Research paper

Nitrogen Uptake Dynamics on Sandy Soil Amended with Coal Clinker Ash Reinforced by a ^{15}N Tracer Isotope Study and Profitability Analysis

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Handling Editor: Ashok Pandey

Received: 29.05.2025 / Accepted: 16.07.2025

Abstract

Increased nitrogen (N) loss and reduced nitrogen use efficiency (NUE) on sandy soils have negatively affected maize productivity. The application of soil amendments has been found to improve NUE in crop production systems. Clinker ash (CA), waste material from coal combustion, is increasingly becoming problematic for the environment. This study hypothesised that applying CA as an amendment to sandy soil would enhance N uptake and NUE in maize. In the ^{15}N tracer study, soils with CA and a low N application rate of 28% +^{15}N increased root length and biomass steadily over the two cycles. The CA with N at 56%+^{15}N increased the ^{15}N tracer in the shoots by 100% compared to sandy soil without ^{15}N. In the field experiment, N uptake and NUE were enhanced under a 100 kg ha^{-1} application rate, and the same treatment had a B: C ratio of 1.89, making this treatment an economically viable option for maize grown on sandy soil amended with CA. The application of CA to sandy soil enhanced N uptake and use efficiency, benefiting maize production while limiting environmental contamination through its continuous accumulation.

Keywords: ^{15}N isotope · Clinker Ash · Sandy Soil · Nitrogen Uptake · Nitrogen Use Efficiency

1. INTRODUCTION

Nitrogen (N) is an essential plant nutrient, yet it remains the most limiting for crop production (Fuertes-Mendizábal et al., 2018). It is needed for plant growth, in some instances in high quantities, which has resulted

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https://doi.org/10.55845/jos-2025-1236

in an ever-increasing demand for N fertilisers at a global level (Adalibieke et al., 2023; Yu et al., 2022). N plant uptake is estimated to be between 30 and 50% of the total applied N (Tilman et al., 2002). This implies a loss of approximately 50% in multiple ways, including leaching through the soil profile, surface runoff, denitrification, volatilisation, and microbial usage (Dhakal et al., 2021; Elrys et al., 2020; Kant et al., 2011). Increasing nitrogen use efficiency (NUE) while decreasing N application rate is a valuable technology for sustainable crop production (Congreves et al., 2021). The application of soil amendments such as biochar (Ding et al., 2022; Ullah et al., 2021; Wang et al., 2020; Xu et al., 2022), fly ash (Külaots et al., 2001.; Zhao et al., 2023), and crop residues (Ding et al., 2010; Gentile et al., 2009; Li et al., 2018), have been found to reduce N losses and enhance its utilisation in crops. Their application improved soil carbon (C) content, which influenced the organic matter (OM) and carbon-to-nitrogen (C/N) ratio. These are soil quality parameters that control the mineralisation or immobilisation of N (Li et al., 2022; Xu et al., 2018; Yang et al., 2022). As the C content of the soil increased, OM stabilisation occurred, which became a sink and source of plant nutrients, improving the nutrient-holding capacity of that soil (Mtambanengwe and Mapfumo, 2006). In sandy soil, this stabilisation is not found due to the quick turnover of OM, resulting in low nutrient holding capacity of these soils (Senjobi et al., 2013; Matichenkov et al., 2020). This exposes sandy soil to nutrient leaching, which negatively affects crop productivity, due to poor nutrient uptake (Sitthaphanit et al., 2009). OM influences the soil's cation exchange capacity (CEC), pH, and availability of nutrients for plants and microorganisms; its unavailability translates to poor soils (Agustini et al., 2017).

Coal clinker ash (CA), a coal combustion by-product, also known as bottom ash, is a potential soil amendment (Park et al., 2023). This ash continues to accumulate in the environment as its recycling remains subdued, primarily due to its heterogeneous particle size (Zhou et al., 2022) compared to fly ash, whose particle size is homogeneous (Kishor et al., 2009). CA was described as an absorbent, as it significantly absorbed NO_3^- and NH_4^+ (Kim et al., 2023; Yamamoto et al., 2016). The growth of Japanese mustard in the CA after the absorption test attested to enhanced N retention (Okazawa and Fujikawa, 2014). CA was found to enhance plant height (Musfira et al., 2021). When applied at 200 and 400 t ha^{-1} to arable soil, it did not significantly influence the yield of maize and radish, but N_2O emissions were significantly reduced with increasing CA application (Hur et al., 2021). Another study showed that when CA was mixed with quartz sand, enhanced maize biomass yield was observed at 50, 75 and 100% doped media (Junfeng et al., 2008). However, there is limited literature that underpins the use of CA in improving crop NUE, especially on sandy soil. When fly ash was used for maize production, dry matter, total N uptake and N efficiency were not enhanced (Cervelli et al., 1989). These findings differed from biochar use. Grain N content was increased by 28% when biochar was applied at 1.9%, an indication of increased N uptake (Abbruzzini et al., 2019). De-ashed biochar increased NUE by 46% in maize production (Rashid et al., 2025). If CA was designated to be an absorber of inorganic forms of N (Kim et al., 2023; Yamamoto et al., 2016), it is possible that this absorption can enhance NUE in crops.

The use of stable isotope markers such as ^{15}N monitors N uptake in plants and how the fertiliser is utilised by plants or lost (Fuertes-Mendizábal et al., 2018). These isotopes can be measured in different plant organs or growth stages, which makes it possible to estimate the NUE of fertiliser applied along the growth stages (O'Connor et al., 2024). The use of soil amendments such as straw, biochar, and coal ash, combined with the ^{15}N

isotope, has increased N uptake and assimilation in plants (Ding et al., 2022; Lei et al., 2023; Ullah et al., 2021). In a study where N isotope was combined with brown coal, N loss was reduced, and N retention was increased in the soil. It was also established that plants obtained N fertiliser for an extended period, which indirectly implied an increased NUE (Lei et al., 2023). Since combining organic amendments and N fertiliser improves uptake and NUE, utilising CA for this purpose in maize production in sandy soils is unclear. Due to increased N loss and reduced NUE on sandy soils, maize production becomes costly as N fertiliser must be applied several times to meet the crop demands at every critical stage (Chikowo et al., 2004; Dhakal et al., 2021; Mtambanengwe and Mapfumo, 2006). For example, maize fertilisation at an optimal N rate was found to leave a substantial amount of N residue in the soil after harvesting (Schröder et al., 1998). In an experiment with sandy soil, 50% of N applied was found in the upper 60 cm of soil (Schröder, 1999), and 37% of N was found within 20 cm after maize harvesting (Yanai et al., 2007). This implied a low uptake of N and, subsequently, low NUE by maize grown on sandy soil. With confirmed capability to absorb nutrients (nitrogen), this study sought to establish CA's influence on N uptake in maize (*Zea mays* L.) from sandy soil, proving this uptake by incorporating an isotope N (^{15}N) as a tracer in a pot experiment and a field experiment where soil was amended with CA. Sandy soil mixed with CA was hypothesised to enhance N uptake and increase NUE in maize under different N application rates. The study's objectives were to (i) assess maize seedlings' growth and N uptake in soils amended with CA at different N application rates with ^{15}N isotope tracer, (ii) determine N residual in sandy soil after harvesting, and (iii) assess sandy soil field maize productivity and economic N uptake at different application rates.

