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## Research Article

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# Phosphorylated Sugarcane Bagasse Based Poly (AA-Co-AM) Hydrogel for dual water retention and Controlled NPK Release to enhance drought resilience in Lupine

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## Abstract

**Background** The excessive application of conventional mineral NPK fertilizers has led to severe environmental and agricultural challenges, including nutrient leaching, soil degradation, and ecological risks. To address these issues, there is a critical need for sustainable alternatives that can efficiently manage soil water and nutrients. This study developed a biodegradable NPK hydrogel composite derived from agricultural waste (sugarcane bagasse) to serve the dual purpose of water retention and controlled nutrient delivery. The hydrogel was synthesized by functionalizing sugarcane bagasse via phosphoric acid phosphorylation, followed by graft-copolymerization with acrylamide (AM) and acrylic acid (AA) using free-radical polymerization. Therefore, pot experiments were conducted to evaluate the efficacy of Phosphorylated Sugarcane Bagasse Based Poly (AA-Co-AM) hydrogel on lupine grown under drought conditions. Hydrogel applied at

0, 0.1 % and 0.2 % (by weight) in pots subjected to water deficit (50 % Field Capacity, FC) or sufficiency (100 % FC).

**Results** FTIR and SEM analyses confirmed the successful grafting of monomers onto the bagasse and the formation of an interconnected porous architecture. The incorporation of acrylic acid (AA) significantly enhanced the material's water swelling capacity, reaching up to 2900%. A specific hydrogel formulation with an AM:AA ratio of 1:1 demonstrated optimal soil biodegradability, degrading by 25% over 4 weeks. Elemental analysis revealed a high nutrient loading efficiency, which was particularly pronounced for nitrogen in AM-dominant matrices. In a two-season pot trial conducted under deficit irrigation (50% field capacity), the soil incorporation of the H1-type hydrogel at 0.1–0.2% (w/w) significantly improved the growth of lupine (*Lupinus termis* L.). Compared to non-amended, drought-stressed controls, the hydrogel-treated plants exhibited increased shoot length (44.42 cm), enhanced chlorophyll and carotenoid content, and higher fresh and dry biomass (23.92 g and 8.32 g, respectively). Additionally, the application of the hydrogel successfully mitigated drought stress, as evidenced by reduced levels of malondialdehyde, hydrogen peroxide, proline, and total soluble sugars, alongside decreased activity of antioxidant enzymes (SOD, CAT, POX).

**Conclusion** This study successfully bridges the gap between agricultural waste valorization and slow-release fertilizer technology. The sugarcane bagasse-based NPK hydrogel composite effectively enhances soil water retention and mitigates the negative physiological impacts of drought stress on plants while providing controlled nutrient delivery. Consequently, this biodegradable hydrogel offers a highly scalable and sustainable strategy to optimize nutrient use efficiency, reduce reliance on conventional mineral fertilizers, and promote resilient agricultural practices.

**Keywords:** Sugarcane bagasse; Controlled-Release fertilizers; Biodegradable hydrogel; Soil Water Retention; Lupine Growth Performance.

## **Introduction**

Global crop production remains basically dependent on mineral fertilizers that supply nitrogen (N), phosphorus (P), and potassium (K), the three macronutrients most restrictive to yield. The use of fertilizers for food production has increased significantly over the last few decades, and the dependence of food production on fertilizers is difficult to overestimate. However, the use of traditional NPK fertilizers is associated with high inefficiency in terms of the amount of nutrients absorbed by plants, as well as negative consequences for the environment, such as eutrophic water bodies, acidification, and loss of soil quality [1]. Moreover, the production of nitrogen fertilizers is associated with high energy costs and the use of natural resources, while the source of phosphorus is limited [2]. Thus, the use of traditional fertilizers is associated with significant challenges for future food security. The use of fertilizers in areas with limited water resources is even more challenging, as the amount of nutrients that reaches the root depends directly on the amount of water available and the flow regime.

