help in improveing soil water infilteration and/or retention, thus greater water availibility for the compost breakdown and other soil microbial activities. Deep ripping has previously been shown with improved water infilteration (Wickramarachchi et al., 2025). Previosu studies also show that compost treated soil have different C sequestration in differetnly wattered soil. For instance, Yeasmin et al. (2022) reported that the poultry manure (organic amendment) showed greater organic C on the continously wet soil relative to the soil kept in a dry and wet alternations. Results from the study conducted by Olson et al. (2013) also suggest that incarporation of compost through deep tilling may provide better water inflitration and saturated hydraulic conductivity than tilling alone.

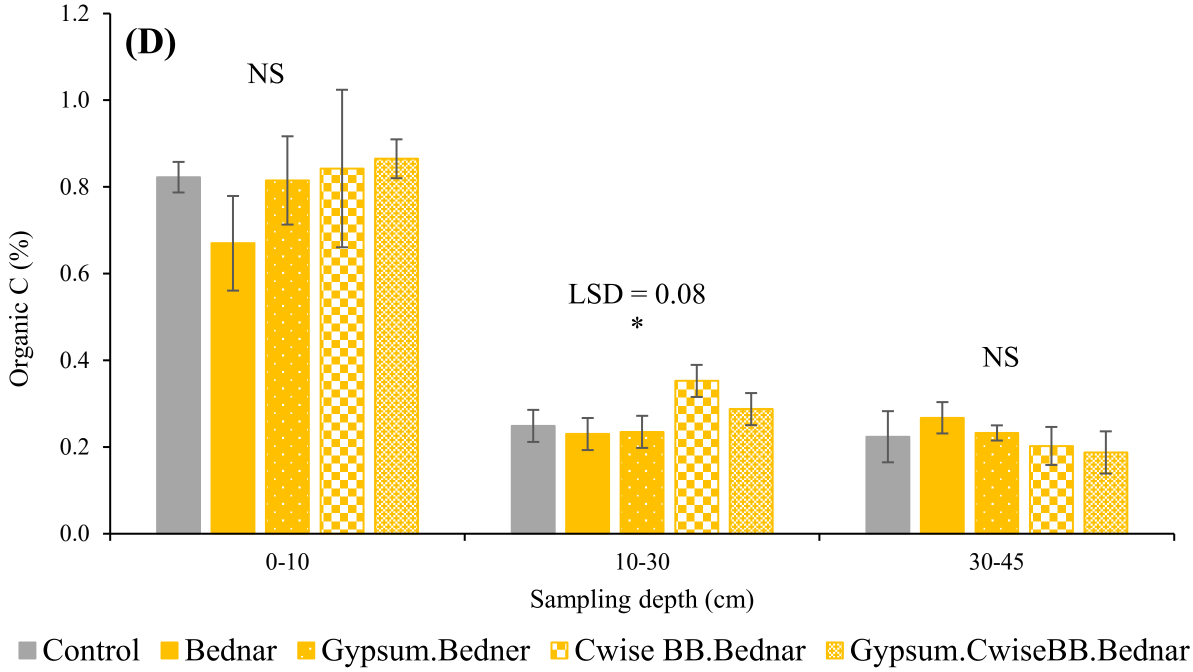




(B)
Total Organic Carbon (t/ha)
LSD = 1.83
(P = 0.059) †
2022
2025
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar



(C)
Total Organic Carbon (t/ha)
NS
2022
2025
Control
Bednar
Gypsum.Bedner
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar



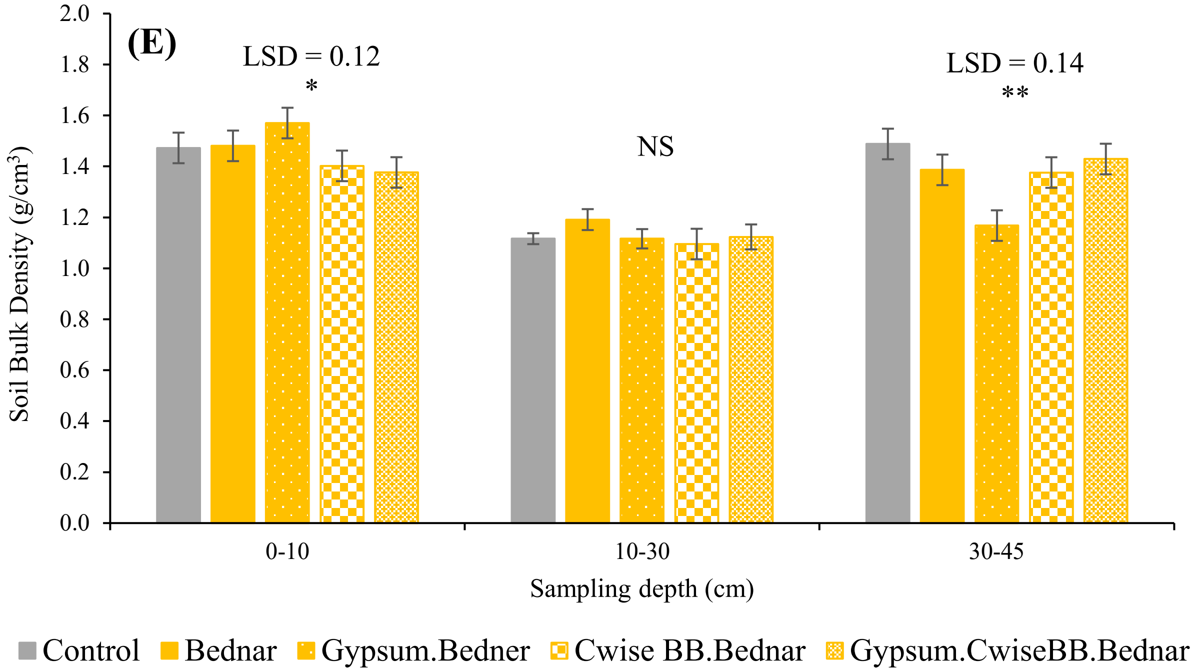


Fig. 14. Soil Total Organic Carbon in **(A)** 0-10 cm, **(B)** 10-30 cm and **(C)** 30-45 cm profile in the large plots experiment recorded at pre-seeding in 2022 and 2025. Panel **(D)** is the Organic Carbon while **(E)** is the soil Bulk Density of different treatments in various soil profiles in 2025. The 2022 data in **A-C** is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. The soil bulk density data had not been recorded in 2022, therefore, the 2025 bulk density data was used to calculate the total organic carbon per hectare for 2022.

NS = P > 0.1, † = P < 0.1, * = P < 0.05. Error bar is either the standard error of the treatment mean (n = 4) when P >0.05 or the standard error of the population mean across the treatments when P ≤ 0.05. Standard error of the population mean was calculated by using the following formula: Square Root of (2 × Mean Square of Error ÷ 4).

3.5.2. Nitrogen (N) – Large Plots Experiment

Both forms of nitrogen, i.e., ammonium and nitrate, were only significantly affected by the applied teratments in the top 10 cm in 2024 (Fig. 15 and 16). Lupin was seeded in 2023 which is why increase in the N could be observed at pre-seeding in the surface soil in 2024 relative to 2023, however, not all the treatments benifitted the same way (Fig. 15 and 16). Benar treatment accumulated 2.1 mg/g more Ammonium N in the top 10 cm than control in 2024 (Fig. 15A). This might be the result of soil loosening which might have allowed better root growth and nodulation and respiration. On the other hand, soil treated with Bednar + C wise compost + Gypsum (BCG) was found with significantly lower N in both the ammonium as well as nitrate form relative to control in the top soil in 2024 (Fig. 15A and 16A). Lower soil N in the soil treated with BCG after legume year (Lupin in 2023) suggests that at least one treatment in the applied combination (Bednar + C wise compost + Gypsum) has negative effect on the nitrogen fixation of ability of the legume lupin. This does not seem to be bednar as it has already shown imrpvement in the soil N (Fig. 15-16). Similarly, Gypsum-bednar and Cwise-Bednar combinations also have slightly more or similar N in the top soil relative to Control (Fig. 15-16). The only combination which seems to have negative effect could be Cwise-Gypsum which has not been tested in the current treatment structure but is present in the Bednar-Cwise Gypsum combination. Another possibility is that in addition to limiting the biological N fixation, the Bednar-Cwise-Gypsum combination might have enhanced the plant N uptake. Gypsum and compost have previously been reported to have enhanced the plant N uptake (Bossolani et al., 2020; Erhart et al., 2005; Ngo and Cavagnaro, 2018). Previous studies also show that sufficient or high N level in soil reduces the nodulation and the N-fixation ability of the N-fixing bacteria in the roots of legume. This has been reviewed in detail on page 978-979 by Zahran (1999). Another study reporting that compost reduced the mycorrhizal colonisation in tomato and wheat (Ngo and Cavagnaro, 2018), also support this explanation. Thus there is a possibility that both the gypsum and Cwise compost in the Bednar-Cwise-Gypsum might not have only enhanced the N uptake but might also have caused negative effects on the biological N fixation in the legume crop and therefore resulting into lower soil N at the end of the season.

