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Preparation and evaluation of a polymeric resin as a stabiliser for desertification control

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Abstract

Desertification and the conversion of soil into dunes, driven by wind or water erosion, are among the most serious environmental issues facing many countries, including developed ones. Arab countries are among the regions with large desert areas or are experiencing desertification. One effective way to combat desertification is by stabilizing sand and soil with various compounds, such as polymer resins. In this study, urea-formaldehyde polymer resins were successfully used to stabilize dune and soil structures. Laboratory and field tests demonstrated that applying resin significantly enhanced soil aggregate stability, increasing the mean weight diameter of soil aggregates from ≤ 0.053 mm in untreated soils to over 1.60 mm in treated soils, and markedly raising the percentage of aggregates larger than 1 mm. These structural improvements directly contributed to increased resistance against wind and water erosion. The results also highlighted the importance of these new resins in increasing maize plant growth rates.

Keywords: Soil stabilization, Polymeric binder, Hydrogel soil conditioner, Soil aggregate, Desert sand fixation

Introduction

Recently, many polymeric materials have been used to stabilize soils and dunes, significantly reducing climate change and global warming [1]. Soils are constantly exposed to erosion from wind and water, leading to the deterioration of their biological, physical, and chemical properties. This occurs because of the erosion of their surface layer, where biological activity or capacity is concentrated [2]. Wind and water erosion mainly happen in dry, semi- arid areas lacking vegetation cover, making them vulnerable to dust storms and dust accumulation that form dunes [3]. Various methods have been employed to address these environmental issues, including the use of polymeric materials. These materials can improve soil stability and reduce surface erosion. Polymeric materials are defined as one-, two-, or three-dimensional chemical networks formed by joining small, similar, repeating units called monomers, which assemble into polymer chains with high molecular weight [4, 5]. These monomers consist of one or more substances arranged in a chain- like structure. The resulting polymer chains, forming three-dimensional networks, are insoluble in water, and their length depends on the number of basic units. These units are often made of carbon and hydrogen; elements such as nitrogen, oxygen, phosphorus, chlorine, and silicon may also be part of their composition [1]. Urea fertilizers are among the most important nitrogen sources for soil, making them suitable for agriculture. However, there are limitations, such as urea's tendency to quickly penetrate sandy soils, which can cause groundwater pollution and plant burning when applied excessively. As a result, many researchers have studied and developed polymeric fertilizers combined with traditional fertilizers, creating various types that boost soil fertility and make it more suitable for farming [6]. Among the most notable are gel polymers, which help soil retain water, promote plant growth, and fight desertification. Additionally, other polymers have been designed to improve soil properties and their ability to absorb and hold water [7]. Several compounds, such as urea-formaldehyde or urea-melamine-formaldehyde, have been reacted with urea to produce polymer fertilizers. Most of these fertilizers are soluble in hot or cold water, with varying degrees of solubility. The most common reaction involves urea-formaldehyde, which produces polymer chains of different lengths- long, medium, or short- along with methylene and other side products. Polymer fertilizers promote the aggregation of fine soil particles and sand [8, 9]. These particles stick to the polymer chains, forming larger particles over 1 mm in diameter, as shown in Figure 1 below.

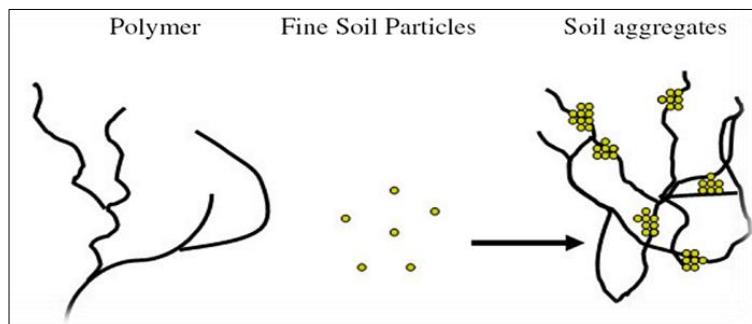


Fig 1: Illustrates how soil aggregates form around polymer chains.