Controlled-release fertilizer (CRF) technologies have emerged as a response to this dual challenge of nutrient-use efficiency and environmental cost. Rather than delivering the full nutrient charge at once, CRFs modulate the rate, timing, and, in some formulations, the location of nutrient release so that supply is better matched to plant demand [3]. Three broad CRF design strategies dominate the literature: (i) physical-barrier systems, in which a granule of conventional fertilizer is coated with a sulfur, polymer or resin layer that slows outward diffusion of dissolved nutrient; (ii) matrix embedding systems, in which nutrient salts are dispersed within a slowly eroding or

slowly permeable solid carrier (e.g., biochar, zeolite or clay minerals) so that release is governed by matrix erosion or ion exchange; and (iii) hydrogel based carriers, in which nutrient is loaded into a crosslinked, water-swellaable polymer network. Coating- and matrix-based systems can achieve precise release kinetics but generally address only the nutrient-delivery half of the crop-stress problem, since they neither retain nor supply water to the rhizosphere; polymer-coated urea, in particular, typically relies on a non-biodegradable synthetic film that persists in soil after the encapsulated nutrient is exhausted. Hydrogel-based carriers are distinguished from both alternatives by their dual functionality: the same crosslinked network that regulates nutrient diffusion outward also imbibes and retains many times its own dry weight in water, allowing a single material to buffer root zone moisture availability and meter nutrient simultaneously release [4]. It is this dual, water and nutrient functionality, rather than nutrient delivery alone, that is the central design premise pursued in the present work.

In addition to fertilizer wastage, agricultural and agro-industrial production generate huge amounts of lignocellulosic residues, such as crop stalks, husks, bagasse, and related by-products that are often under-utilized, burnt, or dumped with consequent costs to the environment and, in the case of burning, direct air quality impacts [5]. These residues are nonetheless a potential source of cellulose and lignin polymers that may be modified into hydroxyl-bearing and, hence, functionalized carboxyl or phosphate groups for use in material design, rather than as an inconvenient waste stream to be disposed of [6]. The reframing of lignocellulosic residues from a waste stream into a valuable resource is central to circular-economy approaches to the bio-economy, and recent studies have demonstrated the potential of these materials to be directly formed into hydrogels, films, and composites for replacing petrochemical counterparts with simultaneous local economic development, notably in rural areas, as a consequence of the value

added to a previously unproductive resource [6]. The intersection between the circular-economy and controlled-release fertilizer literatures occurs when lignocellulosic residues are considered for adaptation into a fertilizer delivery platform of the type described in the present work, simultaneously addressing the waste management and nutrient supply chain issues, and it is this intersection that motivates the current study.

Currently, the majority of hydrogel-based fertilizers described to date, however, are constructed on synthetic, non-biodegradable acrylate backbones; while these networks achieve well hydraulically, their persistence in soil is itself an environmental liability, since accumulated polyacrylamide type residues and their degradation intermediates raise concerns for soil biota and groundwater [7, 8]. Consequently, several research groups have initiated investigations into hydrogel matrices derived from cellulose, starch, or lignin for this specific purpose [9, 10].

Sugarcane bagasse (SB) is a particularly attractive biopolymer feedstock due to its high cellulose content and prevalent accessibility. However, traditional techniques for transforming bagasse into hydrogel matrices generally necessitate extensive pulping processes, including acid hydrolysis, alkali extraction, and chlorine-based bleaching to obtain pure cellulose. These industrial pre-treatment methods produce hazardous by-products (black liquor) and elevate processing expenses, thus undermining the environmental advantages of waste valorization. Additionally, while physical blending untreated biopolymers into synthetic hydrogels increases biodegradation rates, it frequently decreases mechanical strength and swelling capacity. The direct chemical modification of raw unpulped bagasse offers a largely unexamined pathway to develop high-performance and multifunctional hydrogel composites without chemical pre-purification [11].

Commercially available agricultural hydrogels are predominantly manufactured from petroleum-based monomers, including acrylic acid (AA) and acrylamide (AM). These synthetic networks exhibit low biodegradability in soil, high production costs, and the risk of contributing to the long-term accumulation of microplastics and chemical persistence in agricultural environments [12, 13]. To improve the environmental sustainability of poly (AA-co-AM) hydrogels, recent researches have focused on incorporating natural biopolymer matrices derived from abundant agricultural by-products [9]. The transformation of lignocellulosic waste into functional hydrogel structures aligns with the objectives of a circular bio-economy by converting inexpensive agro-waste into valuable agricultural incomes.