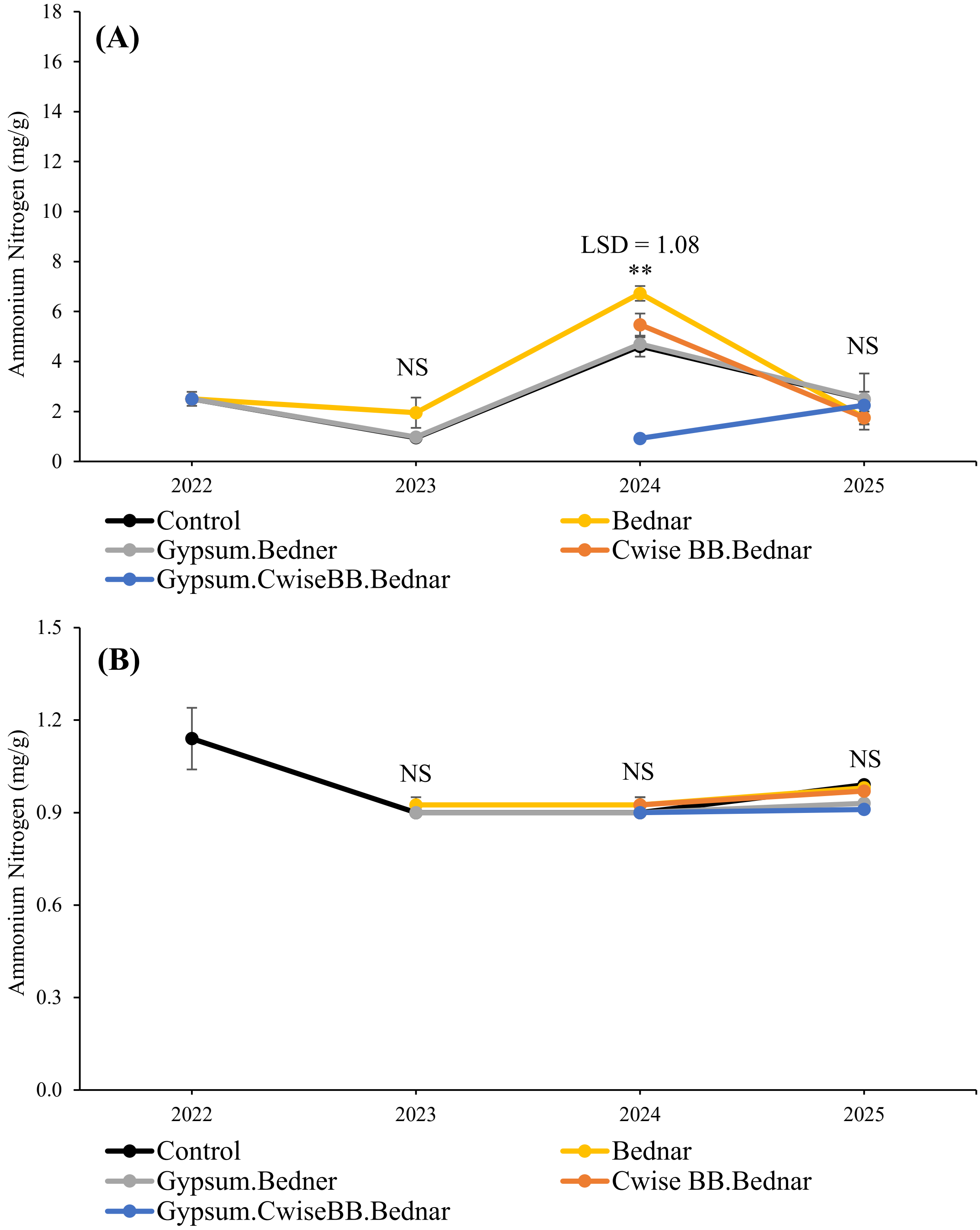


Fig. 15. Ammonium nitrogen in **(A)** 0-10 cm and **(B)** 10-30 cm profile in the large plots experiment recorded at pre-seeding in 2022- 2025. The 2022 data is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. In 2023, only three treatments