Previous studies have demonstrated the potential of various polymers, including polysaccharides and polyacrylamides, for soil stabilization and as nutrient carriers [10-12]. Research on urea-formaldehyde resins has concentrated on their industrial applications and use as slow-release nitrogen fertilizers, highlighting nitrogen release kinetics and plant uptake efficiency [13, 14]. However, a significant gap remains in thoroughly evaluating urea-formaldehyde resins as dual-function amendments that address both the physical and agronomic challenges of degraded sandy soils [15]. Specifically, there is limited integrated research that quantitatively links the soil-structuring ability of urea-formaldehyde resins such as forming water-stable aggregates and resisting erosion with their subsequent impact on crop performance in field conditions within desertification-prone areas [16]. Moreover, although the nitrogen-supplying role of urea-formaldehyde is well documented, its interactions with and potential enhancement of other critical nutrients, such as phosphorus, in plant systems within stabilized soils remain underexplored [17]. This study aims to fill this gap by preparing modified polymer fertilizers from urea-formaldehyde, creating a viscous liquid that can be sprayed over large areas of soil and dunes using a straightforward process. Following application, the hardening reactions of the prepared material initiate, leading to the aggregation of fine soil particles and increasing their weighted diameter by more than 1 mm. Additionally, soils treated with polymer fertilizer become resistant to wind and water erosion, thereby improving their stability against environmental erosion factors [18, 19]. Simultaneously, these fertilizers will help promote plant growth, as they serve as an important source of nitrogen, making the soil suitable for cultivation and reforestation, and contributing to the reduction of global warming, desertification, and dust storms [20, 21].

Materials and Methods

Preparation of a new urea-formaldehyde resin

Methylol urea resin was produced by reacting 7 g of urea with 25 ml of formalin in a 38% solution (Fluka-Aldrich). The reactants were mixed thoroughly with an efficient mechanical mixer, then sodium hydroxide (98%, Alpha) was added to adjust the pH to 10-11. The mixture was stirred for 3 hours at 75°C in an electric reactor equipped with a heater and a mechanical stirrer. After the designated reaction time, 12 g of urea containing 46% nitrogen from Southern Fertilizer State Company (SCF) was added in batches over two hours. The temperature was then gradually raised to 95°C, and the reaction continued for an additional three hours. The product was neutralized with phosphoric acid (Fluka-Aldrich). Finally, the resin was separated by vacuum evaporation of the water. The mechanism of urea-formaldehyde reactions is

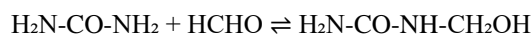
described in five steps within three main stages, as outlined below [22]:

Urea-Formaldehyde (UF) Resin - Reaction Equations

Stage 1: Addition (Methylation) - Alkaline pH

Formaldehyde reacts with urea to form methylol (hydroxymethyl) derivatives

1. **Monomethylolurea formation:** (Urea) + (Formaldehyde) \rightleftharpoons (Monomethylolurea)



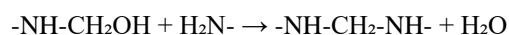
2. **Dimethylolurea formation:** (Monomethylolurea) + (Formaldehyde) \rightleftharpoons (Dimethylolurea)



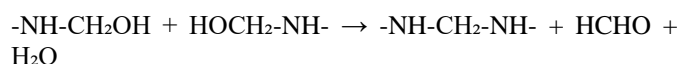
Stage 2: Condensation & Polymerization - Acidic pH

Methylol groups condense, releasing water (and sometimes formaldehyde), forming polymer chains and networks.

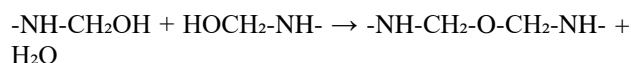
3. **Methylene bridge (-CH₂-) formation: Between methylol and amine hydrogen:**



Then between two methylol groups



4. **Methylene ether bridge (-CH₂-O-CH₂-) formation:**



Stage 3: Network Formation (Curing)

Further condensation under acidic catalyst (e.g., from NH₄Cl) creates a 3D cross-linked network.

5. **Cross-linking via methylene bridges:**

Continuing reactions of types (3) and (4) between polymer chains lead to a rigid, insoluble network. Simplified network segment:



Laboratory experiment

The 25% resin solution was mixed with water and applied to samples of mixed sandy and dune soils from the highway near Nasiriyah until field capacity was achieved. The weighted

diameter was then determined using the wet sieving method, as described by [23]. This process included dry sieving to separate and weigh soil aggregates larger than 1 mm that remained on the 1 mm sieve surface.

Field experiment

The experiment was conducted during the fall season on a plot of land at the southern Basrah station, which is affiliated with the Ministry of Agriculture. Some of its features are listed in Table 1, and its location is shown in Figure 2. Six panels were prepared; three were treated with a 5% urea-formaldehyde resin, sprayed onto the soil surface after being dissolved in a volume of water equal to the soil's field capacity. The experiment involved planting maize seeds. After two months of germination, plant height was measured, and the plants were harvested to record their fresh weight.