Hydrogel soil amendments have a well-documented history as soil conditioners, mainly in sandy or newly reclaimed areas, where they enhance water-holding capacity, lessen compaction and decrease frequency of irrigation [14]. Their agronomic benefits under conditions of deficit irrigation have been verified across a wide range of species and stress levels: superabsorbent and hydrogel amendments have enhanced growth, water-use efficiency, and physiological status in corn, soybean, faba bean, common bean, rice, and canola under water restriction that ranges from mild to severe [15, 16]. This benefit is largely attributed to the hydrogel acting as a rhizosphere water reservoir, which helps to buffer the moisture signal in the root-zone, thereby postponing the initiation of the plant's drought-stress signaling cascade rather than changing that cascade directly [16].

*Lupinus termis* L. is a multi-purpose, climate-resilient leguminous crop with considerable agricultural, nutritional, and pharmacological significance. Lupine grows successfully in the most unfavorable sandy soils where other major pulse crops fail. Seeds of lupine serve as a source of bioavailable plant protein that can be used for food, beauty, and health. This crop is characterized

by high concentrations of protein, ranging from 28-44% of dry matter, dietary fibers, and essential fatty acids. Lupine plants have medicinal and nutritional properties due to the content of quinolizidine alkaloids, polyphenols, tocopherols, and phytosterols. The composition of these secondary metabolites opens up the possibility of using lupine for medicinal purposes, cosmetics, and foods. Thus, the species is promising as a multipurpose crop, as it allows the restoration of poor sandy soils and the production of biologically active substances [17, 18].

Drought stress in legumes such as lupine classically reveals as reduced shoot elongation and biomass accumulation, loss of chlorophyll and carotenoid content through a combination of stomatal closure, reactive-oxygen-species (ROS) mediated pigment degradation and chlorophyllase activation, and a suite of biochemical defence responses: accumulation of osmolytes (proline, soluble sugars) for osmotic adjustment, increased phenolic/flavonoid biosynthesis, elevated lipid peroxidation (malondialdehyde, MDA) and hydrogen peroxide ( $H_2O_2$ ) as oxidative-damage markers, and up-regulation of antioxidant enzymes (superoxide dismutase, SOD; catalase, CAT; peroxidase, POX) [19, 20]. Because osmolyte accumulation and antioxidant enzyme induction are metabolically costly, carbon and nitrogen-diverting responses, a hydrogel amendment that reduces the severity of the underlying water deficit should, if the moisture-buffering mechanism is correct, present as simultaneously higher growth/pigment status and lower osmolyte/oxidative-marker levels relative to non-amended drought controls a pattern that this study explicitly tests via its Results and correlation analysis. Javed et al. [21] applied potato-peel chitosan, cellulose-based, and gum arabica hydrogels on soil and through seed coating to improve drought resilience of rice. The literature reveals a persistent disconnect between hydrogel water management and nutrient delivery functions. Most hydrogel studies focus exclusively on water retention [22, 23] or on single-nutrient delivery (typically nitrogen through urea loading), while

comprehensive NPK delivery from a single hydrogel matrix remains largely unexplored. The few studies that have addressed multi-nutrient delivery typically use physical blending rather than chemical integration, resulting in poor release control. To address these limitations, this study presents a green synthesis strategy that functionalizes raw sugarcane bagasse via direct phosphorylation with phosphoric acid, entirely bypassing the conventional pulping and bleaching steps. This direct treatment achieves the objectives: it introduces hydrophilic phosphate functional groups onto lignocellulosic framework to enhance water uptake and structural crosslinking, while simultaneously binding essential phosphorus (P) directly into the polymer network. The phosphorylated bagasse was subsequently graft-copolymerized with acrylamide and acrylic acid through free radical polymerization to yield a biodegradable and slow-release NPK hydrogel composite. The objective of this work was to evaluate the structural integrity, water retention, biodegradation behavior, and NPK release kinetics of the modified hydrogel system. Furthermore, its agronomic efficacy was validated through pot trials using lupine under both full and deficit irrigation regimes.

## **Materials and Methods**

### **Chemicals and Investigated Plant Materials**

All chemicals and reagents utilized in this research were of analytical quality and acquired from decent sellers. Acrylamide (AM), Acrylic acid (AA), and potassium persulfate (KPS), were purchased from Fluka. N, N-methylene bisacrylamide (MBA) was purchased from Sigma-Aldrich.