were sampled, i.e., control, bednar and gypsum+bednar. In 2024 and 2025, samples were collected from all the treatments. NS = P > 0.05. Error bar is the standard error of the treatment mean (n = 4).

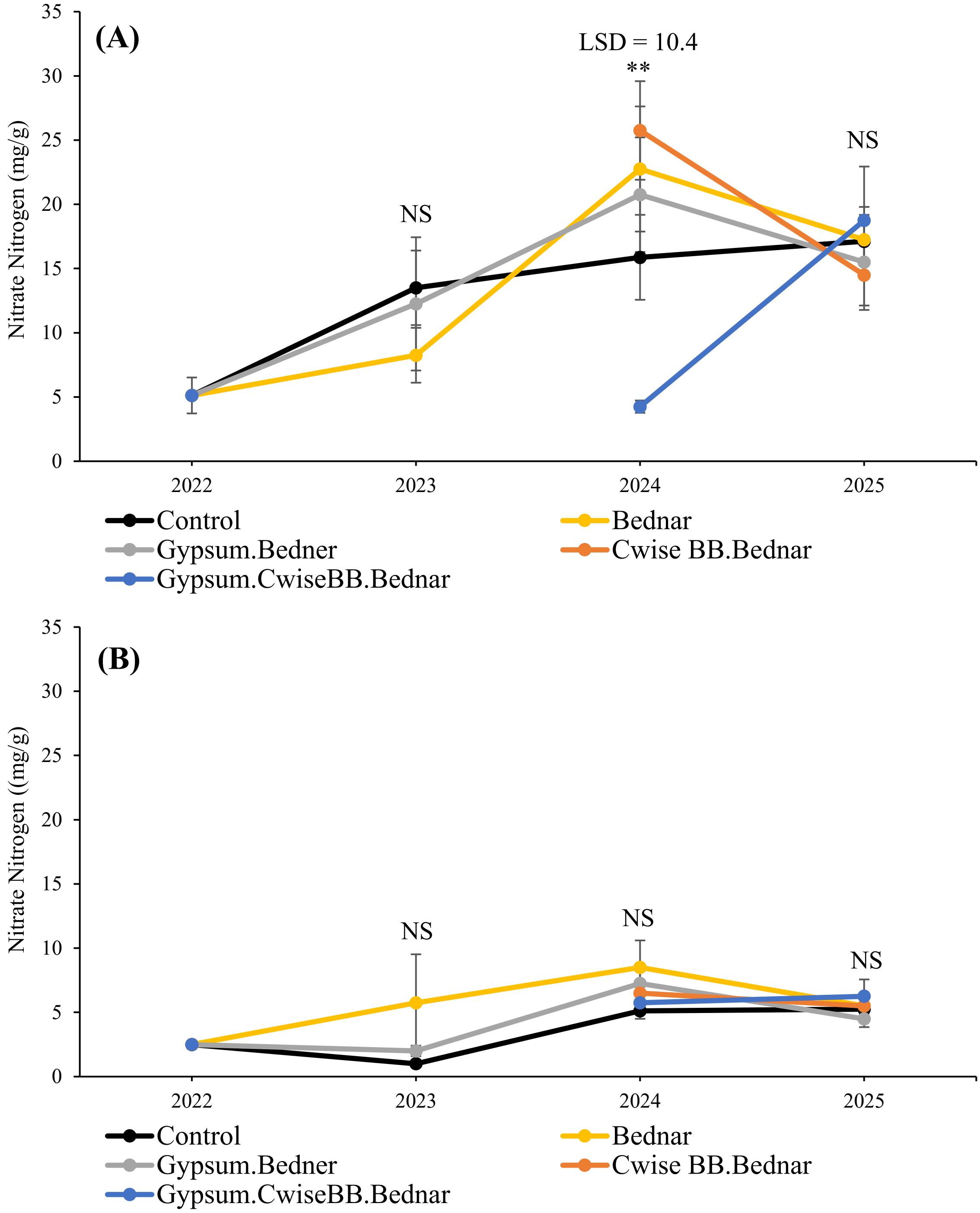
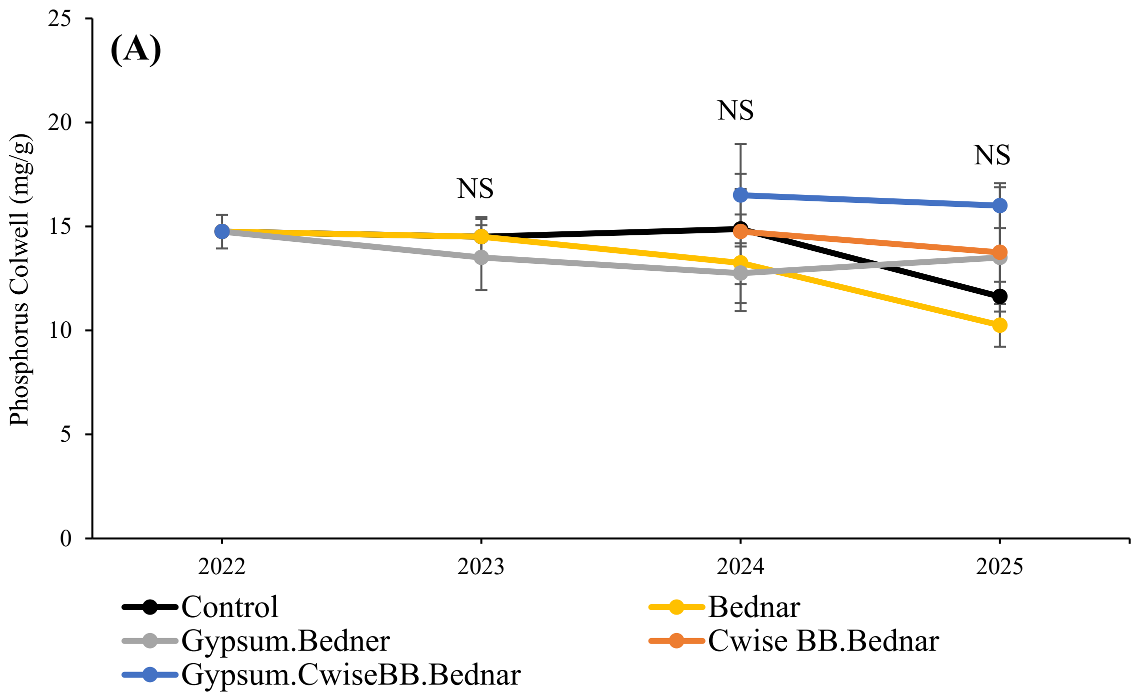