The plants were then dried in an oven at 65 °C, and their dry weight was measured. They were ground and passed through a sieve with 1 mm openings. For analysis, 0.2 g of ground plant tissue was digested with a mixture of sulfuric and perchloric acids (4%), as described by Helbling (1985) [24]. Total nitrogen was determined in the digestion solution using a distillation apparatus, as described by Haddad (2002) [25]. Phosphorus was measured using the ascorbic acid method and a colorimetric spectrophotometer at 700 nm, following the procedure outlined in Zhang & Yang (2020) [26]. At the end of the experiment, soil samples were collected to evaluate the reaction rate in a 1:1 soil suspension and the electrical conductivity in the saturated soil-paste filtrate. Subsequently, soil samples were digested with sulfuric acid to determine total nitrogen, as described in Latta & Leonard (1978) [27]. Figure 2 depicts the site of the field experiment.

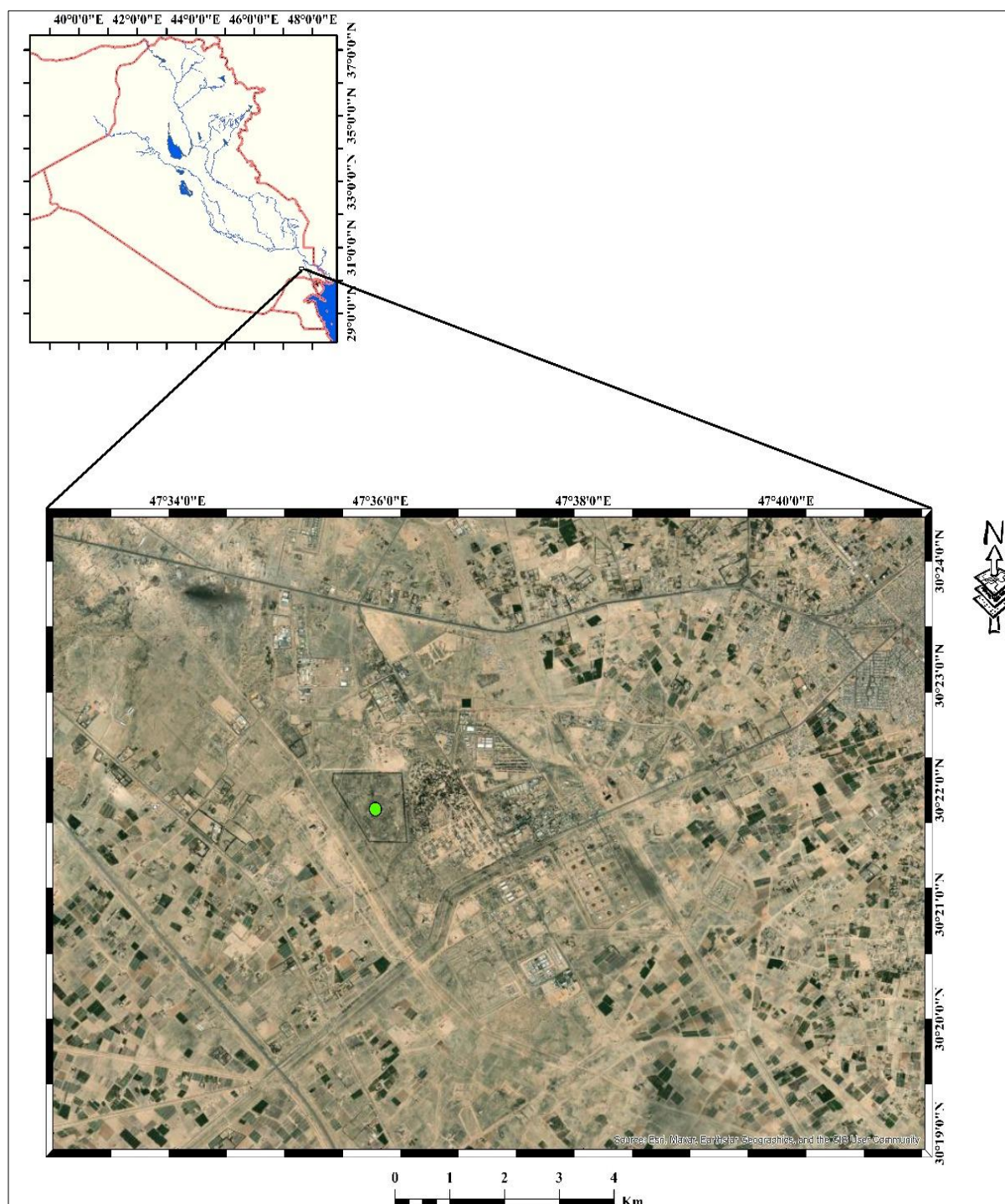


Fig 2: The location of the field experiment site is indicated by the symbol.