Bagasse waste was gained from Misr Edfu company in Kom Al-Amir, Edfu, Aswan Governorate, Egypt. This is a national company specializing in the production of bleached and unbleached pulp for writing and printing papers of various grammages and sizes. The company uses bagasse in a dry form as its main raw material for pulp production, which is ground into a

fine powder. This bagasse contains 44, 22, 21, 8, and 2.75% of  $\alpha$ -cellulose, hemicellulose, lignin, extractives, and ash, respectively.

Lupine seeds (*Lupinus termis* L., CV. Giza 2) were provided by the Agricultural Research Centre, Agriculture Ministry, and Giza, Egypt.

## **Methods**

### **Preparation of NPK hydrogel**

NPK hydrogel was prepared in two steps: phosphorylation of bagasse, followed by grafting with acrylamide (AM) and acrylic acid (AA).

#### **Phosphorylation of Bagasse**

25 g of dry-weight bagasse was boiled in 100 mL of water containing 35 mL of phosphoric acid under reflux at 90 °C for 2 h, followed by washing with distilled water, and coded as PB [24].

#### **Grafting of AM and AA onto PB**

The hydrogels were prepared via free-radical polymerization as follows: First, 10 g of PB was suspended in 100 mL of distilled water under magnetic stirring at 500 rpm and 70 °C in a 1000 mL reagent bottle. Then, KPS (1g) was added to the suspended solution, and stirring was continued for 10 min. The pH was adjusted to 5.5 following the addition of AM and AA monomers with different ratios. The total weight of monomers was 30 g. After 1 h, an aqueous solution of the crosslinker, MBA (2.5 g), was added to the reaction flask, and the temperature was raised to 70 °C. At the same time, stirring was continued for an additional 2 h. The hydrogel was washed with distilled water three times. The hydrogel was then collected and dried [25]. The hydrogels were coded as H1, H2, and H3 corresponding to AM:AA ratios of 2:1, 1:1, and 3:0, respectively.

## **Characterization**

• ATR-FTIR characterization: Attenuated Total Reflection (ATR) was used to characterize the chemical composition and assess changes in the hydrogel samples resulting from loading with the treatment materials. Instrument (Bruker 1238 2310 Platinum ATR diamond cell) Model: Alpha, PN: 1003271\07, SN: 104633, Made in Germany, for measurement in the 4000-600 cm<sup>-1</sup> region, at a resolution of 4 cm<sup>-1</sup>. Spectra were collected by placing the dry gel samples directly on the ATR cell.

• Morphological analysis was performed using scanning electron microscopy (SEM, Quanta-250).

• Swelling of the hydrogels; the swelling capacity of the hydrogels was measured by immersion of the hydrogel in distilled water for 24 h at room temperature to allow complete swelling. The swollen piece was removed and wiped gently between two filter papers. The water uptake (%) was then calculated as an average of three measurements using the following equation [26]:

$$\text{Water Uptake \%} = \frac{(M_2 - M_1)}{M_1} \times 100$$

where; M<sub>1</sub> and M<sub>2</sub> are the dry and wet weights of the hydrogel, respectively.

### **Biodegradation Test**

The biodegradability test was conducted in soil as described in our previous work [27]. To create a homogeneous mass, the inert components were removed, and the top layer of soil was removed. A plastic container was filled with about 100 g of dirt down to a depth of about 3 cm. After being carefully weighed and dried for 24 h at 50 °C, the samples were buried in pots to a depth of 1 cm. To keep moisture levels stable, water was applied every day. After being cleaned with distilled water and dried for 24 h at 50 °C, the samples were weighed weekly for 8 weeks. For every sample, three duplicates underwent biodegradation.

## **Determination of NPK Content**

Samples were digested in an acid solution using an Anton-Paar Multiwave PRO microwave digestion system. Potassium and phosphorus concentrations were measured using the Agilent 5100 SVDV ICP-OES with the VGA 77 accessory, after acid digestion, to ensure a suitable matrix and consistent recoveries [28]. Each series used a calibration curve with a blank and at least three standards from Merck (Germany). Accuracy and precision were checked with external Merck standards, while instrument readings were validated against NIST standard reference materials and quality control samples. Total nitrogen was measured by the Kjeldahl method using a Gerhardt distillation apparatus (APHA, 2021) [28].