2. MATERIALS AND METHODS

2.1 Sites and Description of Pot and Field Experiment

A two-cycle pot experiment was conducted in a greenhouse at Tottori University (35° 30′ N, 134° 13′ E), Japan. A black polythene pot (8.0 cm in height, 9.0 cm in upper diameter and 7.0 cm in bottom diameter) was filled with 300 g of sandy soil or an equivalent mix of sandy soil and CA at 20% weight to weight (w/w) of soil. The sandy soil was collected from Tottori dunes, Tottori, Japan and CA was sourced from a local electricity company. The CA characterisation showed that its water holding capacity (WHC) was 73%, its pH ($H_2O_{1:5}$) was 9.4, EC ($H_2O_{1:5}$) was 12.0 (10^{-2} dS m^{-1}), C content of 23% (scanning electron microscope), and 0.1% N content (C/N corder). The cations were 0.1, 4.7, and 1.2 (mg kg^{-1}) k^{+}, Ca^{2+}, and Mg$^{2+,}$ respectively. Its particle sizes were < 5 mm. The soil's WHC was 28%, pH 5.9, EC 2.0, C% of 15 and N% of 0.2. Cations were 0.8, 3.3, and 4.5 (mg kg^{-1}) k^{+}, Ca^{2+}, and Mg$^{2+,}$ respectively. Before the soil was put in the pot, it was air-dried in the greenhouse and passed through a 2 mm sieve to remove debris. There were two levels of soil (soil only, soil +CA) and three levels of N (100% full N, 56% N+^{15}N and 28% N +^{15}N) combined to make the treatments. Ammonium sulfate (AS) was the source of N, and 100% of N was 100 kg ha^{-1}. The ^{15}N form was ammonium sulfate. Treatment arrangements were: N1, N2, N3, N4, N5, and N6 for S-100N, S-56N+^{15}N, S-28N+^{15}N, CA-100N, CA 56N+^{15}N, and CA-28N+^{15}N respectively. These treatment combinations were replicated four times.

Calculated according to the area of the pot, the treatments N supply was 0.270 g AS (100N), 0.150 g AS +0.120 g ^{15}N (56N+^{15}N), and 0.075 g AS +0.120 g ^{15}N (28N+^{15}N), all applied in cycle 1 (S1). In cycle 2 (S2), no ^{15}N was added, and only AS was applied. Phosphorus (P) was applied at 90 kg ha^{-1} using SSP, and K was applied at 70 kg ha^{-1} using KCl at planting. Ash and soil were mixed by hand using an air-filled polythene bag, which was thoroughly mixed by hand shaking. The mixture was then watered to a filled capacity and left in the greenhouse for a week to acclimatise the ash before sowing the maize seeds. The sowing date for S1 was June 2, and for S2 was June 23, 2024. After sowing, pots were irrigated to field capacity; thereafter, irrigation was done as necessary. Since this experiment was conducted during summer, in a greenhouse, plants were irrigated three times a day to minimise wilting. Growing conditions, such as temperature, relative humidity and airflow, were uncontrolled in this greenhouse, and seedlings were harvested two weeks after emergence.

A field experiment was conducted at the Arid Land Research Centre, Tottori (35.53°N, 134.22°E), Japan. The experiment was established on June 29, 2023, and harvested on September 12, 2023. All soil in the plot was treated with CA at 25 t ha^{-1}. The initial CEC of the soil was 2.66 cmolc kg^{-1}, and the cations were 1.78, 2.02, and 1.80 mg kg^{-1}, K^+, Ca^{2+} and Mg^{2+}, respectively. The pH ($H_2O_{1:5}$) and EC ($H_2O_{1:5}$) dS m^{-1} were 7.3 and 0.0105, respectively. Phosphorus was applied at 90 kg ha^{-1} as SSP, and potassium chloride (KCl) was the source of K at 70 kg ha^{-1} in all plots. Four N rates (NoN, 100, 150, and 200 kg ha^{-1} designated NoN, N100, N150 and N200, respectively) were randomly applied to plots of 1.80 m x 1.80 m replicated four times. The N fertiliser was split-applied 3 times, a third at planting, a third at the 4th-leaf stage and the last at the 6th-leaf stage. 2 seeds of maize were planted at an interrow spacing of 0.60 m and in-row spacing of 0.30 m. The variety used was 'Yume no corn' – 770 (Sakata Seed, Japan). All agronomic management practices were practised at the required time. Monthly average temperatures and precipitation received during the growing season are shown in **Fig. 1**.

2.2 Agronomic Traits for the Field Experiment

The agronomic parameters were measured at the time of harvesting; four samples were randomly picked from two inner rows of each plot, making 16 samples per treatment. Plant height in cm was measured using a tape measure from the root crown to the tip of the tassels. The stem girth was measured using callipers (mm). Total biomass (kg plant^{-1}) was measured when the plant was cut from the root crown and cut into smaller pieces, and its weight was measured using a weighing scale. Fresh cob weight was determined immediately after harvesting using a weighing scale.

2.3 Sampling, Analyses and Calculations

2.3.1 Pot Experiment Samples

All plants were uprooted two weeks after emergence and cut at the root crown to separate the shoot and root. These were oven-dried separately at 70°C for 72 hours. They were ground to a fine powder for further analysis. N content was determined using dry combustion by CN-Corder (Macro corder JM 1000CN, J-Science Lab Co., Ltd, Kyoto, Japan). The ^{15}N stable isotope ratio of N in plant parts (shoots and roots) and soil was determined using the isotope ratio mass spectrometer (EA IsoLink IRMS System, Thermo Scientific ^{TM}).

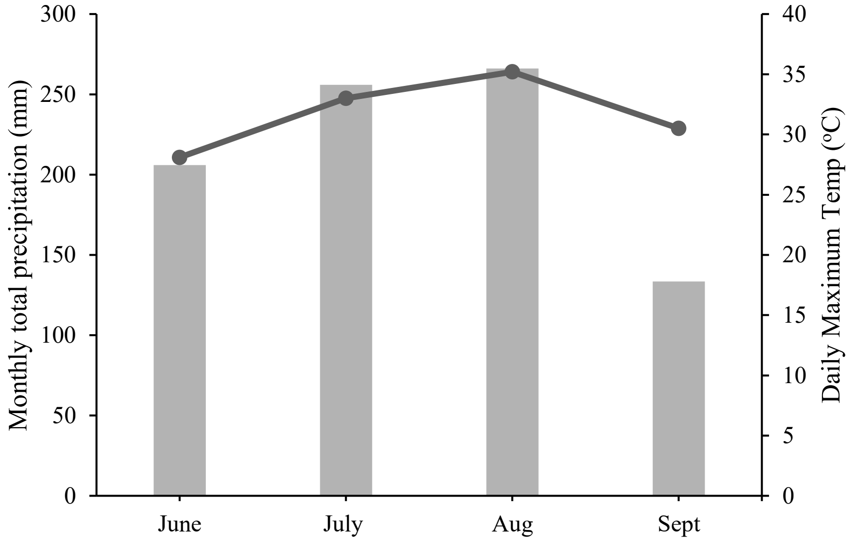

Figure 1. The Monthly Mean Maximum Temperature (°C) and Monthly Total Precipitation (mm) During the Field Experiment Growing Period 29/06/2023 to 12/09/2023. Data courtesy of https://www.data.jma.go.jp/stats/etrn/view/monthly_s3_en.php?block_no=47746&view=13 accessed 26/03/2025.