Table 1: The physical properties of the soil examined.

Type of measurement	Unit	Sand dunes	Loamy sand
<i>Sand</i>	g/Kg	923.9	792.0
<i>Silt</i>		49.2	126.8
<i>Clay</i>		26.9	81.2
<i>Texture</i>		Sand	Loamy sand
<i>pH</i>		7.8	8.1
<i>EC</i>	dS/m	2.4	2.2
<i>CaCO₃</i>	g/Kg	162.5	140.0
<i>N</i>	mg/Kg	0.09	0.06
<i>P</i>		2.2	0.67
<i>OM</i>	g/Kg	0.009	0.0034
<i>pb</i>	Ug/m	1.6	1.56
<i>ps</i>		2.65	2.60
<i>MWD</i>	mm	0.032	0.053
<i>Aggr.> 1 mm</i>	%	8.66	10.40
<i>K⁺</i>	Mmol/L	0.46	0.50
<i>Na⁺</i>		7.5	7.2
<i>Ca⁺⁺</i>		13.4	8.6
<i>Mg⁺⁺</i>		3.3	3.6
<i>Cl⁻</i>		6.5	5.9
<i>HCO₃⁻</i>		2.9	3.2
<i>CO₃⁼</i>		0	0
<i>SO₄⁼</i>		15.7	13.4

Results and Discussion

This article examined various factors influencing the resin composition and conditions. These include the ratios of reactants (such as the amounts of formalin and urea in moles), the effect of temperature, and temperature changes during the reaction stages. The influence of acidity (pH) was also analyzed, including how it varies throughout the reaction

stages, as well as its ratio and concentration, on the hardening reactions. Additionally, the impact of the resin's dilution ratio was studied to identify the best conditions for producing a polymeric resin with optimal properties for use as a soil stabilizer. The results in Table 2 demonstrate the effect of adding urea-formaldehyde on the weighted diameter rate and the size distribution of aggregates larger than 1 mm.

Table 2: The impact of adding urea-formaldehyde on the weighted diameter rate for treated and untreated soil.

Untreated soil	Treated soil		Character	
	Loamy Sand	Sand Dune	Loamy Sand	Sand Dune
MWD (mm)	1.62	1.70	0.053	0.032
Soil aggregate (>1 mm)	> 1 mm	> 1 mm	0.25	0.20

Applying urea-formaldehyde resin to loamy sand and dune soils significantly improved soil aggregation, as shown by higher Mean Weighted Diameter (MWD) values. The MWD of untreated soils was very low, with 0.053 mm for loamy sand and 0.032 mm for dune, indicating weak aggregate stability and a highly dispersed soil structure. Resin treatment caused a sharp increase in MWD, reaching 1.62 mm and 1.70 mm for the respective soil types. The resin's strong binding properties greatly enhanced soil aggregate stability. The percentage of soil aggregates larger than 1 mm rose notably in the treated samples of both soils, serving as a key sign of improved structural stability. The formation of larger aggregates improves pore space, water infiltration, and erosion resistance, which are essential for sustainable soil management in sandy and arid areas.

The combination of urea-formaldehyde resin with similar resins enhances aggregate stability in sandy soils by acting as organic cement between particles. The MWD values observed in this study equal or surpass previously reported ranges, showcasing the effectiveness of the developed resin. The resin

is versatile, yielding successful results in both loamy sand and dune soil types. Amid global efforts to fight soil degradation and desertification, these soil amendments offer an effective means to improve soil structure and function. The findings suggest that urea-formaldehyde resin functions as an effective soil conditioner [27, 28].

Figure 3 shows that desert soils become more fertile after receiving urea-formaldehyde treatment, resulting in improved maize growth, with a significant difference at the 0.01 probability level (Table 3). The untreated soil control produced maize plants weighing about 31.60 grams, while the treated soil produced plants weighing 61.07 grams, which is twice as much biomass. The slow-release nitrogen properties of urea-formaldehyde enable plants to access essential nutrients needed for chlorophyll synthesis. The resin enhances soil structure and water retention, benefiting root development and nutrient absorption. Slow-release fertilizers like urea-formaldehyde are effective for increasing crop yields in dry regions. The research highlights its importance for sustainable farming practices in water-limited areas [29, 30].