## **Pot experiment**

A pot experiment was conducted over two winter seasons in the greenhouse of the Botany Department at the National Research Centre, Dokki, Giza, Egypt, to investigate how varying ratios of NPK hydrogel in soil affect growth, chlorophyll content, biochemical changes and drought tolerance of lupine plants.

## **Experimental Design**

The experiment was designed as a two-factor, randomized complete block design (RCBD) with three replicates. Factor A included two levels of field capacity: D0 = 100 % field capacity (FC) and D1 = 50 % FC. Factor B included three levels of NPK hydrogel; 0% hydrogel (control), 0.1 % (1 g/kg of soil), and 0.2% (2 g/kg of soil). 10 kg of air-dried soil was placed in 35 cm<sup>3</sup> pots. The soil mixture consisted of yellow sand and clay in a 3:1 ratio. The soil was then mixed with hydrogel. After being sterilized with sodium hypochlorite, lupine seeds were sown in pots. For each irrigation level, there is a control group, a group of plants grown with hydrogel supplementation at 0.1 %, and another group supplemented with hydrogel at 0.2 %. Following the

complete establishment of seedlings and the selection of the strongest seedling in each pot (21 days after sowing), watering treatments were initiated. The fertilization was carried out in accordance with the Ministry of Agriculture's advice.

## **Plant sampling and analysis**

### ***Lupine growth traits***

Lupine plants were harvested at vegetative state (60 days old), washed thoroughly with tap water, then with deionized water. A measuring tape was employed to determine the shoot length (cm). The number of leaves was recorded. Lupine shoots were weighed fresh and dried at 70 °C to constant weight to determine shoot dry mass (g/plant).

### ***Photosynthetic pigments***

The method developed by Moran and Porath [29] was used to determine chlorophyll a, chlorophyll b, and carotenoid levels in fresh, fully mature lupine leaf samples (50 mg each). Each sample was combined with 10 mL of N, N-dimethylformamide and refrigerated for 24 h. Afterward, the mixture was centrifuged at  $4000 \times g$  for 15 min, and the optical density was measured using a JASCO V-750 spectrophotometer.

### ***Biochemical analysis***

Proline concentration (Pro) was extracted and quantified following the methodology outlined by Bates et al. [30]. Total soluble sugars (TSS) content of dried lupine leaves was determined using the method of Dubois et al. [31]. Total phenolic compounds (TPC) were analyzed using a Folin-Ciocalteu colorimetric assay adapted from Elzaawely and Tawata [32]. The total flavonoid content (TFC) was assessed using the aluminum chloride method, as modified by Chang et al. [33].

Malondialdehyde (MDA) levels were determined using the procedure established by Heath and Packer [34]. Hydrogen peroxide ( $H_2O_2$ ) was measured using the approach described by Yu et al. [35]. Enzyme extracts were prepared utilizing the method developed by Chen and Wang [36]. Catalase (CAT) activity was measured by monitoring the reduction in absorbance at 240 nm, and superoxide dismutase (SOD) activity was evaluated using the nitroblue tetrazolium reduction method, following the Chen and Wang [36] technique. Peroxidase (POX) activity was determined according to the procedure detailed by Kumar and Khan [37].

### **Statistical analysis**

A two-way analysis of variance (ANOVA) was employed to evaluate the interactions between the two components. The figures were created using the means  $\pm$  standard deviation of each treatment. The average data from the two seasons were statistically examined using analysis of variance. As outlined by Silva and Azevedo [38], differences between the means were assessed using the least significant differences (LSD) method.