The ^{15}N uptake in the maize shoots and roots, and the ^{15}N retention rate, were calculated according to the formula given by Robinson (2001):

$$APC\ (15_N) = [1 - (1000 \div \delta 15_N + 1003.676)] \qquad (1)$$

$$Ndmf\ (g\ kg^{-1}) = \left(\frac{APC(15_N)}{C}\right) x\ \text{tN} \qquad (2)$$

$$\%15_N\ uptake = (15_N sample - No\ 15_N sample) \div No15_N\ sample\ \times 100\% \quad (3)$$

APC (^{15}N) is the ^{15}N atom % excess from the plant or soil (%). C represents the ^{15}N atom % excess in AS, which was 10.0 %. Ndmf (g kg^{-1}) is ^{15}N from ^{15}N AS of total N (tN) in the plant or soil.

2.3.2 Field Experiment Samples

Leaves of harvested plants were detached from the stem after the air-drying of the whole plant biomass. These were oven-dried at 70 °C for 72 hours and ground into powder. The total N uptake, nitrogen uptake, nitrogen recovery and nitrogen use efficiency were determined by the following equations:

$$Total\ N\ uptake = N\ content\ (\%) x\ above\ ground\ biomass \quad (4)$$

$$Nitrogen\ Uptake\ Efficiency\ (kg\ kg^{-1}) = Total\ N\ uptake \div N\ application\ rate \quad (5)$$

$$Nitrogen\ Recovery\ Efficiency\ (kg\ kg^{-1}) = \frac{N\ uptake\ from\ N\ treatment - N\ uptake\ from\ no\ N}{N\ application\ rate} \quad (6)$$

$$Nitrogen\ use\ Efficiency\ (\%) = Grain\ yield\ \div Total\ N\ uptake\ x(100\ \%) \quad (7)$$

2.4 Partial Economic Analysis

This analysis was carried out on the field experiment only. The fertiliser costs were based on a hectare of land, and the cob yield was adjusted downwards by 10 % (Badu-Apraku et al., 2012.; Ngoune Tandzi and Mutengwa, 2019). Total revenue was calculated based on the fresh-cob yield average price of \$6.86 per kg, according to https://www.selinawamucii.com/insights/prices/japan/sweet-corn/ accessed 24 March 2025.

$$Net\ benefit = Total\ Revenue\ (USD) - Total\ Variable\ Cost\ (USD) \quad (8)$$

$$B{:}C\ ratio = \frac{Total\ Revenue\ (USD)}{Total\ Variable\ Cost\ (USD)} \quad (9)$$

2.5 Data Analyses

For all agronomic variables and soil analyses from the pot or field experiment, results were expressed as the mean of four replications. The ^{15}N sample analysis results were expressed as mean values of three replications. Data processing and graphs were done using Microsoft Excel. One-way ANOVA was conducted using IBM SPSS version 29 to determine statistical differences among treatments, and a post hoc test using Tukey's HSD test at $p < 0.05$. The Levene statistics test (in-built test in SPSS) was used to test the homogeneity of variance, whose p-value should be greater than 0.05 for equal variance across treatments. For the normality test, the Q-Q plots (inbuilt in SPSS) were used.

3. RESULTS

3.1 Shoot Dry Biomass and Root Length of Maize Grown With 15N Tracer

Shoot dry weight (**Fig. 2a**) was significantly influenced by different N treatments at $p < 0.0001$ and 0.003 in S1 and S2, respectively. In S1, CA-100N had the highest shoot dry biomass at 29.75 (10^{-2} g), CA-56N+^{15}N's shoot dry biomass increased by 669% in S1 and reduced by 78 % in S2 over S-56N+^{15}N. The CA-28N+^{15}N treatment shoot dry weight increased by 145% at 13.5 (10^{-2} g) in S1, and in S2, the dry weight increased to 16.5 (10^{-2} g). Root length (**Fig. 2b**) at $p < 0.0001$ for the two cycles, had CA-100N with the longest roots at 15 cm and the shortest in S-100N at 1.75 cm in S1. The other treatments did not significantly differ. In S2, CA-28N+^{15}N had the longest roots at 18.4 cm, and the shortest were found in S-100N and CA-100N at 3.4 and 3.1 cm, respectively.

3.2 ^{15}N Isotope Composition in Shoots, Roots, and Soil

There were significant differences among treatments for ^{15}N isotope tracer found in the shoots, roots and soil samples at $p < 0.0001$ **(Fig. 3)**. In S1 (**Fig. 3a**), the shoots of no-^{15}N treatment (100N) had the tracer found in them, and the S-100N had the highest at 4.4 g kg$^{-1,}$ and CA-100N had the least at 1.9 g kg^{-1}. On average, the sandy treatments with ^{15}N tracer had 4% more ^{15}N than CA-^{15}N treatments. In S2, the highest ^{15}N amount in shoots was detected in CA-56N+^{15}N, a 15% increase over the similar treatment of sandy soil. S-100N treatment had the least at 3.2 g kg^{-1} of the ^{15}N. For the ^{15}N tracer in roots (**Fig. 3b**), the CA-56N+^{15}N treatment had the highest ^{15}N in both seasons at 2.7 and 2.4 g kg$^{-1,}$ respectively, and CA-100N also increased its ^{15}N uptake by 44% in S2 over S1. For soil after harvesting in S2 **(Fig. 3b)**, the ^{15}N tracer was found in S-100N and CA-56N+^{15}N at 53% above the lowest amount in CA-28N+^{15}N at 0.9 g kg^{-1}.