Fig. 16. Nitrate nitrogen in **(A)** 0-10 cm and **(B)** 10-30 cm profile in the large plots experiment recorded at pre-seeding in 2022- 2025. The 2022 data is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. In 2023, only three treatments were sampled, i.e., control, bednar and gypsum+bednar. In 2024 and 2025, samples were collected from all the treatments. NS = P > 0.05. Error bar is the standard error of the treatment mean (n = 4).

3.5.3. Phosphorus, Potassium and Sulfur – Large Plots Experiment

Phosphorus, Potassium and Sulfur were not significantly influenced by any of the applied treatments in the large plots experiment in any of the studied soil profiles (0-10 and 10-30 cm) in any year (2022-2025) (Fig. 17-19).



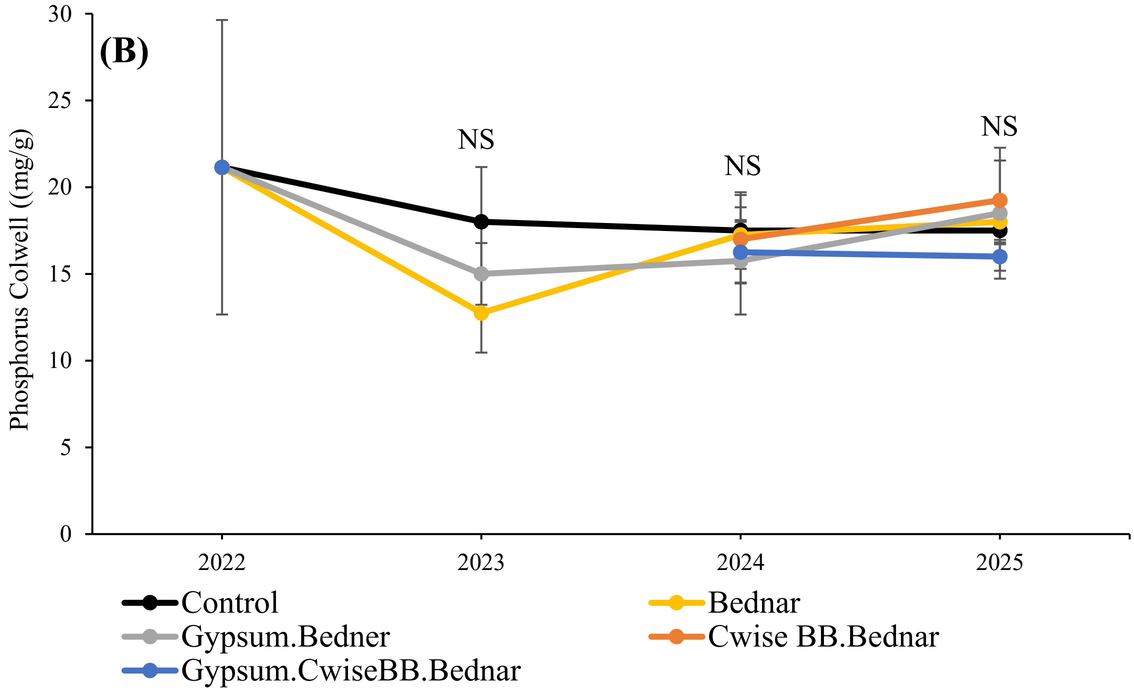
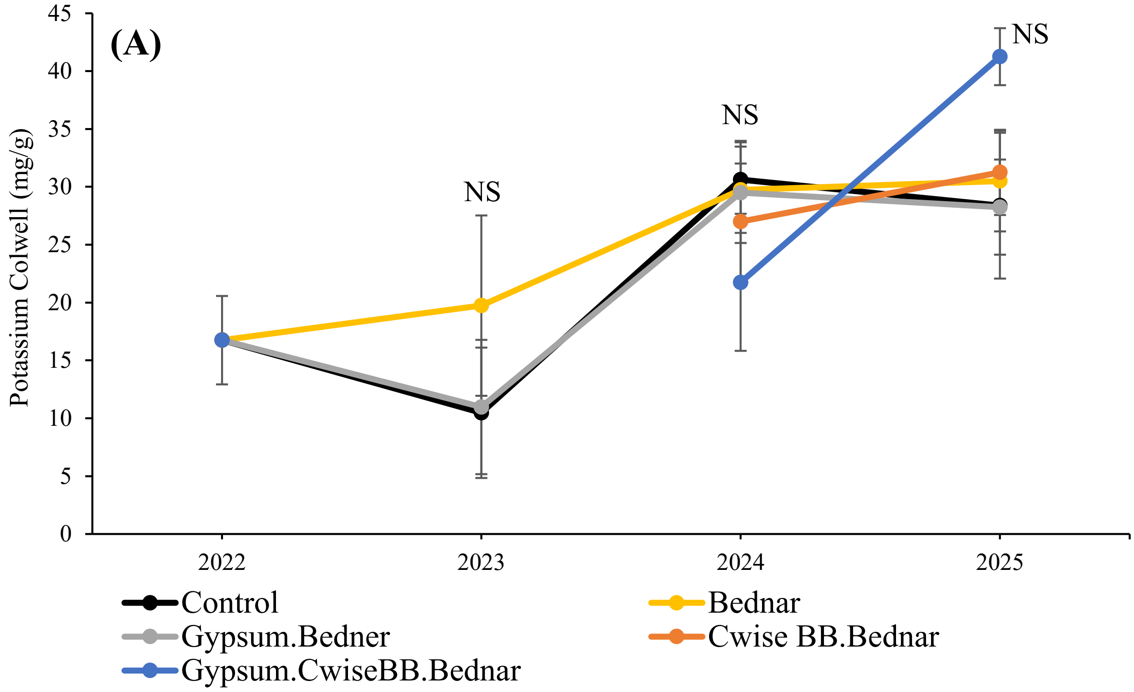


Fig. 17. Phosphorus Colwell in **(A)** 0-10 cm and **(B)** 10-30 cm profile in the large plots experiment recorded at pre-seeding in 2022- 2025. The 2022 data is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. In 2023, only three treatments were sampled, i.e., control, bednar and gypsum+bednar. In 2024 and 2025, samples were collected from all the treatments. NS = P > 0.05. Error bar is the standard error of the treatment mean (n = 4).