### **Results and Discussion**

Phosphorylation of bagasse with phosphoric acid (PB) introduces phosphate groups onto the cellulose backbone. This increases hydrophilicity and reactivity by increasing the density of functional groups ( $-PO_3H$ ,  $-OH$ ). This improves hydrophilicity, essential for hydrogel formation, and provides anchoring sites for graft polymerization. The modification creates active sites for subsequent graft polymerization and improves compatibility with synthetic monomers. Activating PB with KPS and sulfuric acid generates free radicals, further activating the PB surface and initiating grafting reactions. This initiation enables the incorporation of AM and AA into the cellulose matrix. Due to their excellent swelling capacity and biocompatibility, AM and AA. Herein, multifunctional hydrogels were developed by grafting AA and AM monomers into PB,

297 followed by cross-linking with MBA. The hydrogel formation proceeded via free radical  
298 polymerization initiated by KPS at 70 °C, as shown in **Figure 1**. Grafting AM onto PB produces  
299 (PB-g-poly (AM)), a hydrogel that contains both amide groups (–CONH) and phosphate  
300 functionalities. This composition results in high water absorption and ion-exchange capacity.  
301 Makes it suitable for moisture retention and nutrient delivery. Incorporating AA through  
302 copolymerization yields hydrogels with adjustable ionic properties. Incorporating both acidic and  
303 neutral functionalities first improves swelling behavior, thereby enhancing pH responsiveness,  
304 making these materials suitable for controlled-release systems. Accordingly, controlled  
305 phosphorylation and graft copolymerization of bagasse produce hydrogels with distinct structural  
306 and functional characteristics. Systematic variation in monomer composition enables the design of  
307 application-specific hydrogels. This process bridges the gap between waste valorization and  
308 advanced material development. Among the prepared hydrogels, H1 (PB:AM: AA = 1:2:1) has a  
309 balanced mix of two main group types, leading to moderate water swelling and responsiveness to  
310 changes in acidity. H2 (PB:AM: AA = 1:2:2), by contrast, contains more of one group, which gives  
311 it more ability to attract ions and swell under alkaline conditions. Comparing these hydrogels  
312 shows how the ingredient ratio affects their behavior: H3 focuses on holding water and exchanging  
313 ions; H1 aims for a balance between swelling and responsiveness; H2 boosts the ability to attract  
314 charged particles for trapping substances. This flexibility makes PB-based hydrogels useful in  
315 farming. Also, using bagasse as a plant waste supports sustainable practices by turning low-value  
316 materials into valuable ones.