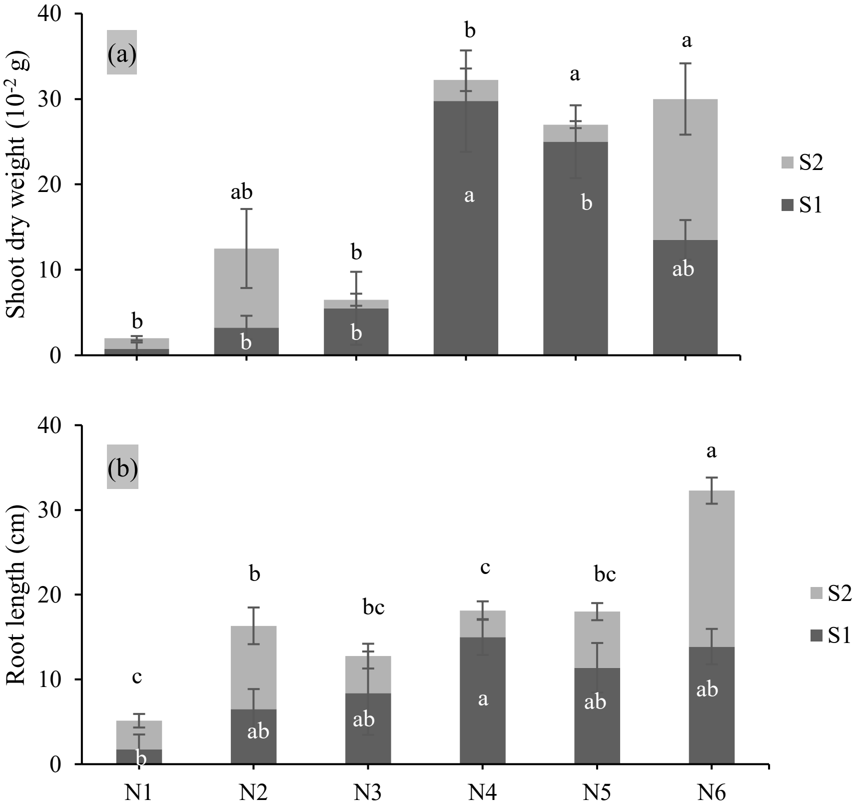

Figure 2. (a) Maize Shoot Dry Biomass (10^{-2} g) at $p < 0.0001$ and 0.003 in S1 and S2, respectively. (b) Root Length (cm) of Maize at $p < 0.0001$ for the Two Seasons. The letters inside the columns and above the error bars represent mean separation by Tukey's HSD at $P < 0.05$. N1, N2, N3, N4, N5, and N6 stands for S-100N, S-56N+^{15}N, S-28N+^{15}N, CA-100N, CA-56N+^{15}N, and CA-28N+^{15}N respectively.

3.3 ^{15}N Isotope Uptake % Over the No ^{15}N Treatment (^{15}N Natural)

A comparison of ^{15}N treatments to no-^{15}N treatments (S- and CA-100N) was done **(Fig. 4)**. For shoots (**Fig. 4a**), in S1, the CA-56N+^{15}N and CA-28N+^{15}N treatments had a significant quantity of ^{15}N uptake over the no-^{15}N treatments at 106% and 83%, respectively. In shoots S2, there was a reduction in ^{15}N tracer found in CA treatments, with the sandy treatments (S-56N+^{15}N and S-28N+^{15}N) having reasonable amounts of the tracer at 45% and 60%, respectively. For roots (**Fig. 4b**), in S1, CA-56N+^{15}N and CA-28N+^{15}N treatments had more ^{15}N tracer found than sandy treatments at 67% and 45%, respectively. In S2, there was ^{15}N tracer in the S-56N+^{15}N treatment at 29%. After S1 and S2 (**Fig. 4c**), the ^{15}N tracer was found in S-28N+^{15}N and CA-56N+^{15}N at 5% and 47% over the non-treated soil, respectively.

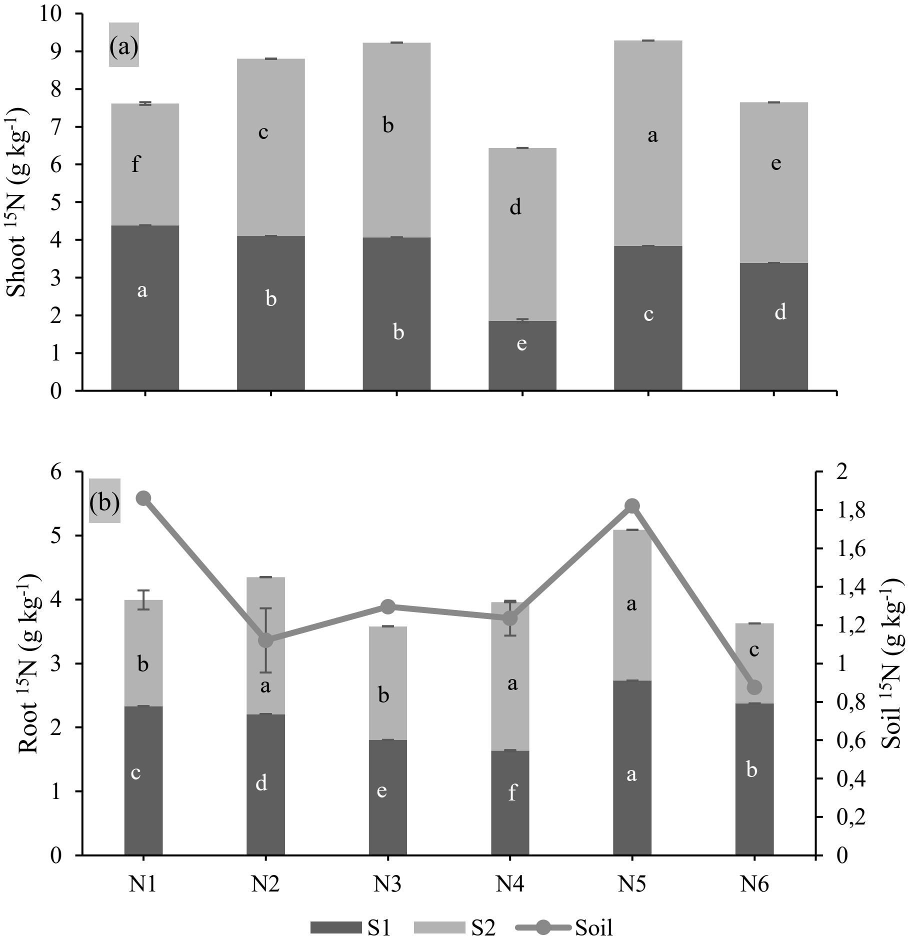

Figure 3. (a) ^{15}N Tracer Found in Shoots of Maize Grown in S1 and S2 at $p < 0.0001$. (b) ^{15}N Tracer Found in Roots of Maize Shoots After 14 Days of Growth from Emergence, Line Graph Showing the ^{15}N Tracer Retained in the Soil After the Growing Period. The letters inside the columns represent mean separation by Tukey's HSD at $P < 0.05$. N1, N2, N3, N4, N5, and N6 stands for S-100N, S-56N+^{15}N, S-28N+^{15}N, CA-100N, CA-56N+^{15}N, and CA-28N+^{15}Nrespectively.