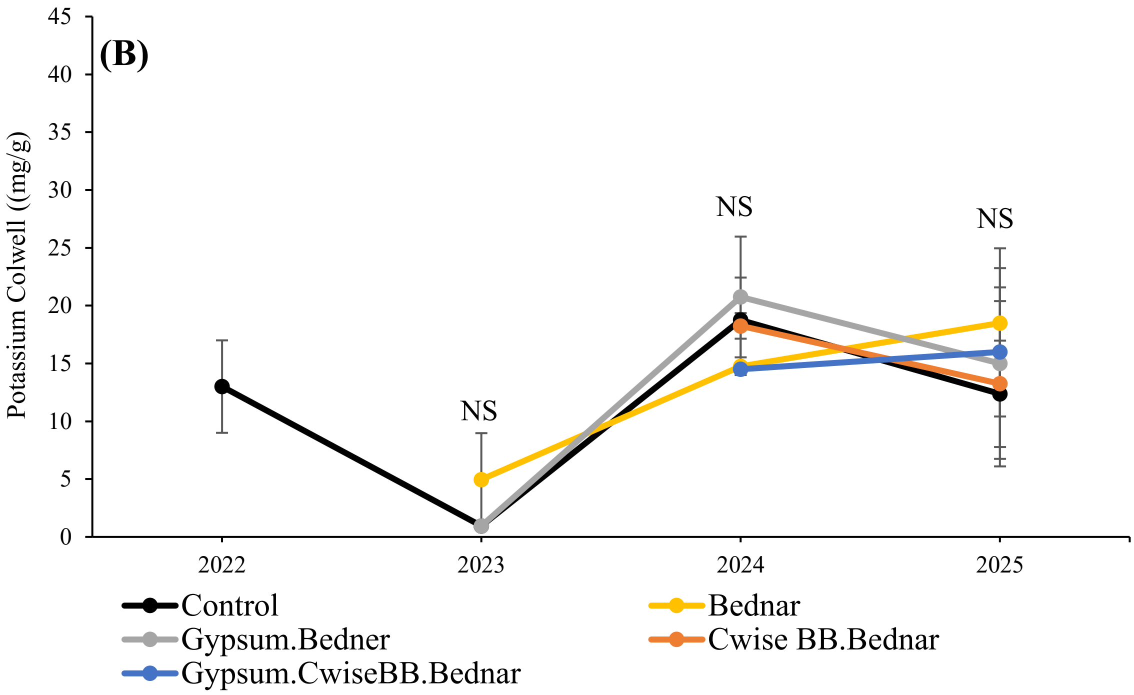
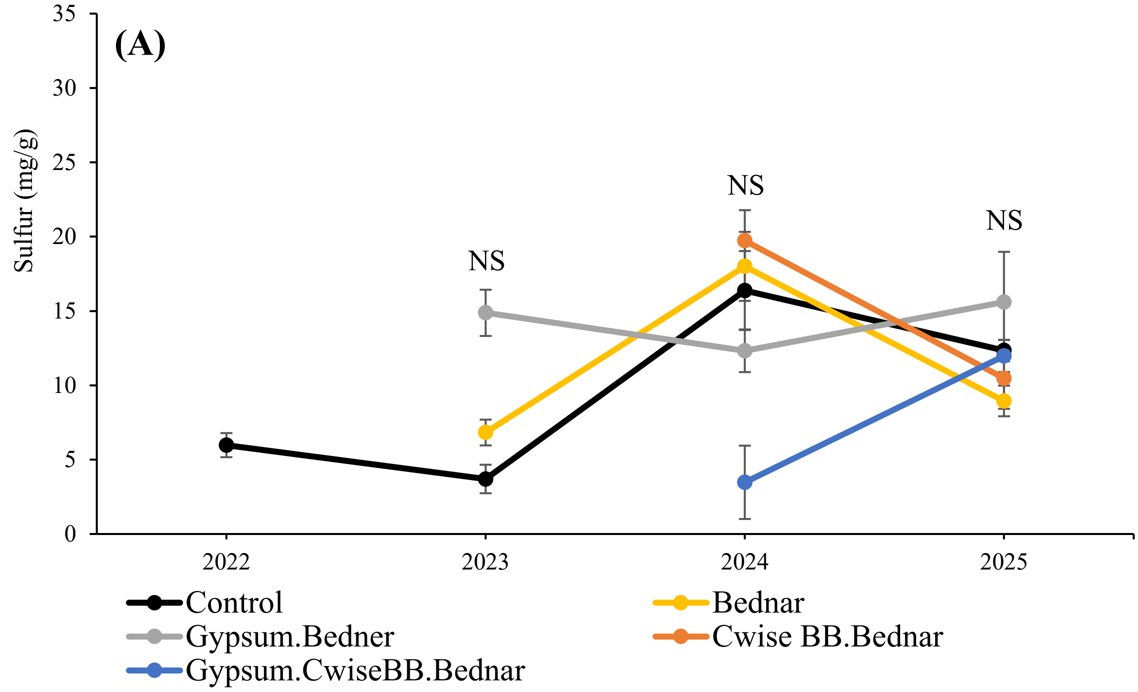


Fig. 18. Potassium Colwell in **(A)** 0-10 cm and **(B)** 10-30 cm profile in the large plots experiment recorded at pre-seeding in 2022- 2025. The 2022 data is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. In 2023, only three treatments were sampled, i.e., control, bednar and

gypsum+bednar. In 2024 and 2025, samples were collected from all the treatments. NS = P > 0.05. Error bar is the standard error of the treatment mean (n = 4).



