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RESEARCH ARTICLE

Optimising digestate fertilisation for onion (*Allium cepa* L.) production under semi-arid conditions: Effects on soil fertility, crop performance and yield

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Abstract

Onion (*Allium cepa* L.) farming in the Fez–Meknes region is heavily dependent on mineral fertilisers, yet prolonged use has weakened soil quality and nutrient efficiency. This study assessed whether anaerobic digestate (AD) could provide a viable alternative in semi-arid conditions and regions. The experiment took place in the field during the 2023–2024 season in a randomised complete block design, comparing six treatments: an unfertilized control, local recommended mineral fertilisation (10:30:10) and digestate applied at (10, 20, 30 and 40 dry weight (DW) t/ha). Soil characteristics, plant growth traits, biomass and yield were recorded at 30, 60 and 90 days after planting and at harvest. Differences among treatments were statistically significant according to ANOVA ($P < 0.05$). Digestate doses shifted soil fertility indicators. Organic matter rose by +21.1 %, available phosphorus by +64.1 % and mineral nitrogen by +483 %, while electrical conductivity increased with higher application rates. Onion plants also responded strongly. At 60 days after planting, the (40 DW t/ha) dose raised plant height by +38.8 % and by 90 days after planting, the same treatment sharply increased the leaf number (+94.5 %). Biomass patterns followed a similar trend, with bulb fresh weight at 60 days after planting climbing by +140.8 % under (40 DW t/ha). Yield gains were clear across all digestate levels: the control treatment produced 54.64 t/ha, the recommended mineral fertilization reached (73.69 t/ha) and the highest value appeared at (30 DW t/ha) with 75.25 t/ha (+37.8 % above the control treatment), slightly exceeding both the recommended mineral fertilization and the (40 DW t/ha) treatment.

Keywords: anaerobic digestion; biomass allocation; bulb yield; Morocco; nutrient use efficiency; onion (*Allium cepa* L.); semi-arid agriculture; soil fertility

Introduction

Vegetable farming in the Fez-Meknes region depends largely on mineral fertilisers and most farmers apply mineral fertilisers (NPK) without soil testing or dose adjustment (1). The continuous use of mineral fertilisers (NPK) leads to nutrient imbalance, reduced microbial activity (MA) and gradual soil degradation in intensively cultivated soils (2). These issues are more severe in crops (3). Understanding these conditions, nutrient use efficiency drops and farmers rely on drip irrigation to manage scarce water resources (1). Dryland systems also show low nitrogen cycling efficiency when mineral fertilisers are used alone, which increases the need for alternative inputs with different nutrient-release patterns (4). At the same time, agriculture and agro-industry in Morocco produce large amounts of organic residues that can be converted into digestate through anaerobic digestion, helping close the nutrient loop (5).

Onion (*Allium cepa* L.) is one of the main vegetable crops in Fez-Meknes alongside potato and garlic (1). Its performance is affected by water fluctuations and drought has been shown to limit nutrient availability and reduce growth at key stages (6). Semi-arid vegetable systems also face soil fertility decline because continuous cultivation often returns little organic matter to the soil (3). Even with these constraints, many farmers continue to depend on industrial fertilisers to maintain yields, although manure use is already widespread in the region (1). Anaerobic digestate uses local crop residues and manure to produce biogas energy and the digestate is a by-product from the process, which brings nutrients back to the soil and recycles organic waste in mixed crop-livestock areas such as Fez-Meknes (5, 7). Unlike raw manure, digestate contains more stable organic matter and nutrients in forms that plants can absorb more easily, so its fertilising effect tends to be more consistent during crop growth (8, 9). These features make digestate a practical organic option for vegetable systems that need reliable nutrient inputs. Results from several studies in cereals, forage, Corn silage (10) and watermelon (11) show that digestate can support nitrogen uptake and maintain or even increase yields when compared with mineral fertilisers (12, 13).

Digestate behaviour in soil depends strongly on salinity, irrigation patterns and soil texture and these interactions must be assessed directly under field conditions because they influence nutrient mobility and crop tolerance thresholds (14). The Fez-Meknes region produces substantial quantities of livestock manure and crop residues that can serve as a feedstock for biogas and digestate production (7). Most farms in the region (Fez-Meknes) are small and already use organic manure in their fields, but many farmers are still unfamiliar with digestate, a by-product from biogas technology (7). This gap in knowledge makes it important to test digestate under the local soil climate conditions. This study examines how digestate influences onion production in the Meknes area. The field experiment trial compares digestate with an unfertilized control and locally used mineral fertilisation (NPK) by monitoring soil properties, plant growth, biomass accumulation and yield at key growth stages. The objective is to evaluate whether digestate can serve as a practical fertiliser option for onions under semi-arid field conditions. We hypothesised that intermediate digestate application rates would optimise onion growth and yield by improving soil nutrient availability and promoting balanced biomass allocation, whereas higher rates could reduce nutrient use efficiency due to increased soil salinity under semi-arid conditions.

Materials and Methods

Field site description and weather conditions

The experiment was carried out during the 2023-24 growing seasons (from March to July) on the agroecological research platform of the Ecole Nationale d'Agriculture de Meknes (ENA Meknes) (33° 50'27.0"N, 5°28'37.1"W). The site is exposed to a Mediterranean semi-arid climate. Winter rainfall occurs in irregular events, while cropping periods are marked by rising temperatures and limited rainfall. Seasonal conditions during the field experiment followed this typical pattern for the region. Meteorological data for the period (Minimum means, maximum monthly temperatures and cumulative rainfall) were obtained from the on-site station at the pedagogic farm at ENA Meknes. These variables are provided in Fig. 1. The field experiment was conducted on an institutional platform and no specific field permits were required for its implementation.

Soil and digestate characterization

Before transplant, soil samples were taken from the (0-30 cm) layer following Z-pattern sampling. The soil was air-dried, sieved and analysed in the Ferticonseil Laboratory at ENA Meknes for texture, pH, electrical conductivity (EC), organic matter (OM), macro-nutrients and micro-nutrients. The digestate was obtained from the Central Danone anaerobic digestion unit in solid form. It was derived from activated-sludge, non-compliant dairy products and expired goods processed at the Meknes and Fkih Ben Saleh dairy production facilities. Digestate dry matter was determined by oven-drying 100 g samples at 90 °C for 72 hr until a constant weight was reached. Key soil and digestate properties are summarised in Table 1.

Since there are currently no Moroccan regulations governing the use of digestate in agriculture, the application rates applied in this study were based on French legislative guidelines (Decree No. 97-1133) and, according to it, digestate application is limited to a maximum of 30 DM t/ha over 10 years (15). To evaluate the yield response at higher than recommended doses, an additional rate of 40 t/ha DW was included.

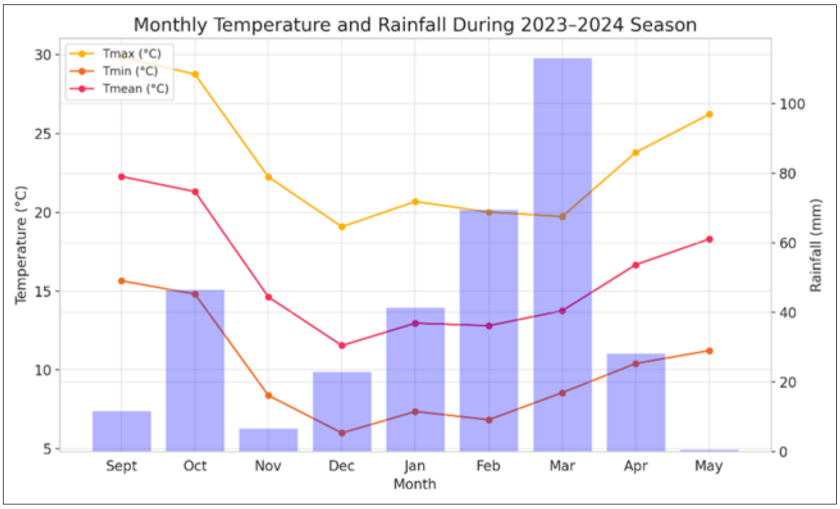

Fig. 1. Monthly average maximum, minimum and mean temperatures (°C) along with total rainfall (mm) recorded during the 2023–2024 onion growing season at the experimental site (ENA, Meknes, Morocco).