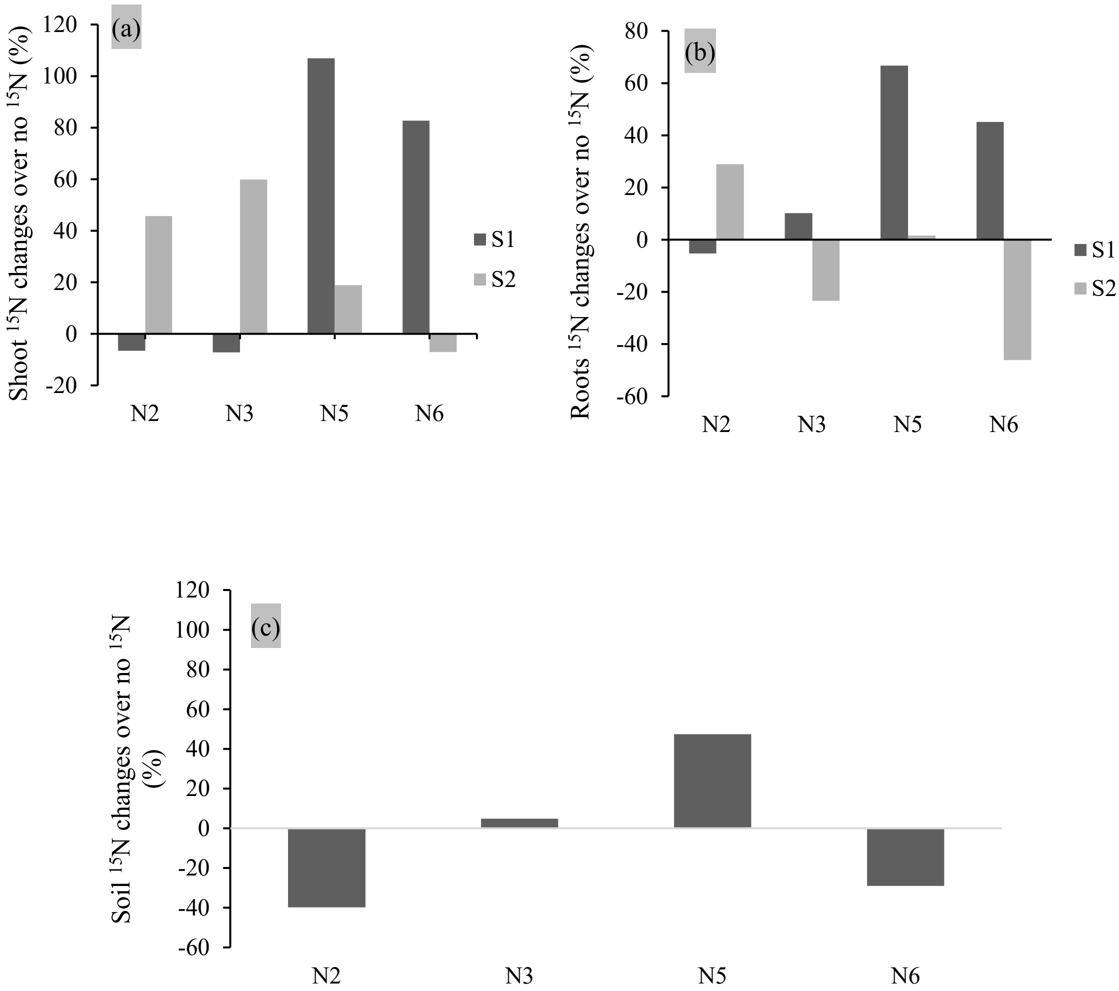

Figure 4. (a) Shoot and (b) Root ^{15}N Uptake Changes Over No ^{15}N in S1 and S2. (c) Soil ^{15}N Retention Changes in 15N-Treated Soil Over No ^{15}N After the Growth of Maize Seedlings for 2 Seasons. N2, N3, N5, and N6 stands for S-56N +^{15}N, S-28N +^{15}N, CA-56N+^{15}N, and CA-28N+^{15}N respectively.

3.4 Field Agronomic Traits as Influenced by Different N Application Rates Under CA-Treated Sandy Soil

The agronomic parameters considered in this experiment included plant height (cm), girth (mm) and total biomass per plant (kg) (**Table 1**). There were significant differences ($p < 0.0001$) among treatments; the NoN performed below all the N rates. There was a 48% reduction in plant height of NoN compared to N_{200}, which had the tallest plants at 113.5 cm. The same treatment (NoN)'s girth was narrower than the rest by an average of 51%. Fresh cob weight (**Fig. 5a**) also followed the same trend, with NoN having the least yield at 822 kg ha$^{-1,}$ which was 1403% lower than N_{200} with 12361 kg ha^{-1}. Biomass (**Fig. 5b**) significantly differed among treatments; the NoN had the least biomass at 633 kg ha$^{-1,}$ which was 590% lower than the N_{150} treatment with 4369 kg ha^{-1}.

Table 1. Plant Parameters Under Different N Application Rates from the Field Experiment

Treatment	**Final plant height (cm)**	**Girth (mm)**	**Total biomass kg plant^{-1}**
NoN	59.2±5.26b	10.2±0.84b	0.1±0.01b
N**100**	106.9±3.04a	20.0±0.63a	0.5±0.05a
N**150**	107.7±3.06a	20.8±0.62a	0.4±0.02a
N**200**	113.5±3.86a	21.9±0.45a	0.5±0.04a
Grand mean	96.8	18.2	0.4
p Value	***	***	***