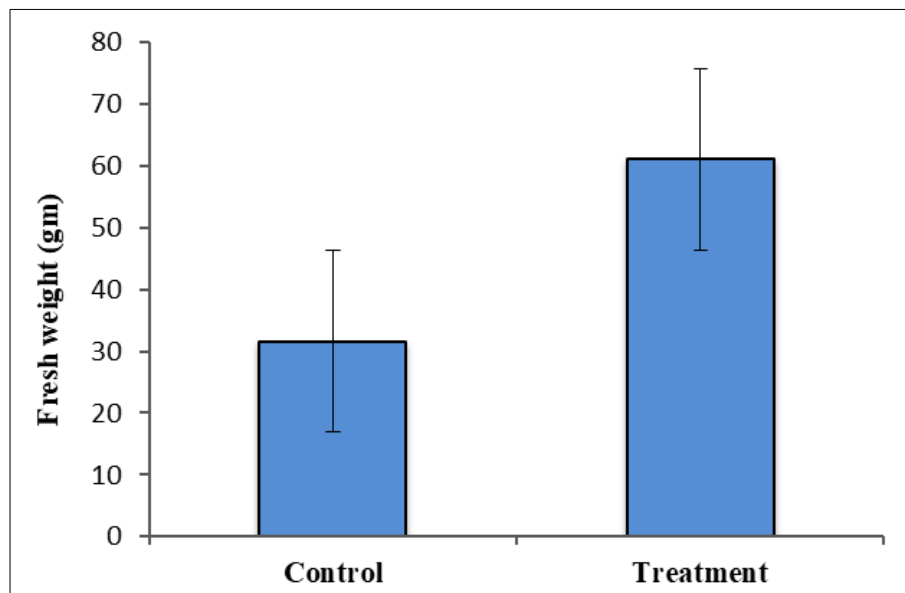


Fig 3: The impact of adding urea-formaldehyde on the fresh weight of maize plants.

Table 3: Variance analysis of the studied characteristics.

Source	df	F							
		Wet weight	Dry weight	Plant high	N content	P content	Aval.N	EC	pH
Treatment	1								
Error	4	24.47**	44.95**	52.48**	2.31 ns	44.22**	23.05**	0.13 ns	1.00 ns
Total	5								

The dry weight measurements of the maize plant are shown in Figure 4 after the experiment concluded. The experimental data indicate that the treated soil yielded 14.65 g of dry weight, while the untreated (control) soil produced 6.69 g. The results demonstrate a statistically significant difference between treated and untreated soils at the 0.01 significance level (Table 2). The increase in dry weight in the treated soil

was notable, driven by improved vegetative growth, which directly contributed to greater dry matter accumulation. Research studies have demonstrated that crop yields increase with higher nitrogen application rates. The slow-release property of urea-formaldehyde provides plants with a consistent supply of nitrogen, leading to vigorous growth and enhanced biomass production [31].

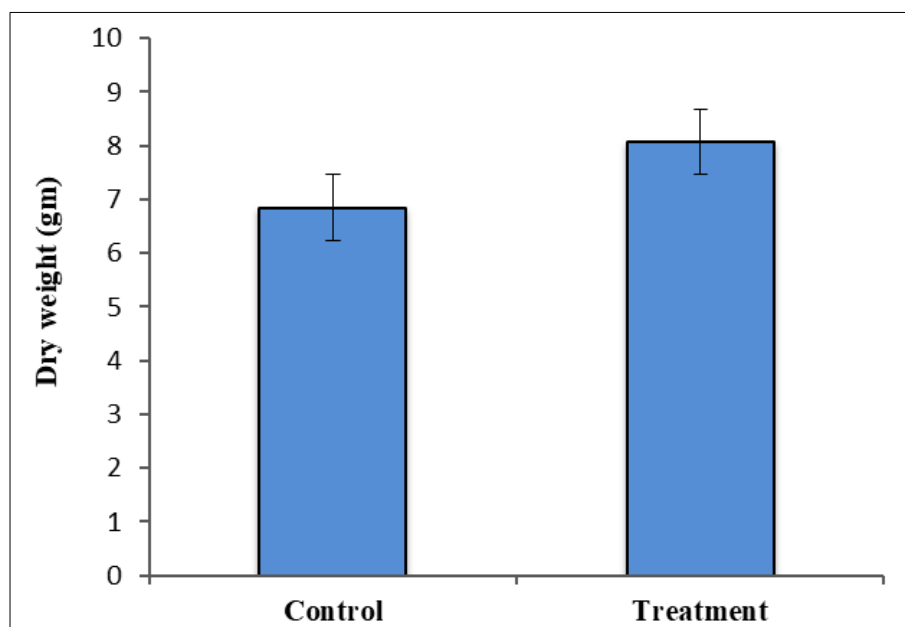


Fig 4: The impact of adding urea-formaldehyde on the fresh weight of maize plants.