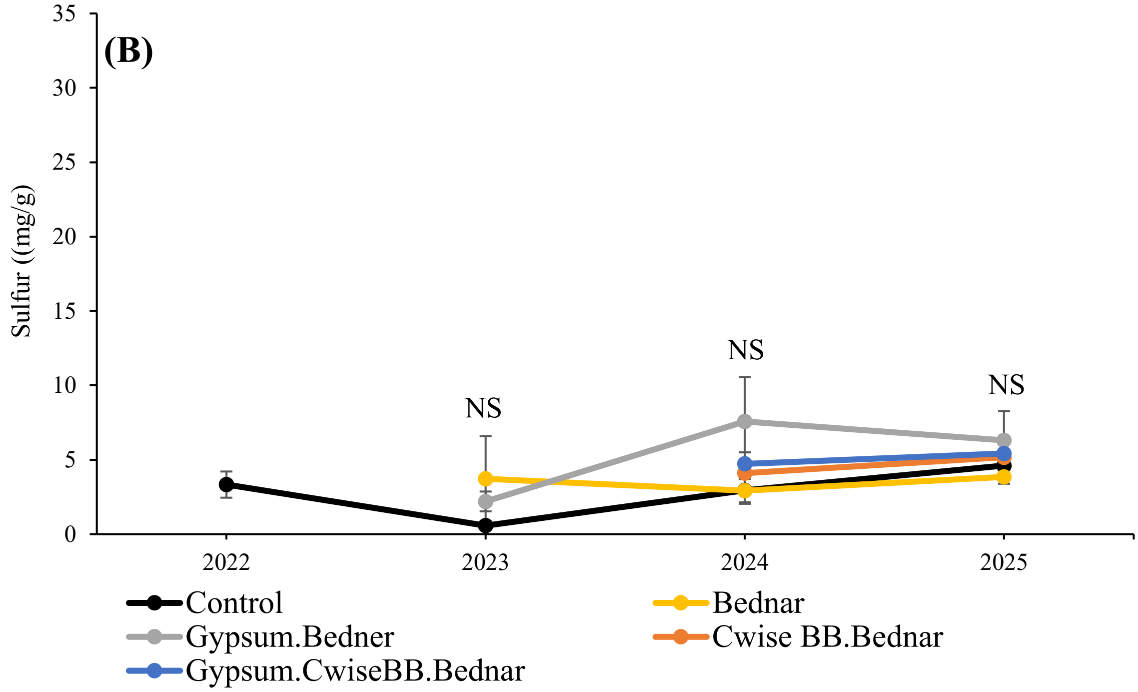
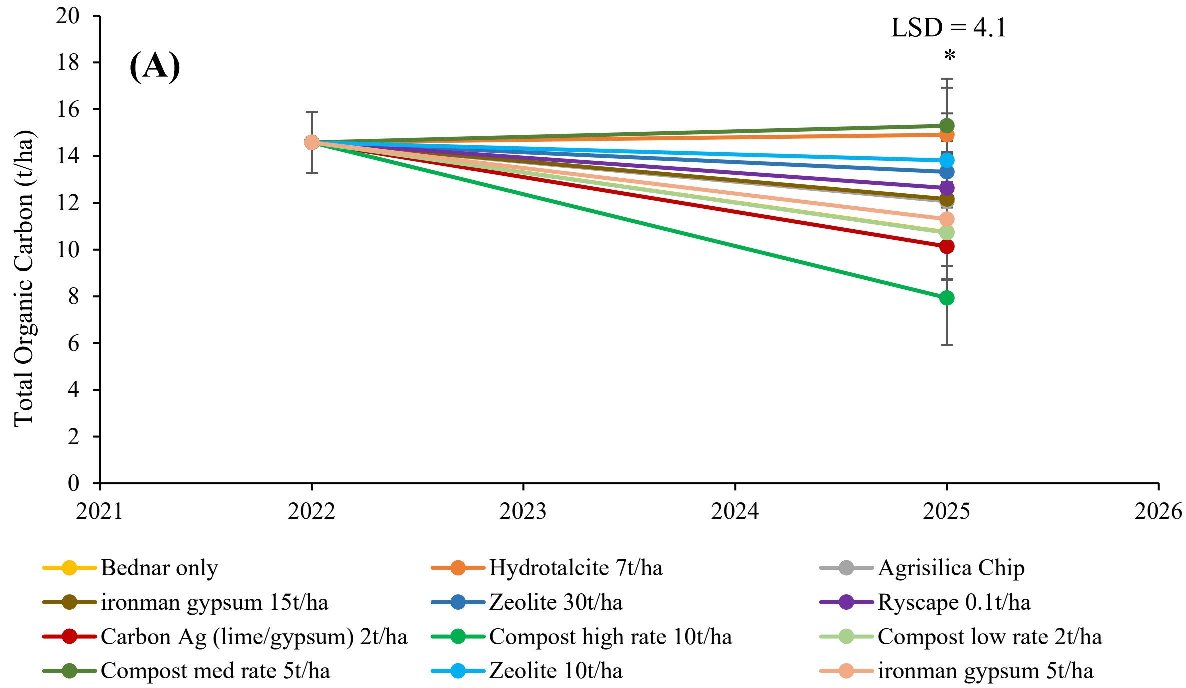
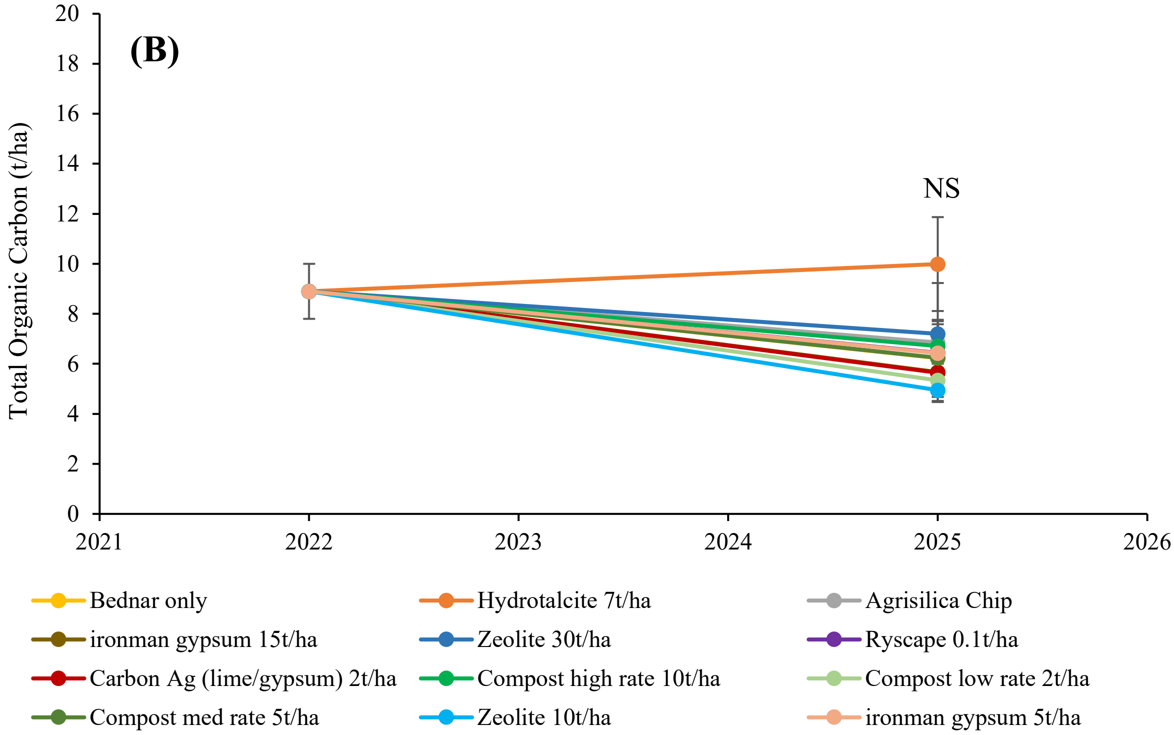