Table 1. Physicochemical characterization of the soil and digestate used in the experiment.

Parameters (Unit)	Soil	Digestate
Clay %	33.2	-
Loam %	36.3	-
Sand %	29.3	-
pH (H_2O)	7.62	7.22
Electrical conductivity (dS/m)	0.190	0.544
Organic matter (%)	4.50	26.56
Mineral nitrogen (mg/kg)	5.3	525.0
P_2O_5 (mg/kg)	79	1904.0
K_2O (mg/kg)	562	12000.0
Ca (meq/100 g)	37.5	3.2
Zn (mg/kg DW)	-	3.97
Cu (mg/kg DW)	-	<0.01
Ni (mg/kg DW)	-	68

Trial design and field layout

The trial followed a randomised complete block design (RCBD) with six treatments and three replications. The treatments were an unfertilized serving as a negative control, a mineral fertiliser (NPK 10:30:10) applied at 1 kg/plot in line with the local practices for onion cropping in the Meknes region and four digestate application rates of (10, 20, 30, 40, 40 DW t/ha); labeled (D_1, D_2, D_3 and D_4). The experiment covered an area of 253 m^2 and was divided into three blocks, each containing six 9 m^2 (3 × 3 m) plots spaced 1 m apart. Onion rows were spaced 40 cm apart with 20 cm between plants within rows. The experimental design setup is illustrated in Fig. 2. Each plot was arranged with 8 rows of 15 plants, giving a total of 135 plants per plot. Rows 2 and 7 were assigned for destructive sampling and rows 4 and 5 were used for non-destructive measurements. The plant material (red onion (*A. cepa* L.)) was obtained from a local supplier. A field view of the crop at 60 days after planting is provided in Fig. 3.

Irrigation and field maintenance

Irrigation was provided through drip lines, with one line per crop row delivering 1.6 L/hr. Irrigation was applied two to three times per week, with frequency and timing adjusted to crop demand and developmental stage, seasonal weather and local irrigation guidelines. Weed control was carried out manually with a hoe at key growth stages. No chemical pesticides or fungicides were applied and field management followed agroecological practices.

Observational protocols and sampling scheme

Plant performance was monitored through non-destructive and destructive measurements taken at 30, 60 and 90 days after planting (DAP) and at harvest. The non-destructive samples include recording plant height, leaf number and bulb diameter. These observations were recorded from eight plants located in the two central rows (Rows 4 and 5) of each plot. Destructive sampling was done at the

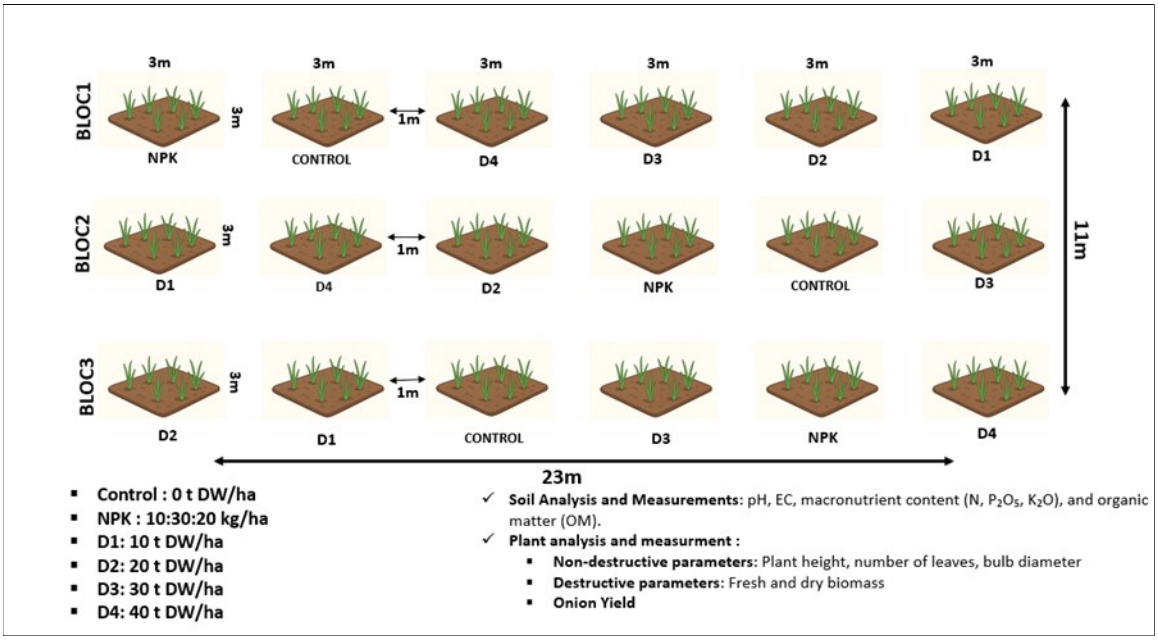

Fig. 2. Schematic illustration of the experimental setup.

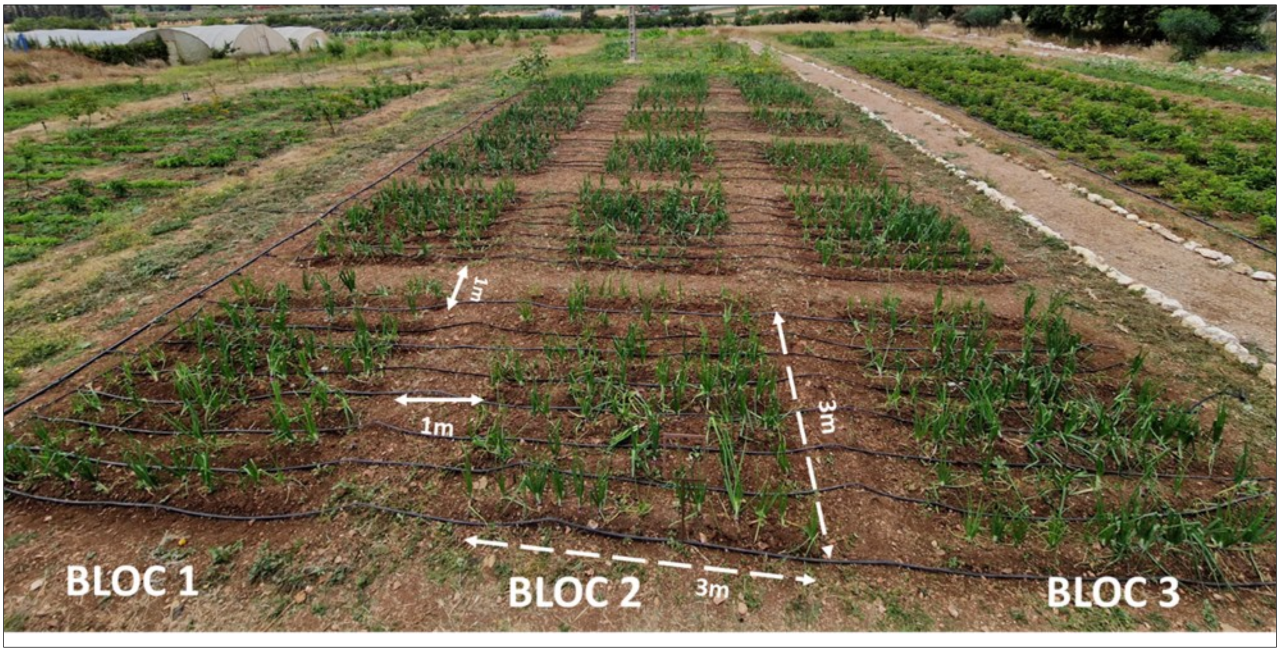

Fig. 3. Field view of the onion fertilization trial at 60 DAP conducted under a randomized complete block design (RCBD) with three blocks (Bloc 1, Bloc 2, Bloc 3). Each block comprises six treatment plots (3 m × 3 m) separated by 1 m alleys. Treatments correspond to control, (NPK) mineral fertiliser and four digestate doses. Onion plants were established using locally sourced red onion plantlets (*Allium cepa* L.). Drip irrigation lines are visible along each planting row. D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha

same points (30, 60, 90, DAP), with six plants taken from two rows (row 2 and row 7). No samples were taken from rows 1 and 8 to limit the edge effect. During destructive sampling, the total fresh weight and DW of bulbs and leaves were determined. For the DW, bulbs and leaves were dried in an oven at 70 °C until they reached a stable weight. The final harvest was done one day after the (90 DAP) when about 80 % of the foliage had fallen over, showing the crop had reached maturity. Yield data were expressed in kg per 8 plants and tons per hectare.

Statistical processing

Statistical analyses were performed in XLSTAT (2024, Lumivero, USA) and Python (version 3.11). Data normality was verified with the Anderson-Darling test and a log transformation was applied when distributions were non-normal. One-way ANOVA was executed on the data and treatment differences were separated using the LSD test at $P < 0.05$. Principal Component Analysis (PCA) and Redundancy Analysis (RDA) were executed in Python through the (sklearn.decomposition.PCA) and (skbio.stats.ordination.RDA) libraries to assess relationships among variables and to identify the digestate doses with a strong effect on yield traits and biomass. All analyses were based on three replicates per treatment (n=3) and evaluated at 5 % significance ($P < 0.05$).

Results

Effect of digestate on soil properties

The effects of digestate application on post-harvest soil physicochemical properties are presented in Table 2. One-way ANOVA revealed significant treatment effects on all measured soil parameters ($P < 0.05$). Soil pH decreased progressively with increasing digestate rates, declining from 7.88 in the control and NPK treatments to 7.57 at the highest digestate dose (D_4). Organic matter (OM) content increased significantly under all fertiliser treatments, rising from 5.29 % in the control to a maximum of 6.41 % under (D_4), with intermediate digestate doses also showing marked improvements. Electrical conductivity (EC) increased consistently with digestate application rate, ranging from 0.45 dS/m) in the control to 0.88 dS/m at D_4, while remaining comparatively low under mineral fertilisation. Available phosphorus (P_2O_5) exhibited a strong dose-dependent response, increasing from 167 mg/kg in the control treatment to 274 mg/kg in D_4 (+64.1 %), whereas mineral nitrogen showed the largest proportional increase, reaching 30.9 mg/kg at D_4 compared with 5.3 mg/kg in the control. Potassium availability (K_2O) increased at higher digestate doses, with the highest value observed at (D_4) (813 mg/kg), while lower digestate rates showed values comparable to or slightly below the control. Overall, digestate application substantially enhanced soil nutrient availability compared with both the unfertilized control and mineral fertilisation, with the most pronounced effects occurring at intermediate to high application rates (Table 2).

Effect of digestate application on onion growth parameters

Vegetative development of the onion differed significantly among fertilisation treatments at all sampling dates (30, 60, 90 days after planting (DAP)), as confirmed by ANOVA (F, df=5, 138; $P < 0.05$). Digestate application consistently enhanced plant height (PH), leaf number (LN), collar diameter (CD) and bulb diameter (BD) compared with both the unfertilized control and mineral fertilisation, with the magnitude of differences increasing over time. Growth responses were particularly pronounced at intermediate and high digestate doses, indicating a cumulative effect of digestate on onion vegetative development (Fig. 4). At 30 DAP, plant height (PH) rose from 38.54 cm in the control to 42.03 cm under NPK treatment (+9.1 %) and ranged from 45.54 cm to 52.95 cm across digestate treatments, corresponding to increases of +18.2 % to +37.4 % relative to the control (Fig. 4C). Leaf number (LN) followed a similar trend, rising from 7.21 leaves in the control to 7.58 leaves under (NPK) treatment (+5.1 %) and reaching 8.25 leaves at (D_1) (+15.3 %) (Fig. 4B). Collar diameter (CD) increased from 1.08 cm in the control to 1.14 cm under NPK treatment (+5.7 %) and up to (1.35 cm) at in D_4 (+25.7 %) (Fig. 4D). Bulb diameter (BD) also increased under digestate, with values ranging from 1.34 cm to 1.52 cm which is +25.6 % and +10.7 % compared with 1.21 cm in the control (Fig. 4C)

At 60 DAP, growth differences among treatments became more pronounced. pH increased from 61.19 cm in the control to 66.03 cm) in NPK (+7.9 %) and reached 84.93 cm at D_4 (+38.8 %) (Fig. 4A). Leaf number (LN) rose modestly under NPK treatment (10.83 leaves; +2.8 %) but increased progressively with digestate dose, reaching 12.00 leaves at D_4 (+13.8 %) (Fig. 4B) increased from 2.13 cm in the control to 3.02 cm at D_4 (+41.8 %) (Fig. 4D), while BD increased from 2.86 cm to 3.91 cm (+36.7 %) across the same treatments (Fig. 4C). At 90 DAP, digestate treatments maintained a clear advantage over both the control and the NPK. pH increased from 73.86 cm in the control to 76.49 cm under NPK (+3.6 %) and up to 93.44 cm at (D_4) (+26.5 %) (Fig. 4A). Leaf number (LN) showed the strongest response at this stage, rising from 13.79 leaves in the control to (16.50) under NPK (+19.7 %) and reaching 26.83 leaves at D_4 (+94.5 %) (Fig. 4B). CD increased from 2.40 cm in the control to 2.96 cm at D_4 (+23.3 %) (Fig. 4D). BD ranged from 7.08 to 7.50 cm under digestate treatments, with the highest value observed at D_3 (+13.4 % relative to the control) (Fig. 4C). Visual differences in onion growth among treatments at 60 and 90 DAP are illustrated in (Fig. 5).

Effect of digestate and NPK application on onion biomass accumulation

Biomass accumulation responded significantly to fertilisation regime at all sampling dates (30, 60 and 90 days after planting, DAP), as confirmed by ANOVA and post-hoc LSD tests (df =5, 102; $P < 0.05$). Destructive sampling showed that digestate application consistently enhanced bulb fresh weight (BFW), leaf fresh weight (LFW), bulb DW (BDW) and leaf DW (LDW) compared with both unfertilized control and mineral fertilisation. Differences among treatments became

Table 2. Changes in pH, electrical conductivity (EC), rganic matter (OM) and available macronutrients of post-harvest soil after onion cultivation under control (C), mineral fertilization (NPK) and different digestate doses D_1: 10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha, D_4: 40 DW t/ha). Data represent means ± SD (n = 3).