The results in Figure 5 indicate that the maize plant's height increased, with the treated soil significantly outperforming the

comparison soil (Table 2). The height reached 67.33 cm in the treated soil compared to 40.33 cm in the comparison soil.

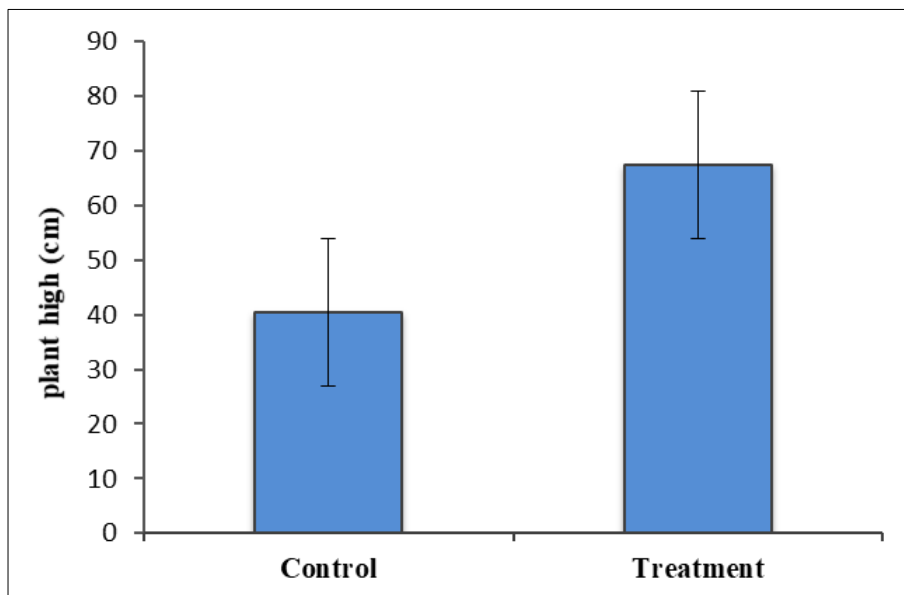


Fig 5: The effect of adding urea-formaldehyde on maize plant height.

Figure 6 shows the effect of adding urea-formaldehyde on the nitrogen content of maize plants. Nitrogen levels in the treated soil increased to 19.81 mg g⁻¹ plant, compared with 18.43 mg g⁻¹ plant in the control treatment. However, this difference was not statistically significant (Table 2). This may be due to increased plant size, which can lower nitrogen content [32]. Conversely, results in Figure 7 and Table 3 reveal significant differences in the plant's phosphorus content, with values reaching 4.38 and 2.51 mg g⁻¹ plant for the treated and

control soils, respectively. This could be because the added nitrogen promoted root growth and expansion, allowing the roots to access more phosphorus [33]. Additionally, Figure 8 and Table 3 show significant differences in soil nitrogen concentration, with values of 1.95 and 1.38 mg g⁻¹ for the treated and control soils, respectively. This is likely due to the material's ability to retain nitrogen longer and release it gradually, maintaining its bioavailability [34, 35].

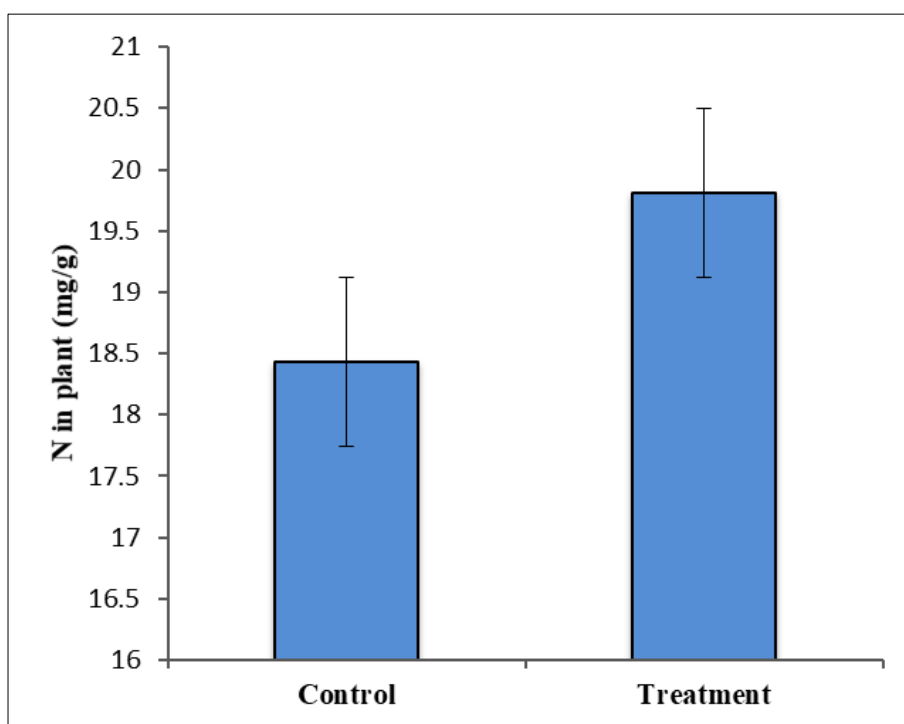


Fig 6: The effect of adding urea-formaldehyde on the nitrogen content of maize dry weight.