Fig. 19. Sulfur in **(A)** 0-10 cm and **(B)** 10-30 cm profile in the large plots experiment recorded at pre-seeding in 2022- 2025. The 2022 data is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. In 2023, only three treatments were sampled, i.e., control, bednar and gypsum+bednar. In 2024 and 2025, samples were collected from all the treatments. NS = P > 0.05. Error bar is the standard error of the treatment mean (n = 4).

3.5.4. Total Organic Carbon (TOC) – Small Plots Experiment

Total Organic Carbon (TOC) in the small plots experiment was significantly influenced by the applied treatments only in the top 10 cm in 2025 (Fig. 20A-C). In the top soil (0-10 cm) in 2025, only the hydrotalcite (7 t/ha) and medium compost rate (5 t/ha) had significantly greater TOC than control while the rest of the treatments were statistically similar to control (Fig. 20A). These results are in line with the previous studies showing an increase in the soil organic C after the application of compost (Atoloye et al., 2022; Grigatti et al., 2024; Wong et al., 2023), however, in the current study the medium compost rate performed better than the higher compost rate surprisingly. Similarly the role of hydrotalcite in carbon sequestration is also evident from the previous studies such as Suescum-Morales et al. (2022) and Grünewald et al. (2008).




(B)
Total Organic Carbon (t/ha)
NS
2021
2022
2023
2024
2025
2026
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha

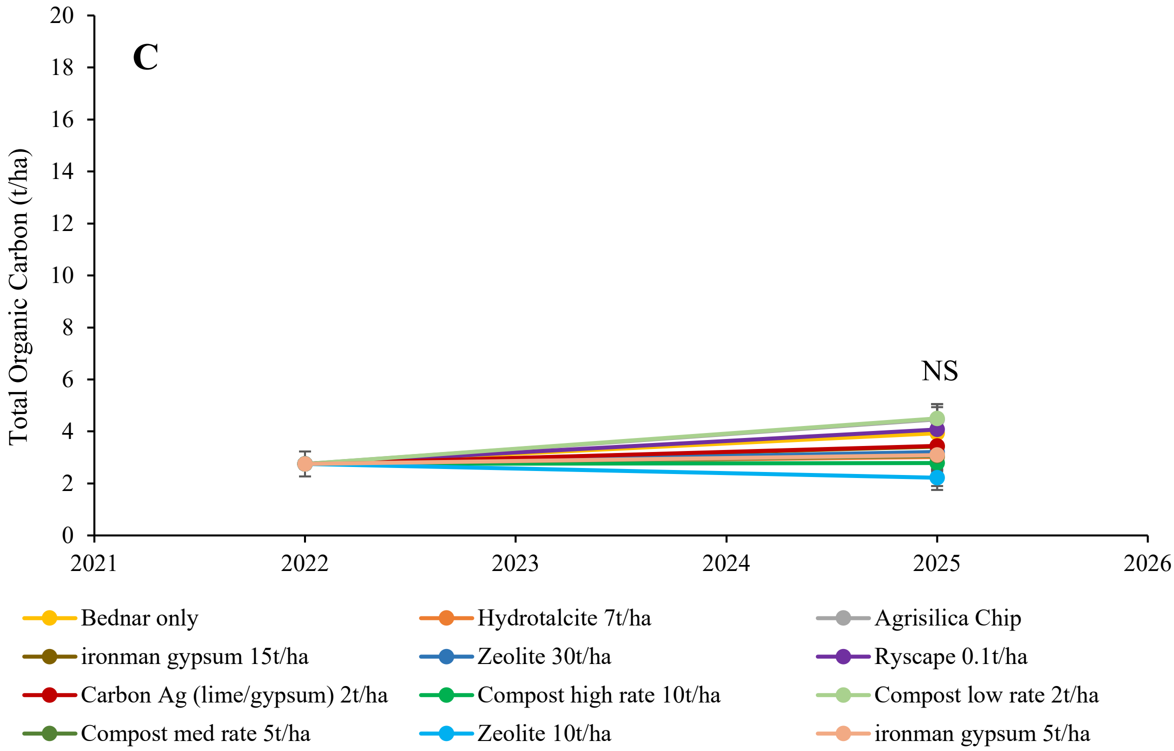

C
Total Organic Carbon (t/ha)
NS
2021
2022
2023
2024
2025
2026
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha

Fig. 20. Soil Total Organic Carbon in **(A)** 0-10 cm, **(B)** 10-30 cm and **(C)** 30-45 cm profile in the small plots experiment recorded at pre-seeding in 2022 and 2025. The 2022 data is a baseline data recorded before the application of the treatments by taking 4 composite samples each from 10 different sampling points scattered across the experimental area. The soil bulk density data had not been recorded in 2022, therefore, the 2025 bulk density data was used to calculate the total organic carbon per hectare for 2022.

NS = $P > 0.1$, † = $P < 0.1$, * = $P < 0.05$. Error bar is either the standard error of the treatment mean ($n = 4$) when $P > 0.05$ or the standard error of the population mean across the treatments when $P \leq 0.05$. Standard error of the population mean was calculated by using the following formula: Square Root of (2 × Mean Square of Error ÷ 4).

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