	Control	NPK	D_1	D_2	D_3	D_4
pH	7.88 ± 0.04	7.88 ± 0.04	7.82 ± 0.04	7.66 ± 0.05	7.66 ± 0.04	7.57 ± 0.02
OM (%)	5.29 ± 0.08	6.12 ± 0.05	6.27 ± 0.04	6.68 ± 0.07	6.00 ± 0.01	6.41 ± 0.03
EC (ds/m)	0.45 ± 0.02	0.43 ± 0.02	0.48 ± 0.02	0.77 ± 0.03	0.63 ± 0.03	0.88 ± 0.02
P_2O_5 (mg/kg)	167 ± 4	199 ± 5	195 ± 4	217 ± 6	251 ± 5	274 ± 5
K_2O (mg/kg)	662 ± 10	806 ± 18	598 ± 11	634 ± 8	681 ± 15	813 ± 13
Mineral N (mg/kg N)	5.3 ± 0.2	8.1 ± 0.2	9.4 ± 0.3	14.4 ± 0.3	17.8 ± 0.4	30.9 ± 1.0

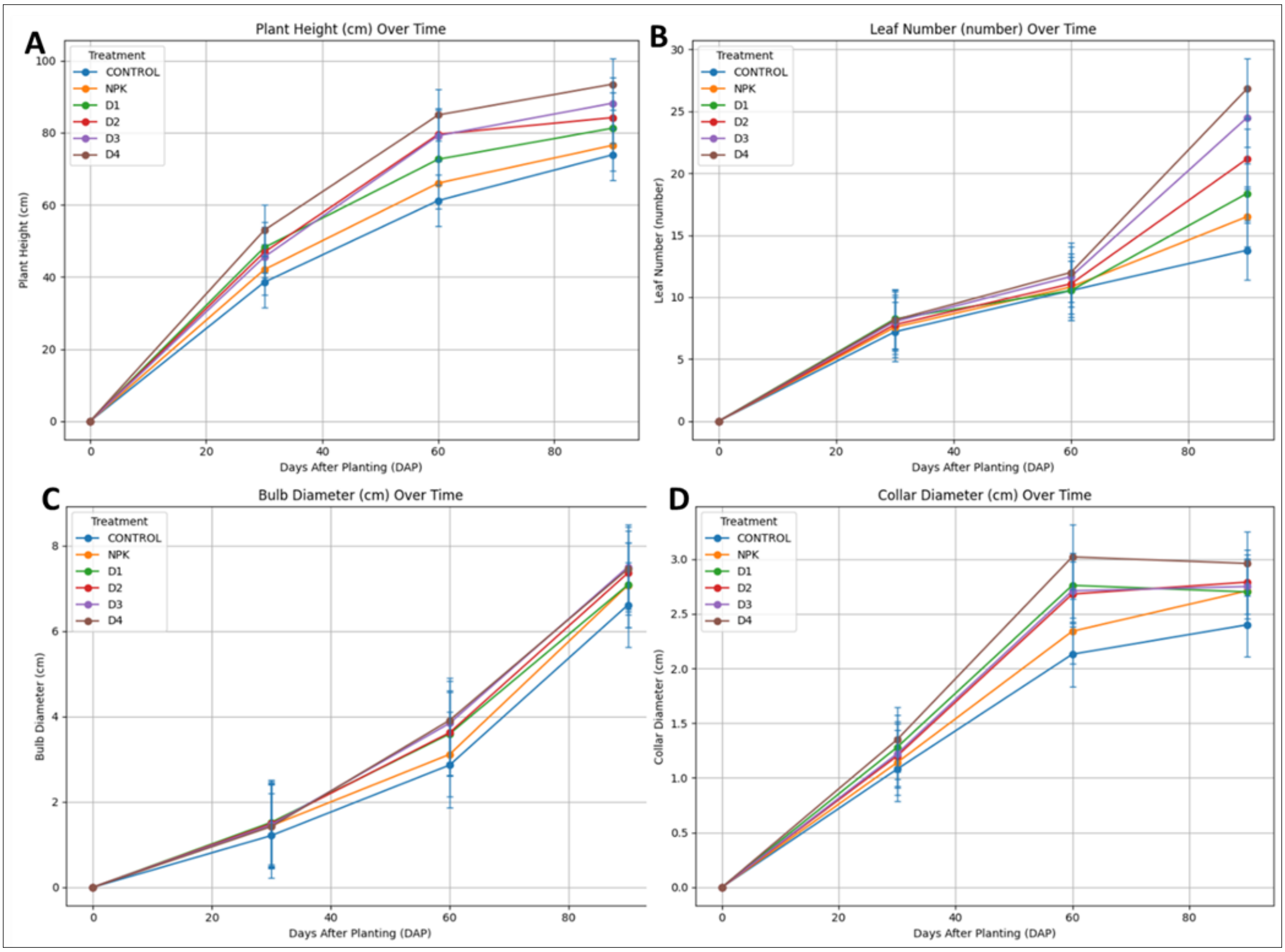

Fig. 4. Effect of digestate and mineral fertilization on onion growth parameters measured at different crop development stages. A. Plant height (cm), B. Leaf number (count), C. Bulb diameter (cm) and D. Collar diameter (cm) over time (Days After Planting, DAP). Data represents mean values ± standard error (n = 8 plants per treatment per sampling date). Treatments: Control (unfertilized), NPK (mineral fertiliser) and four digestate doses (D_1), (D_2), (D_3), (D_4). Measurements were conducted as part of a randomized complete block design (RCBD) field trial. D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha

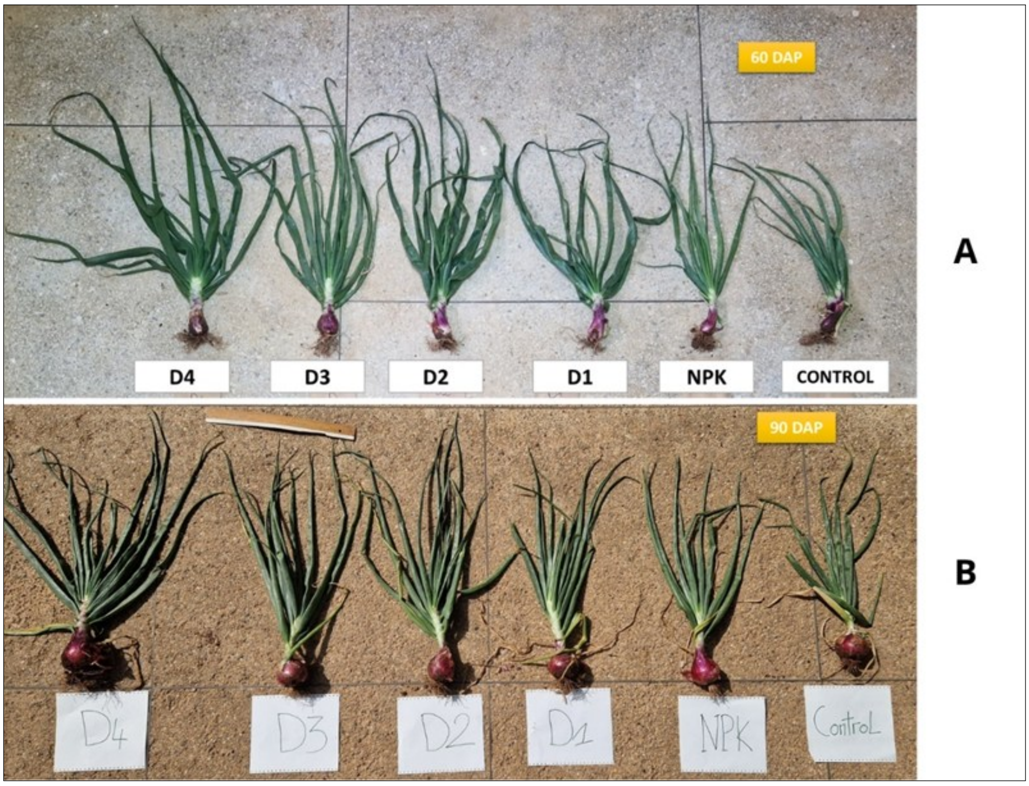

Fig. 5. Onion plants under different fertilization treatments at two growth stages: A. 60 days after planting (60 DAP) and B. 90 days after planting (90 DAP). Treatments from left to right: (D_4), (D_3), (D_2), (D_1), NPK and Control. D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha

progressively larger as the crop developed, with intermediate and high digestate doses showing the strongest biomass accumulation, particularly at 60 and 90 DAP (Fig. 6). At 30 DAP, digestate treatments already promoted higher biomass than both the control and the NPK. Bulb fresh weight increased from 0.0485 kg in the control to 0.066-0.075 kg under digestate treatments, corresponding to increases of +27 % to +54 %, whereas NPK reached 0.064 kg (+37 %) (Fig. 6A). Leaf fresh weight (LFW) showed a stronger response, increasing by +62 % to 97 % under digestate compared with (+36 %) under NPK (Fig. 6B).