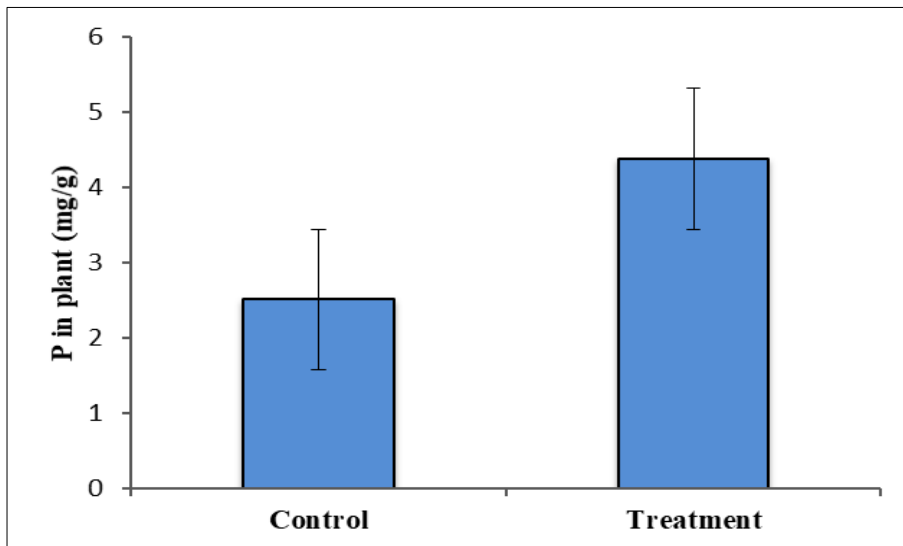


Fig 7: The impact of adding urea-formaldehyde on the phosphorus content of maize dry weight.

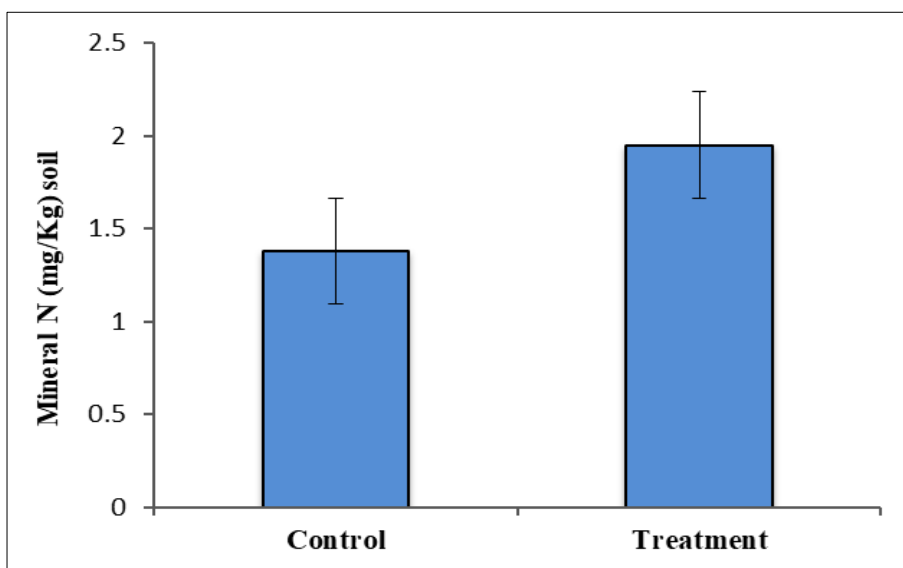


Fig 8: The effect of adding urea-formaldehyde on the nitrogen concentration of maize plants.

Based on the results in Figures 9 and 10 and Table 3 above, there are no significant differences in electrical conductivity

or soil pH between the treated and control soils, indicating that the added material does not impact the soil environment.