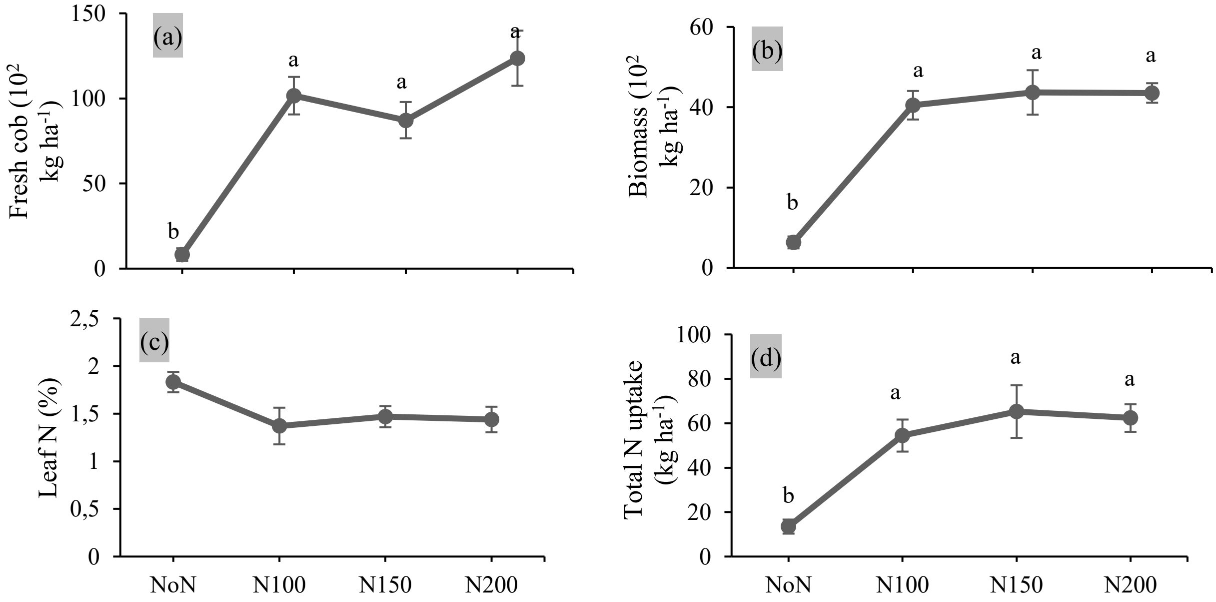

Figure 5. (a) Fresh Cob Weight (10^2 kg ha^{-1}), (b) Dry Biomass Weight (10^2 kg ha^{-1}), (c) Leaf N% and (d) Total N Uptake (kg ha^{-1}) of Maize Grown on Sandy Soil Amended with Clinker Ash (CA) at Different N Application Rates. The letters above the error bars represent mean separation by Tukey's HSD at P < 0.05.

3.5 Leaf N, Total N Uptake, N Uptake Efficiency, N Recovery Efficiency, and N Use Efficiency

Leaf N (%) content (**Fig. 5c**) did not differ among the treatments, with N content of less than 2%. Total N uptake differed significantly among treatments at $p < 0.001$ (**Fig. 5d**). In NoN, N uptake was 13 kg ha^{-1}; in N100, uptake was 55 kg ha^{-1}, and 45% was lost one way or the other. At N150, 57% was lost, so 65 kg ha^{-1} was found in the biomass. For the N200 treatment, the total N uptake was 62 kg ha$^{-1,}$ implying 69% was lost. As the N application increased, N loss also increased. For N uptake efficiency (**Fig. 6a**), N100 had the highest at 55 kg kg$^{-1,}$ although it did not differ significantly from the other N treatments; it was 25% higher than N150 and 77% higher than N200. The NoN had zero efficiency since no N was applied.

The same trend was observed in the nitrogen recovery efficiency (**Fig. 6b**), where N100 had the highest NRE at 41 kg kg$^{-1,}$ which was 17% higher than N150 and 71% higher than N200. Nitrogen use efficiency (**Fig. 6c**) also differed among treatments ($p < 0.001$), with the NoN treatment having the lowest NUE at 1%, N100 at 19%, N150 at 13%, and N200 at 15%.

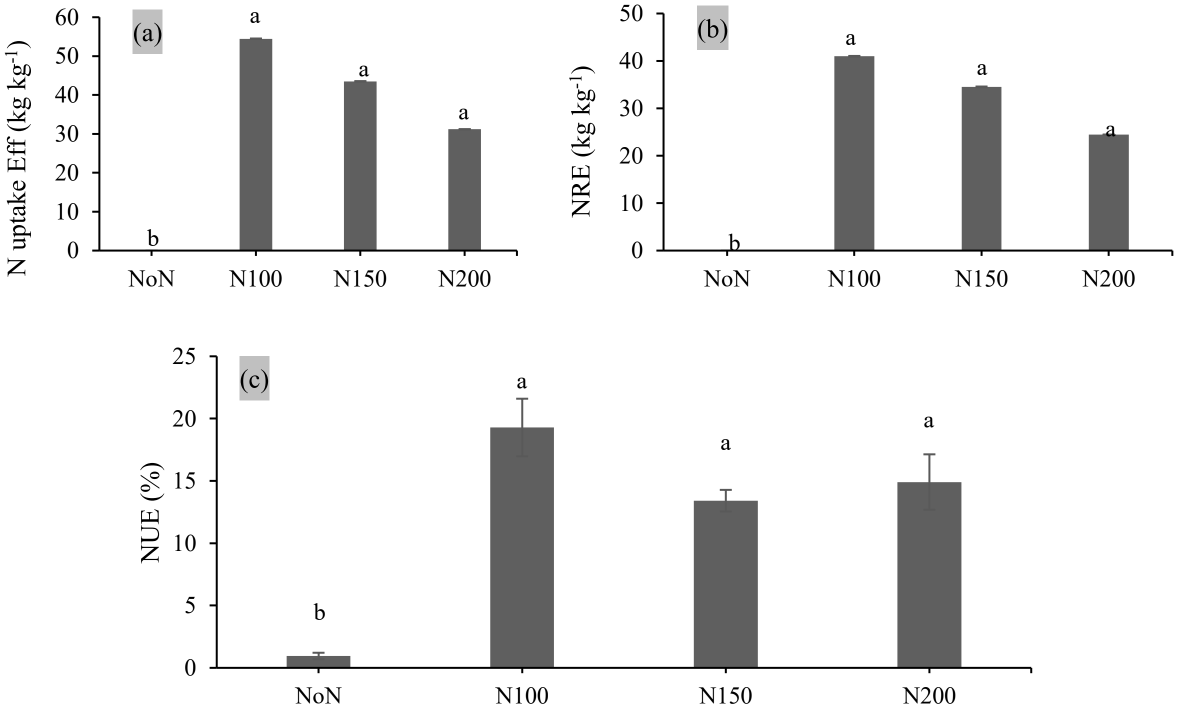

Figure 6. (a) Nitrogen Uptake Efficiency (kg kg^{-1}), (b) Nitrogen Recovery Efficiency – NRE (kg kg^{-1}), and (c) Nitrogen Use Efficiency – NUE (%) of Maize Grown on Sandy Soil Applied with Clinker Ash (CA) at Different N Application Rates. The letters above the error bars represent mean separation by Tukey's HSD at $P < 0.05$.

3.6 pH, EC, and CN Ratio Changes Due to Different N Rate Applications to Ca-Treated Sandy Soil

pH changes (**Fig. 7a**) were influenced by the application of different N rates ($p < 0.0001$). At the end of the season, NoN pH changed to 7.4, which did not differ from N100, which was at pH 7.3. N200's pH changed to 7.1, and N150 had the least pH change at 6.8. N rates applied to soil did not significantly influence the EC (10^{-2} dS m^{-1}) at harvesting time (**Fig. 7b**). N150 had 1.8 (10^{-2} dS m^{-1}), a 118% decline from NoN, and N200 was also reduced by 37% compared to NoN. The CN ratio of the soil did not differ significantly (**Fig. 7c**) with different N rates applied. N100 CN ratio reflected a reduction of 22% at 8.7 to NoN at 11.1, and N200's reduction was 41% below NoN treatment at 6.5.