Dry biomass responses were more moderate at this stage; bulb DW increased by +52-54 % under low to intermediate digestate doses D_1-D_2, while higher doses showed smaller gains (Fig. 6C-6D). By 60 DAP, biomass differences among treatments were clearly amplified. BFW increased from 0.1722 kg in the control to 0.2167 kg in NPK, while digestate treatments reached 0.2999- 0.4145 kg, representing increases of +74.2 % to +141 %, with the D_4 treatment surpassing the NPK treatment by more than +91.3 % (Fig. 6A). LFW followed a similar pattern, increasing by +69.5 % to 125 % under digestate compared with (+31.7) under NPK (Fig. 6B). Bulb DW (BDW) increased by (+77 %) to (+130 %) under digestate, substantially exceeding the response observed with mineral fertilization (42.3 %) (Fig. 6C). LDW also showed higher values under digestate, with increases of up to (103 %) at D_4 (Fig. 6D).

At 90 DAP, the four biomass parameters reached the maximum values across all treatments. BFW increased from 1.975kg in the control treatment to 2.830 kg under the NPK treatment +43.3 %, while digestate treatments ranged from 2.550 to 2.850 kg, corresponding to increases of +29.1 %, to +44.3 %, with D_4 showing the highest value (Fig. 6A). LFW increased from +18.3 % to +42.7 % under digestate compared with 34.9 % under NPK (Fig. 6B). BDW showed consistent enhancement under digestate, reaching +37.5 % to 50 % relative to the control, compared with (+20 %) under NPK (Fig. 6C). LDW increased more modestly at this stage, with digestate treatments maintaining values (18-27 %) above the control (Fig. 6D). Digestate application promoted greater and more sustained biomass accumulation than mineral fertilization, with the strongest differences observed at mid and late growth stages.

Effect of digestate and NPK application on onion yield

Onion yield responded clearly to fertilisation regime, as assessed by fresh bulb yield per 8 plants and the corresponding per-hectare yield ($Yield_{t/ha}$). Both digestate and mineral fertilisation increased yield relative to the non-amended control, with clear differences among treatments. The highest yield was observed under the intermediate digestate dose (D_3), whereas the highest digestate rate (D_4) produced yields comparable to mineral fertilisation. Yield results are presented in Fig. 7 and representative harvested bulbs for each treatment are shown in Fig. 8. The control treatment produced the lowest yield, with 3.75 kg/8 plants, corresponding to 54.64 t/ha. Under NPK, yield increased to 5.05 kg/ 8 plants (73.69 t/ha), representing a +34.9 %

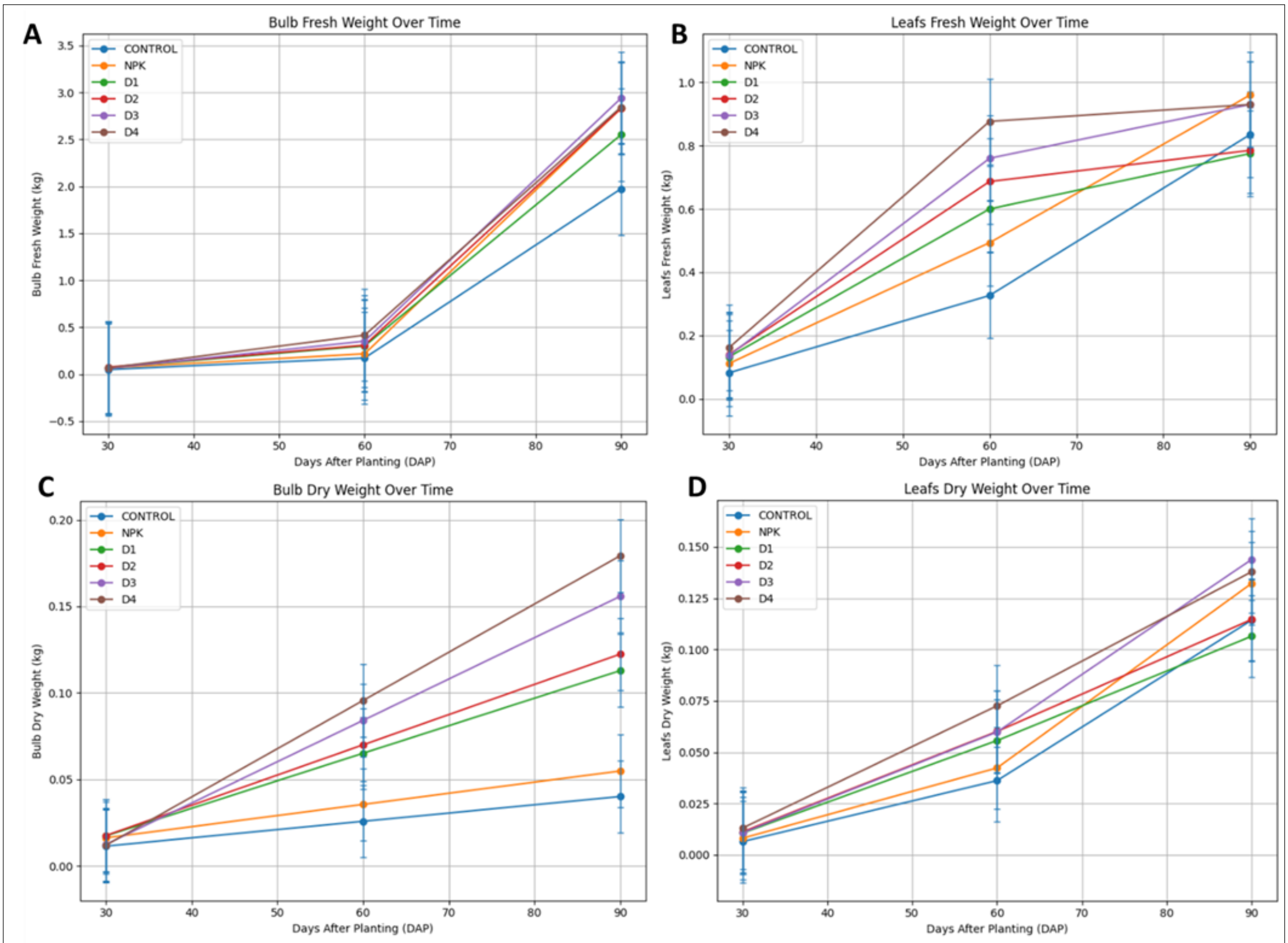

Fig. 6. Evolution of onion biomass components as influenced by fertilisation treatments from 0 to 90 days after planting (DAP). Treatments include a non-amended control, mineral fertiliser (NPK) and four increasing digestate application rates: D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha. Panels represent: A. bulb fresh weight (BFW), B. leaf fresh weight (LFW), C. bulb DW (BDW) and D. leaf DW (LDW), all expressed per 8 plants.

increase relative to the control. Among the digestate treatments, D_3 resulted in the highest yield, reaching 5.16 kg/ 8 plants (75.25 t/ha, which was the maximum value recorded across all treatments and corresponded to a +37.8 % increase compared with the control (Fig. 7- 8E). The remaining digestate doses also produced clear yield improvements relative to the control. D_1 yielded 4.43 kg/ 8 plants (64.65 t/ha; +18.3 % vs. control) (Fig. 7- 8C), while D_2reached 4.82 kg/ 8 plants (70.29 t/ha; +28.6 %) (Fig. 7D-8D). The highest digestate dose (D_4) produced 5.03 kg/8 plants (73.42 t/ha), a value comparable to that obtained under (NPK) (Fig. 7- 8F). Overall, onion yield followed a non-linear response to digestate application rate, with the intermediate dose (D_3) outperforming both lower and higher digestate rates as well as mineral fertilisation under the conditions of this study (Fig. 7- 8).