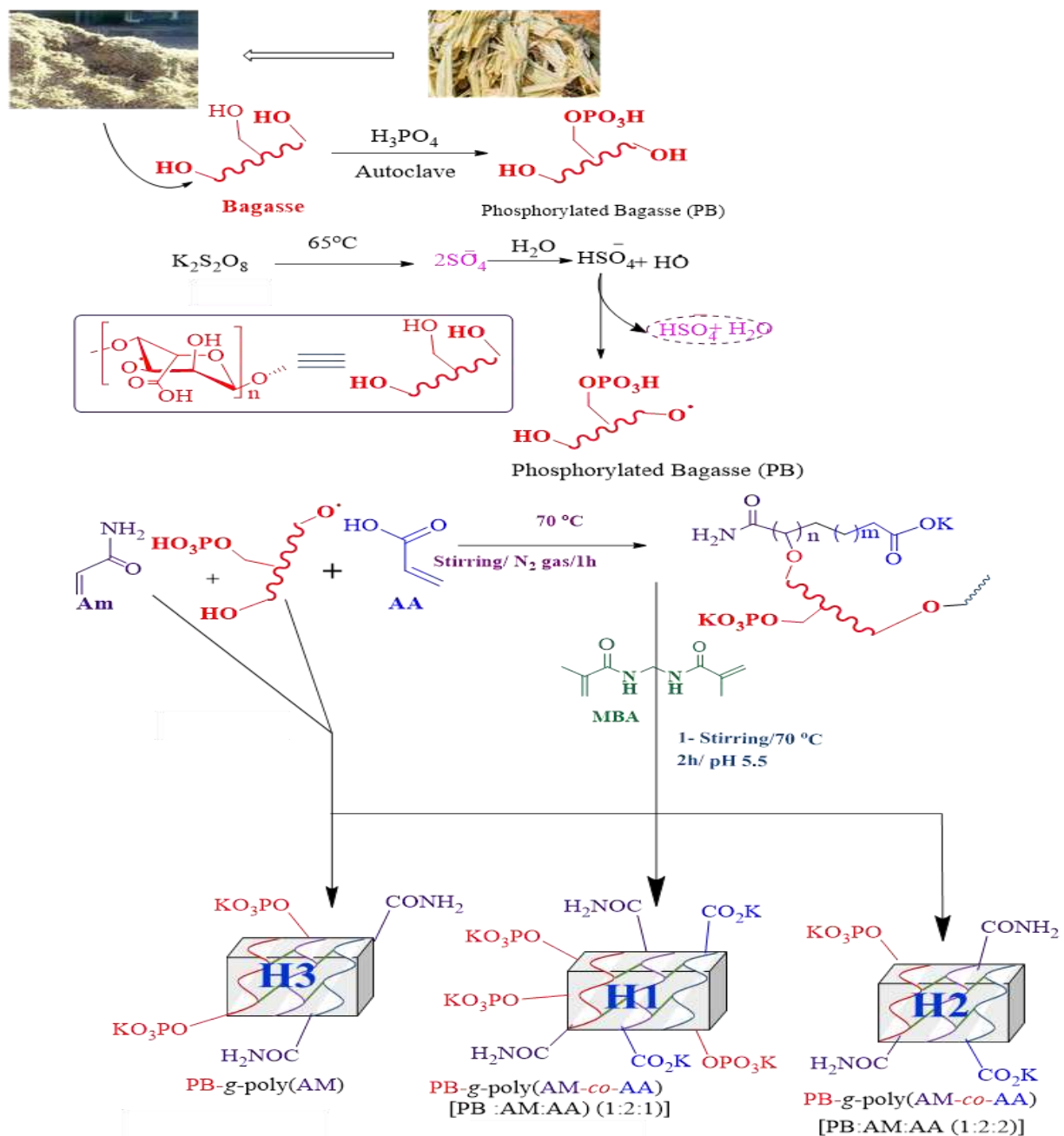


**Figure 1.** Schematic representation for the preparation of NPK hydrogels.

## FT-IR characterization

The ATR spectra of B, PB, H1, H2, and H3 provide evidence of chemical modifications.

The spectrum of B shows characteristic absorption bands linked with lignocellulosic materials. A

323 broad band around  $\sim 3400\text{ cm}^{-1}$  marks O–H stretching vibrations in cellulose and hemicellulose.  
324 Peaks near  $2900\text{ cm}^{-1}$  arise from C–H stretching of aliphatic chains. Absorptions in the  $1730\text{--}1740$   
325  $\text{cm}^{-1}$  region indicate C=O stretching of ester or carboxyl groups in hemicellulose. These features  
326 confirm the usual lignocellulosic composition of B. Upon phosphorylation, the spectrum of PB  
327 shows new absorptions in the region  $\sim 1240\text{--}1260\text{ cm}^{-1}$ , corresponding to P=O stretching  
328 vibrations, and bands near  $\sim 1050\text{ cm}^{-1}$ , indicative of P–O–C linkages [39]. These signals confirm  
329 successful incorporation of phosphate groups into the bagasse backbone. The reduction in intensity  
330 of the hydroxyl band ( $\sim 3400\text{ cm}^{-1}$ ) suggests partial substitution of –OH groups by phosphate  
331 functionalities, consistent with chemical modification.

332 The H1 spectrum shows strong absorptions around  $1650\text{ cm}^{-1}$ , characteristic of C=O  
333 stretching in amide groups, confirming the grafting of AM. Additionally, a band near  $1560\text{ cm}^{-1}$   
334 corresponds to N–H bending vibrations, further supporting amide incorporation. The presence of  
335 a broad O–H stretching band ( $\sim 3400\text{ cm}^{-1}$ ) and C=O stretching from carboxyl groups ( $\sim 1720\text{ cm}^{-1}$ )  
336 indicates contributions from AA. The coexistence of amide and carboxyl functionalities  
337 demonstrates successful dual grafting, with AM dominating due to the 2:1 ratio. Similarly, the H2  
338 spectrum shows balanced intensities for the amide ( $1650, 1560\text{ cm}^{-1}$ ) and carboxyl ( $1720\text{ cm}^{-1}$ )  
339 bands, reflecting equal incorporation of AM and AA [40]. The broad hydroxyl band ( $\sim 3400\text{ cm}^{-1}$ )  
340 remains pronounced, suggesting hydrogen bonding interactions between grafted chains and  
341 residual cellulose hydroxyl groups. This balanced chemical composition supports the  
342 morphological heterogeneity observed in SEM, where fibrous and particulate domains coexist.  
343 The H3 spectrum is dominated by amide-related absorptions ( $1650$  and  $1560\text{ cm}^{-1}$ ), with minimal  
344 contribution from carboxyl groups. The absence of AA results in reduced intensity of the  $\sim 1720$   
345  $\text{cm}^{-1}$  band, confirming that nitrogen-rich amide functionalities are the primary modification. This

correlates with the elemental analysis, which showed that H3 had the highest N content, and with SEM observations of a porous, granular morphology.