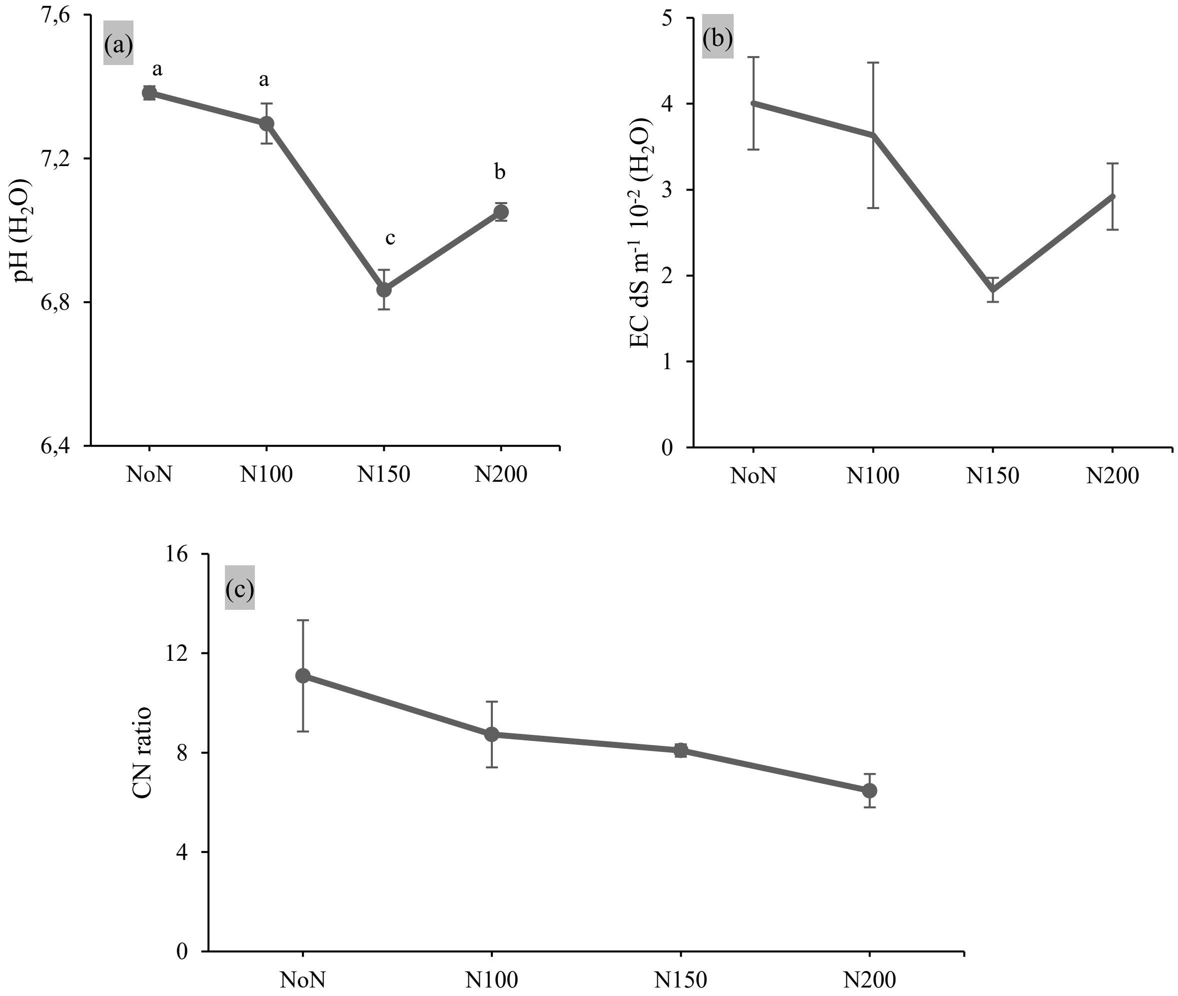

Figure 7. (a) pH Changes as Influenced by Nitrogen Application to Sandy Soil Ameliorated with Clinker Ash (CA) at Different Rates at $p < 0.0001$, (b) EC Changes at Different Application Rates at p = ns and (c) CN Ratio Changes at Different N Application Rates at p = ns.

3.7 Partial Economic Analysis

The partial budget (**Table 2**) shows that N200 realised the highest net benefit of 792 USD, making it the best choice. The second-best application rate was N100 with 650 USD. The NoN treatment had a negative net benefit of 464 USD. Based on the B: C ratio, N100 and N200 had the same ratio of 1.89. The NoN had 0.19, which was the least of all treatments.

Table 2. Partial Economic Analysis of N Rate Treatments per Hectare

Treatment	**Cob weight yield adjusted by 10%**	**Total revenue (USD)**	**Total variable cost (USD)**	**Net Benefit**	**B: C ratio**
NoN	740.4	111.80	575.66	-463.86	0.19
N**100**	9145.1	1380.91	731.31	649.60	1.89
N**150**	7849.9	1185.33	809.24	376.09	1.46
N**200**	11125.1	1679.89	887.09	792.80	1.89

4. DISCUSSION

4.1 The ^{15}N Tracer Study

This study was conducted to understand the influence of CA on N uptake, utilisation and retention in sandy soils using the ^{15}N isotope tracer. The ^{15}N tracer found in the NoN application in S1 (**Fig. 3a**) proved that the soil had the natural ^{15}N abundance. The ^{15}N abundance is determined by N inputs, soil N changes, and N losses (Xu et al., 2010), and it provides insights into biogeochemical interactions that take place between plants and their environment (Wang et al., 2022). The capability of CA to enhance N uptake was shown in the high percentages over the no ^{15}N treatment in S1. In S2, when no ^{15}N was applied, the CA treatments had little to below-zero ^{15}N in the shoots and roots (**Fig. 4a &b**). The natural ^{15}N abundance, uptake in the S-100N treatment, did not contribute to the growth of maize seedlings as shown in the low shoot dry weight (**Fig. 2a**). A significant amount of ^{15}N was retained in the soils, as shown after the study; the treatment had the highest amount of ^{15}N (**Fig. 3c**). CA-100N, which had the lowest ^{15}N, detected had the highest dry biomass, suggesting enhanced N uptake and utilisation due to CA application (**Fig. 3a**), which meant that CA influenced the N reactions in the soil, which made it to be available through N mineralisation (Zhang et al., 2022). In the CA-28N+^{15}N treatment, ^{15}N uptake was enhanced as the treatment exhibited the lowest ^{15}N content after the experimental cycles. The CA-treated soil had low ^{15}N uptake in S1; however, in S2, when no ^{15}N was applied, the CA-56N+^{15}N treatment showed the highest uptake of ^{15}N. This demonstrated that CA inhibited loss of this N, supported by the highest retention of ^{15}N at the end of the experiment (**Fig. 3c**). CA treatment utilised the applied ^{15}N, and the natural ^{15}N abundance was retained equally as in S-100N. The application of CA amendments increased N uptake and utilisation, as established by Lei et al. (2023) in their experiment with brown coal in combination with 200 N kg ha^{-1}. The longer roots of plants in the CA-100N indicate healthy plants whose underground growth was reflected in the increased biomass above ground. These results are supported by Xia et al. (2013), who found a positive correlation between root length on individual maize plants and above-ground shoot biomass. CA-28N+^{15}N treatment reduced N application to 28% and yet, its biomass in S1 was comparable to CA-100N. In S2, it had the highest biomass and root length. These findings are supported by the explanation that there is increased nutrient use efficiency at low rates of N. In an experiment where N application was reduced by 20%, there was no yield difference compared to the full application rate (Asibi et al., 2022). Low N increase the plant's ability to forage for N available in the soil profile through increased root biomass (Flynn et al., 2023). However, it should be noted that the increased biomass and root growth were limited to the CA-treated soil; the sandy soil under the same treatment did not enhance shoot or root biomass. This shows that CA enhanced uptake and utilisation at this low N application rate. The ^{15}N isotope at the end of the study period was significantly reduced in this treatment, which implied increased usage of N for aboveground biomass.