Summary of agronomic responses to digestate application

To facilitate interpretation of the main agronomic trends, a summary of the effects of digestate and mineral fertilisation on soil fertility, plant growth, biomass accumulation and yield is provided in Table 3. This table synthesises the relative performances of each treatment across the measured parameters.

Principal component analysis (PCA) of onion growth and yield responses to digestate

Principal component analysis (PCA) was performed to explore the relationship between the measured parameters, combining all the agronomic traits with destructive parameters (biomass) of the digestate-treated onion plants (Fig. 9). The first two components, PC1 and PC2, accounted for (56.47 %) and (42.53 %) of the total variance. PC1 represented a gradient linked to overall biomass accumulation and yield performance, with strong positive loadings for

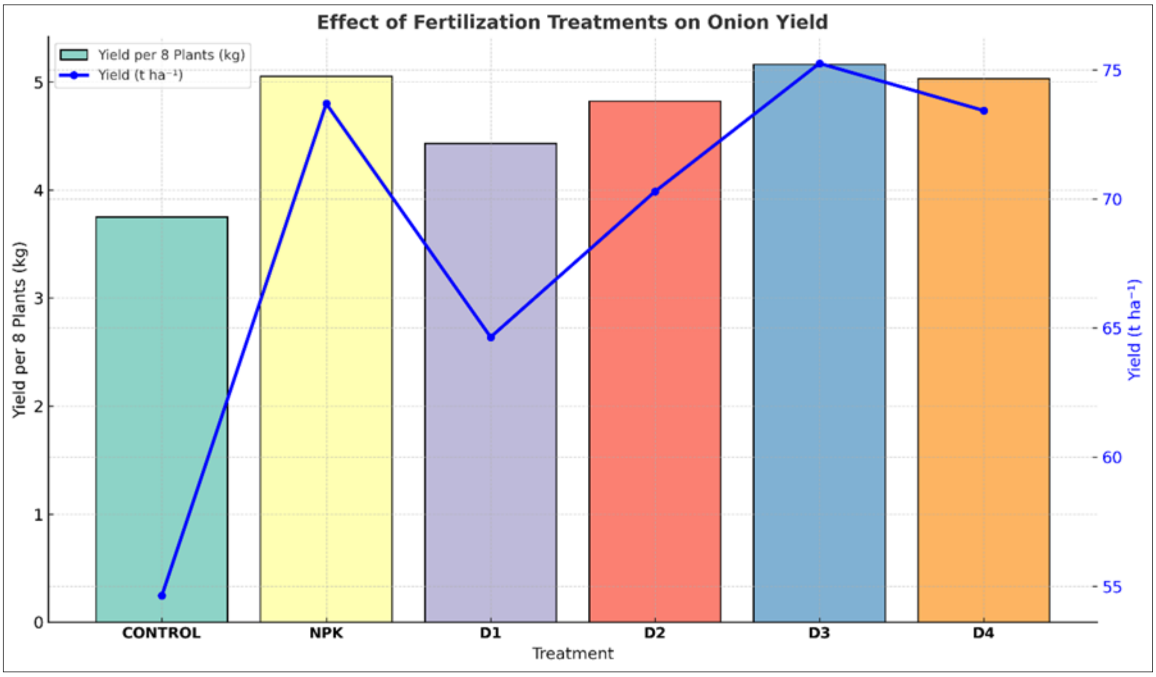

Fig. 7. Effect of mineral (NPK) and organic digestate D1, D_2, D_3 and D_4 fertilisation treatments on onion yield expressed as fresh bulb weight per 8 plants and extrapolated yield (t/ha). D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha

Fig. 8. Representative onion bulbs harvested at 90 days after planting (90 DAP) under different fertilization treatments: A. Control; B. NPK; C. D_1; D. D_2; E. D_3 and F. D_4. D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha

Table 3. Summary of key agronomic responses of onion (*Allium cepa L.*) to digestate and mineral fertilization under semi-arid field conditions.

Category	Control	NPK	D_1 (10 DW t/ha)	D_2 (20 DW t/ha)	D_3 (30 DW t/ha)	D_4 (40 DW t/ha)
Soil fertility						
Organic matter	Baseline	↑	↑↑	↑↑↑	↑↑	↑↑↑
EC (salinity)	Low	Low	Slight ↑	Moderate ↑	Moderate ↑	Highest ↑
Available P_2O_5	Lowest	↑	↑	↑↑	↑↑↑	Highest
Mineral N	Lowest	↑	↑	↑↑	↑↑↑	Highest
Growth (90 DAP)						
Plant height	Lowest	↑	↑↑	↑↑	↑↑	Highest
Leaf number	Lowest	↑	↑↑	↑↑	↑↑↑	Highest
Bulb diameter	Lowest	↑	↑↑	↑↑	Highest	↑↑
Biomass allocation						
Bulb fresh weight	Lowest	↑	↑↑	↑↑	↑↑↑	↑↑↑
Bulb DW	Lowest	↑	↑↑	↑↑	↑↑↑	↑↑↑
Yield						
Yield (t/ha)	54.6	73.7	64.7	70.3	75.3 (highest)	73.4

↑ = increase relative to control; magnitude reflects observed trends across Tables and Figures

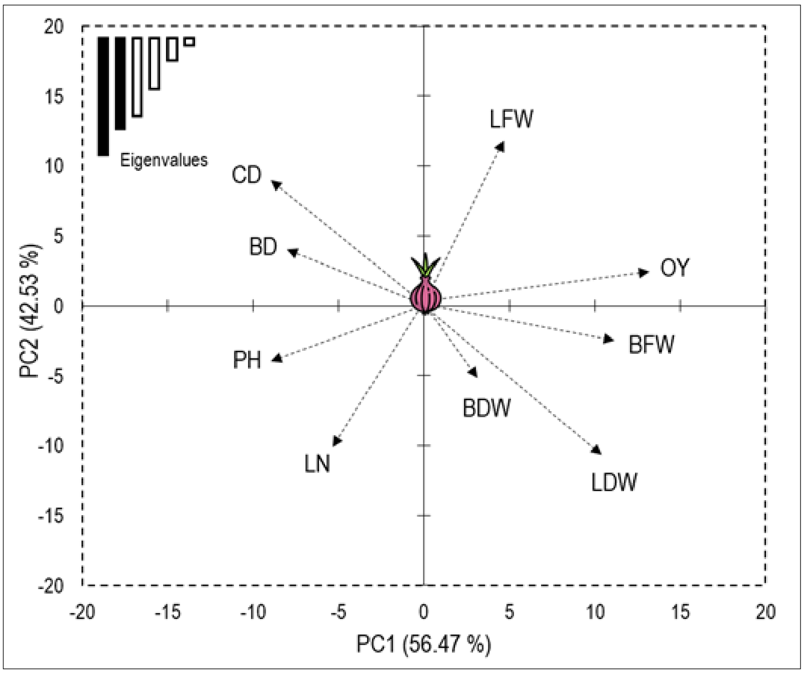

Fig. 9. Principal component analysis (PCA) showcasing the correlation patterns of agronomic parameters of Onion as processed with different digestate treatments.

onion yield (OY), bulb fresh weight (BFW) and leaf fresh weight (LFW). This pattern indicated a strong positive association among these variables, suggesting that plants forming heavier bulbs also accumulated greater total biomass and achieved higher yields. PC2, in contrast, separated structural and morphological traits, collar diameter (CD), bulb diameter (BD) and plant height (PH) from variables related to dry matter accumulation, such as bulb DW (BDW) and leaf DW (LDW). Leaf number (LN) showed a low (negative) loading on this axis, indicating that plants with more leaves tended to have smaller structural traits in this study. Taken together, the ordination pattern suggests that onions followed different physiological pathways depending on the digestate rates they received.