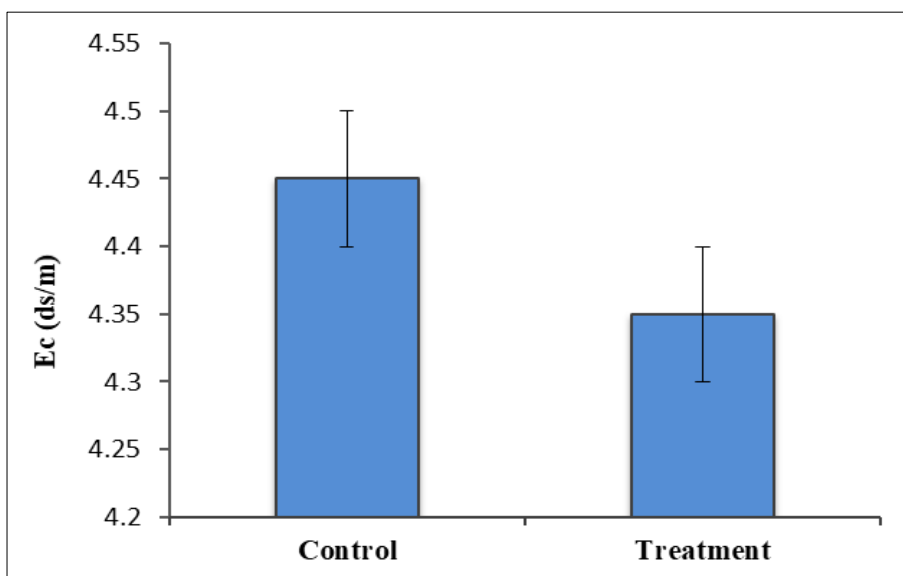


Fig 9: The effect of adding urea-formaldehyde on the electrical conductivity values of the maize plant.

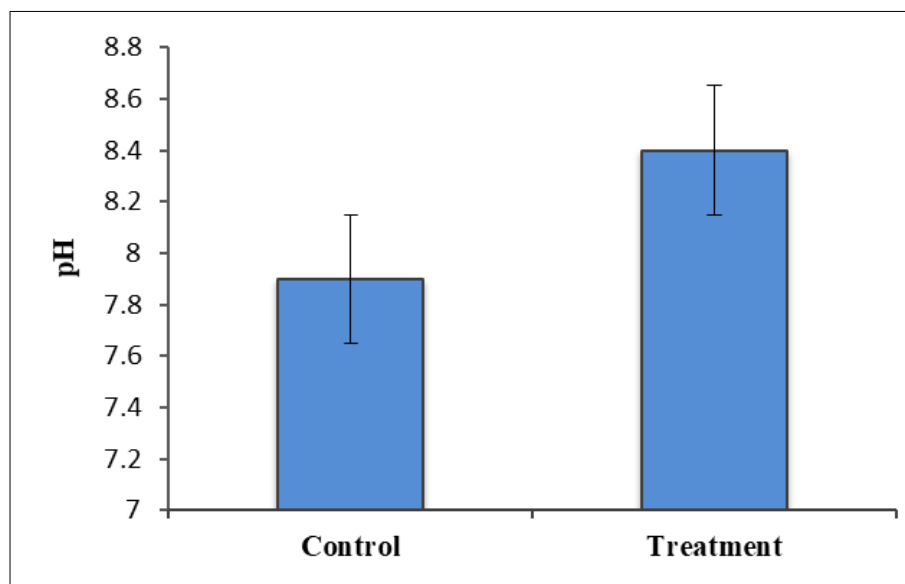


Fig 10: The effect of adding urea-formaldehyde on the pH levels of maize plants.

Conclusion

This study successfully developed and evaluated a urea-formaldehyde polymeric resin as an effective stabilizer for sandy soils and dunes, demonstrating its potential to fight desertification. The optimized resin formulation, influenced by reactant ratios, temperature, acid function, and dilution, significantly improved soil cohesion by forming stable aggregates, as evidenced by the increased weighted diameter (1.62-1.70 mm vs. 0.032-0.053 mm in untreated soils). Additionally, the resin boosted agricultural productivity in desert regions, as shown by improved maize growth. Treated soils yielded higher fresh weight (61.07 g vs. 31.60 g), dry weight (14.65 g vs. 6.69 g), and plant height (67.33 cm vs. 40.33 cm), thanks to the gradual nitrogen release from the resin. Phosphorus uptake increased notably (4.38 mg/g vs. 2.51 mg/g), likely due to better root development. The resin also maintained nitrogen availability over time (1.95 mg/g vs. 1.38 mg/g) without negatively affecting soil pH or electrical conductivity. These results emphasize the dual benefits of the polymeric resin: stabilizing sandy soils to prevent erosion and improving fertility for sustainable farming in dry areas. Future studies could explore long-term environmental effects and the feasibility of scaling up desertification control.

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