4.2 N Uptake Enhancement of Maize Produced on Sandy Soil Ameliorated with Clinker Ash

Fresh cob and biomass weight were not significantly different among the N-applied treatments (100, 150, and 200 kg ha^{-1}). These results are similar to what Asibi et al., (2022) found, that increasing N did not change the biomass yield in the two seasons they conducted their study. Also, Flynn et al., (2023) found that increasing N application lowered above-ground biomass and yield. The Cob yield in the NoN applied plot was the lowest, which shows that P_2O_5 and K_2O fertilisers alone cannot yield much without an N source. The absence of N on sandy soils brings no yield in maize production (Dhakal et al., 2021). Regardless of the application of soil amendments, the physiological needs of N for maize are not enhanced in the abundance of N fertiliser. Biomass yield was significantly increased at 120 kg N ha^{-1} and reduced at rates of 160, 180, and 240 kg ha^{-1} in a study by Dhakal et al., (2021). Crop N utilisation is estimated to be between 30-50 % (Flynn et al., 2023; Schröder et al., 1998; Tilman et al., 2002; Yanai and Katawatinth, 2007). In our study, the N uptake efficiency was 55%, 43% and 31% at 100, 150, and 200 kg ha^{-1}, respectively. The 100 kg ha^{-1} N uptake was increased above the estimated N utilisation quoted above. The differences in the NUE of the N applications (**Fig. 6c**) proved that the physiological needs of this crop were fully met. Every genotype has functional traits that affect N uptake and utilisation, and at different N levels, the same genotype will have different NUE (Hamidi et al., 2021). Our findings contradicted this, as shown (**Fig. 6c**), that N levels did not increase NUE. In another study on sandy soil, when 90 kg ha^{-1} N was used, the total N uptake was 48% (Chikowo et al., 2004), which was less than our results in CA-treated sandy soil. Another agronomic practice that this study undertook, which improved N uptake and NUE, was to split the application of the N fertiliser. This practice matches the soil N availability with crop N needs, improving NUE and reducing N loss (Chikowo et al., 2004; Hu et al., 2021; Sajjad et al., 2024; Singh et al., 2024). This explains why there were no differences in the N variables measured among the N treatments, so N availability was not limited at any growth stage of the crops. The low N uptake efficiency at higher N application reflected increased N loss through ways such as leaching, ammonia volatilisation (Dhakal et al., 2021). This was supported by the non-significant changes in the CN ratio (**Fig. 7c**). Also, the C/N ratio was below 20, which meant N mineralisation was not limited (Li et al., 2022); therefore, plants were able to uptake N for their physiological processes as it was available.

4.3 The Partial Economic Analysis

The synchrony between nutrient supply and crop needs demands care to avoid over-supply of nutrients to optimise trade-offs between yield and income (Hamidi et al., 2021). This necessitated a partial economic analysis to evaluate the trade-offs between our cob yield and income. A B: C ratio of 1 implies a profitable enterprise; when it exceeds 1.5, that enterprise is economically viable (Dhital, 2017; Suryavanshi et al., 2020). N200 treatment had the highest net benefit of USD 793 and a B: C ratio similar to N100 at 1.89. Considering the B: C ratio, the N100 becomes the most profitable, due to the lower cost of production. Its net benefit of USD 650 was higher compared to Dhakal et al., (2021), at N rate of 120 kg ha^{-1} to sandy loam soils, had a net benefit of USD 500, and a B: C ratio of 1.54, a 23% below our findings On clay soils, the maize B: C ratio was 2.31 (Suryavanshi et al., 2020), which was a 22% increase over our results. In another study, maize was compared to several other crops; its B: C ratio was chosen as the best at 1.4 (Moumita et al., 2017). When compared, our results were superior by 35%. The application of CA increased the enterprise's B: C ratio.

4.4 Study Limitations

The CA used was one particle size of < 5 mm, yet CA can be found in particle sizes ranging from 0.1 to 10 mm. The study's length period for both experiments was a limitation (two weeks after emergence for pot and one season for the field experiment). The pot experiment was done just to trace uptake at the seedling stage; there is a research gap on ^{15}N uptake in various parts of the crop, including grain. Therefore, the tracer study needs to be conducted in the field under natural conditions. The one season for the field crop may not have been enough to fully understand how nitrogen dynamics are influenced by CA application on sandy soil. A long-term study under different types of sources of nitrogen may give a deeper understanding of N dynamics in sandy soil ameliorated with CA.

4.5 Conclusion

This study exhibited the importance of incorporating clinker ash (CA) into sandy soil to enhance N uptake and use efficiency. In the ^{15}N isotope tracer study, sandy soil applied with CA had enhanced shoot and root dry weight. The lower application of N at 28 %+^{15}N, including CA, had superior results in that N application was reduced, yet results were comparable to full N applications. There is evidence of N retention seen in CA-56N+^{15}N treatment retaining as much as S-100N, the difference is that the CA treatments increased the biomass and root parameters, which the S-100N did not achieve. In the field experiment, the different N levels did not significantly improve the agronomic parameters; however, the N uptake, N use efficiency, and N recovery at the N100 application rate were above the other application rates. This was confirmed by the high B: C ratio, making the N application rate of 100 kg ha^{-1} on sandy soil ameliorated with CA an economically viable enterprise. The study results, compared to several other studies, showed that application of CA to sandy soil in the field improved the N uptake, use and recovery. There remains a gap to trace N uptake in the field through long-term experiments.

AUTHOR CONTRIBUTIONS

Conceptualization, Agnes A. Dube; Data curation, Agnes A. Dube and Mutsa Muhambi; Formal analysis, Agnes A. Dube; Investigation, Agnes A. Dube and Mutsa Muhambi; Methodology, Agnes A. Dube and Eiji Nishihara; Resources, Eiji Nishihara; Supervision, Eiji Nishihara, Mitsuru Tsubo, and Kuniaki Sato; Validation, Mitsuru Tsubo, Kuniaki Sato and Eiji Nishihara; Writing – original draft, Agnes Dube and Mutsa Muhambi; Writing – review & editing, Mitsuru Tsubo, Kuniaki Sato and Eiji Nishihara.

ACKNOWLEGDEMENTS

Support from colleagues and staff members of different specialised laboratories of Tottori University is acknowledged.

DECLARATIONS

Competing interests: The authors declare no competing interests.

Data Availability: Data will be made available upon request.

Funding: This research received no external funding

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