Redundancy analysis (RDA)

To further characterise the influence of each digestate treatment D_1 to D_4, a redundancy analysis (RDA) was carried out, integrating all agronomic parameters, including both destructive and non-destructive measurements (Fig. 10). Yield-oriented parameters were given greater weight than the other traits because of their direct importance at the farm scale. The first two canonical axes, RDA1 and RDA2, explained 49.91 % and 35.08 % of the total variation, respectively. In all the treatments, D_3 and D_4 showed the strongest influence on the measured parameters (variables). Yield (related components) including OY, BD, BFW and BDW were located closest to the D_3 and D_4 treatments in the ordination space, showing that these doses had the strongest influence (Fig. 10). Traits such as LN, PH and LFW were also linked to the higher digestate levels, though to different extents. By contrast, the (NPK) and D_1 treatments aligned mainly with general vegetative growth traits and contributed less to (OY). The D_2 treatment fell in an intermediate position, indicating a more balanced relationship among the evaluated variables (Fig. 10).

Discussion

Effect of digestate application on soil physicochemical properties

Digestate application substantially enhanced soil organic matter and nutrient availability while inducing a moderate, dose-dependent increase in electrical conductivity, without causing immediate salinity constraints for onion under the conditions of this study. Soil pH declined only slightly, moving from 7.88 in the control treatment to 7.57 under the 40 DW t/ha treatment. A similar pattern was reported in which drops of 0.15, 0.23 and 0.39 units at 15 DW t/ha, 30 DW t/ha and 60 DW t/ha, respectively (10). Research also reported small declines in pH after applying digestate, although the exact response often varies with the type of digestate used and the

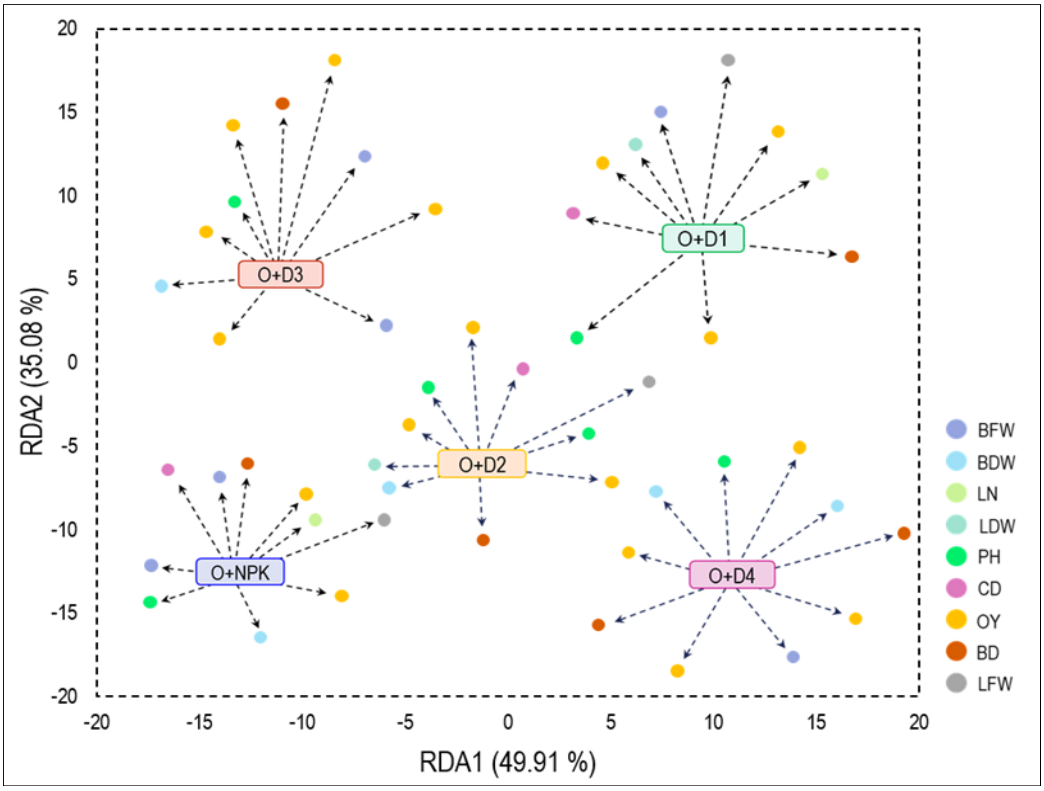

Fig. 10. Redundancy analysis (RDA) highlighting the general impact of different digestate treatments applied to onion on destructive and non-destructive agronomic parameters. D_1:10 DW t/ha, D_2: 20 DW t/ha, D_3: 30 DW t/ha and D_4: 40 DW t/ha

natural buffering strength of the soil (16, 17).

Organic matter (OM %) increased from 5.29 % to 6.41 % at 40 DW t/ha. Research reported that OM increases of +9.4 and +14.6 % at 30 DW t/ha and 60 DW t/ha (10). Similar improvements in total organic carbon, ranging from 9.7 to 14.8 g/kg, were noticed. Microbes could quickly use the labile carbon in digestate and this fast uptake contributes to the increase in organic matter (OM) (18, 19). Electrical conductivity (EC) rose from 0.45 to 0.88 dS/m. Research indicates that (EC) increases from 189 to 212 and 255 µS/cm at 15,30, 60 DW t/ha, showing a comparable dose-dependent pattern (10). A comparable rise in EC, noting increases from 195 to 394 µS/cm after applying organic residues, was noticed (20). Research attributed this rise mainly to the buildup of humic-like materials and extra dissolved ions in the soil, while 20-25 % EC rises to increased levels of K^+, Ca^{2+} and Mg^{2+} (16, 21).

Although electrical conductivity increased to 0.88 dS/m at the highest digestate dose, this value remains below commonly reported salinity thresholds for onion (*Allium cepa* L.). Onion is generally classified as a salt-sensitive to moderately salt-sensitive crop, with yield reductions frequently reported when soil electrical conductivity exceeds approximately 1.2-1.4 dS/m, depending on cultivar and growing conditions (22, 23). This indicates that, under the conditions of the present study, digestate application did not induce salinity levels likely to cause immediate yield limitation. However, under semi-arid conditions characterised by limited rainfall and leaching, repeated application of digestate at high rates may progressively increase soil salinity over time. Such long-term salinity buildup may pose risks for soil health and nutrient use efficiency if application rates are not properly managed (24). Available P_2O_5 increased from 167 to 274 mg/kg. A similar increase, with available P rising from 15 to 28 mg/kg) after digestate use (18). A dose of 170 m^3/ha of liquid digestate raised soil P from 6 to 19 mg/kg, reflecting its high proportion of easily accessible phosphorus (11). K_2O levels increased from 662 mg/kg in the control treatment to 813 mg/kg under the (40 DW t/ha) treatment, indicating a clear response to digestate addition. Research indicates that proportional K increases of 12-21 % at 15-60 DW t/ha and soil K rises of 120-210 mg/kg with digestate additions (10, 18). Research noted that liquid digestate often contains roughly 2-3 kg K_2O/m^3, a value that fits well with the potassium rise in our plots (11).

In our study, mineral nitrogen rose from 5.3 to 30.9 mg/kg. A similar rise was noted in which increases of 40-80 mg/kg were observed after digestate use. Research indicates that digestates' high ammonium content, often 60-80 % of total N, is rapidly nitrified once applied (11, 19). Mineral N increased sharply with different digestate doses, rising by 47 %, 96 % and 148 % at 15 DW t/ha, 30 DW t/ha and 60 DW t/ha (10). Beyond improving organic matter and macronutrients, digestate also supplies trace elements. Nickel (68 mg kg^{-1} DW) stayed within European limits (50–100 mg kg^{-1} DW), but its gradual buildup under repeated applications in semi-arid soils with low leaching still requires careful monitoring (15, 25). Nutrient interactions were clear, as the high NH_4^+ content can compete with Ca^{2+}, Mg^{2+} and K^+ for root uptake and surface-applied ammonium may increase volatilisation or leaching when it is not well matched with crop demand (26, 27).

Effect of digestate application on onion growth parameters

Digestate strongly stimulated vegetative growth, with the highest responses at 30–40 DW t/ha. Compared with mineral fertilisation, digestate produced more sustained increases in vegetative traits, particularly at later growth stages, indicating a more continuous nutrient supply. Plant height (PH), leaf number (LN), collar diameter (CD) and bulb diameter (BD) all increased in a clear dose-dependent pattern, especially at 60 and 90 DAP. The gains in PH and LN mainly reflect the gradual release of N and P, which support continuous vegetative growth. Similar stimulation in maize and tomato under digestate fertilisation was reported (10, 28). Research has found greater shoot biomass and leaf expansion in watermelon and cauliflower after digestate application, reflecting its readily available nitrogen (11). For BD, digestate consistently surpassed the control and NPK at most stages in onions treated with organic bio-stimulants and improved bulb development in low-salinity organic systems were noticed (29, 30).

Effect of digestate on biomass allocation

Digestate application at all 4 doses (rates) increased onion biomass at 30, 60 and 90 DAP, showing its ability to sustain both vegetative and reproductive growth. At 60 days after planting, bulb fresh weight (BFW) and dry matter rose markedly under D_3 (30 DW t/ha) and D_4 (40 DW t/ha) digestate treatments, confirming a clear dose-response pattern. These results indicate that cattle slurry digestate increased onion both shoot and bulb biomass under arid conditions, outperforming untreated and mineral-fertilised plots, a response linked to the steady release of nitrogen and phosphorus that maintained growth over time (31). Research also showed that substituting basal fertilisers with digested pig slurry increased onion above-ground biomass, with clear gains in fresh and DWs, indicating that well mineralised organic nutrients can equal or surpass synthetic fertiliser performance (32). Dry matter accumulation responded strongly to digestate; BDW under (D_4) treatment at 60 DAP was almost 3 times the control treatment and kept this lead until harvest day, showing more efficient assimilate allocation to the bulb. A comparable shift in onions when vermi-compost was combined with mineral fertiliser, with greater partitioning toward storage tissues (21). By 90 days after planting (90 DAP), total plant weight was highest in the (D_3) treatment (3.87 kg), slightly above the D_4 treatment, suggesting that intermediate doses create more favourable biomass conditions without the added salt or nutrient load associated with higher inputs. Research has demonstrated that improved onion biomass and quality occurred when organic and mineral sources were balanced, while excessive organic inputs brought limited returns (33). Digestate also supported a more balanced shoot-to-bulb allocation. Although LFW increased only moderately, the larger gains in BFW and BDW show a stronger sink response under digestate application. A similar shift in onion cv. Caribe-71 were noticed when microbe-enriched biogas effluent was applied, leading to improved biomass distribution and stronger bulb filling (31). These patterns of biomass partitioning are further supported by multivariate analysis. The PCA results showed that bulb fresh weight (BFW) and bulb DW (BDW) were strongly associated with onion yield along the first principal component, confirming that greater assimilate allocation to the bulb was a key determinant of productivity. In addition, the RDA highlighted that treatments D_3 and D_4 were positioned closest to yield-related variables (OY, BFW, BDW), whereas NPK and lower digestate doses were more strongly associated with general vegetative traits. This indicates that digestate rates promoting efficient biomass partitioning toward storage organs were also those driving improved yield performance.

Effect of digestate application on onion yield

Digestate application and doses clearly increased onion yield and showed that it can serve as a sustainable alternative to synthetic fertilisers. All digestate treatments produced higher yields than unfertilized control, with the highest value in D_3 (30 DW t/ha). The yield increase followed the dose but was not fully linear. The final yield increased from 54.64 t/ha in the control to 75.25 t/ha in (D_3) (+37.8 %), slightly higher than the (NPK) treatment (73.69 t/ha). A similar pattern in maize, where medium digestate doses (15-30 DW t/ha) gave the highest grain yield because nutrient release matched crop needs and improved soil fertility (10). D_4(40 DW t/ha) gave a slightly lower yield than D_3(73.42 t/ha), showing that adding more nutrients beyond the optimum does not always raise yield. This result reflects nutrient saturation, where extra inputs reduce nutrient use efficiency and can cause osmotic stress in salt-sensitive crops such as onion. Onions grown under agroecological conditions reached their best yields with moderate organic inputs, when nutrient release matched crop growth stages (34). Research also showed that combining organic and mineral fertilisers increased yields and improved storability compared with the control and NPK alone (35). Research indicates that digested pig slurry could fully replace mineral fertilisers while maintaining or even raising yield (32). Research observed similar gains when organic and inorganic sources were used together, a result also noted by Messele, who stressed the need for balanced N and P (36, 37). Research underlined the importance of enough nitrogen and potassium for good bulb yield and quality and organic manures, alone or with NPK, improved onion growth in field conditions (38, 39). The strong yield response to digestate came from better vegetative growth and more dry matter in the bulb. Singh et al. reported a similar effect in tomato, where digestate improved root growth, shoot vigour and fruit set, raising yield per plant (28).

The fact that D_3 treatment outperformed both NPK and D_4 treatments shows the need to identify an optimal digestate dose for onion. Research noted that digestate inputs should match soil capacity and crop uptake to reduce losses and environmental risks (10). The small yield decline in (D_4) compared with (D_3) confirms the importance of dose control (35, 37). This non-linear response is consistent with RDA results, which showed that yield and bulb-related traits clustered most closely with the intermediate digestate treatment (D_3), whereas the highest dose (D_4), despite strong biomass production, did not further strengthen the association with yield.

Conclusion

The results of this work show that anaerobic digestate can support onion production under the semi-arid conditions of Fez–Meknes while improving key aspects of soil fertility. Digestate applications increased organic matter, available nutrients and mineral nitrogen and these changes were reflected in stronger vegetative growth, higher biomass and better bulb development throughout the season. All digestate doses enhanced yield relative to the unfertilized control and the intermediate rate of (30 t of DW/ hectare) produced the highest yield, slightly surpassing both mineral fertilisation and the highest digestate dose. Although the present study demonstrates clear agronomic benefits of digestate application for onion production under semi-arid conditions, the results are based on a single growing season and one experimental site. Therefore, conclusions regarding long-term sustainability and broader regional application should be interpreted with caution. Seasonal climatic variability, irrigation management and cumulative nutrient and salinity dynamics may influence crop responses over time. Future multi-season field trials and long-term monitoring are needed to better assess interannual variability, soil salinity evolution and nutrient accumulation under repeated digestate applications, particularly in semi-arid environments.

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Authors' contributions

JH contributed to conceptualisation, methodology, investigation, data curation, formal analysis, visualisation and writing-original draft. SEL contributed to visualisation, formal analysis, writing, review and editing. RL: supervision, writing, review and editing. FR contributed to supervision, project administration, writing, review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used "Grammarly" solely for grammar, spelling and punctuation correction at the final editing stage. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

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