This confirms the successful phosphorylation of bagasse and the subsequent grafting of AM and AA. Phosphorylation (PB) introduces phosphate groups, enhancing P content. Dual grafting (H1 and H2) incorporates amide and carboxyl functionalities. Comparing the spectra, the AM/AA ratios are reflected in the relative intensities of the corresponding functional group bands. Grafting with only AM in the H3 results in the highest N incorporation, as evidenced by stronger amide bands than in the other grafting conditions.

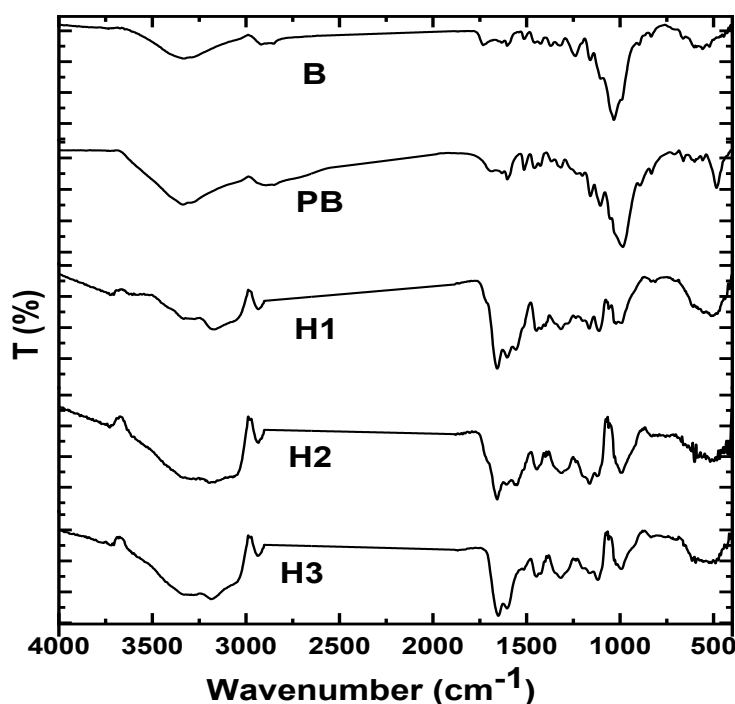


**Figure 2.** ATR spectra of B, PB, H1, H2, and H3.

**Swell ability**

**Figure 3** illustrates the swell ability of the prepared hydrogels and compares them with blank (B) and phosphorated (PB) fibers. The B fibers showed swelling of around 450 %, and the PB fibers' swelling was increased to 500%. Indeed, this increase was not considered a significant change, especially compared with the hydrogels' swelling values. The swelling behavior of the prepared hydrogels was recorded, with a significant difference observed between the hydrogel components, which in turn affect the hydrogel structure. Obviously, the addition of AA has elevated the swelling behavior of the hydrogel, which reached 2400 %, whereas the hydrogel without AA reached 700 %. Moreover, the increase in AA by 1-fold corresponded to a 2900 % increase. In sum, the swelling behavior of hydrogels was significantly affected by the AM:AA ratio. Hydrogels incorporating AA displayed substantially greater swelling than those composed exclusively of AM. This increase results from the presence of ionizable carboxyl groups in AA, which dissociate, generating electrostatic repulsion within the polymer network and elevating osmotic pressure via counter-ion diffusion. These mechanisms expand the hydrogel matrix and promote increased water absorption. H2 (AM:AA = 1:1) exhibited the highest swelling, attributable to its balanced composition of neutral amide groups and a high concentration of ionizable carboxyl groups. H1 (2:1) displayed moderate swelling, corresponding to its lower AA content. In contrast, H3 (3:0), consisting solely of AM, demonstrated the lowest swelling capacity because its non-ionic amide groups depend exclusively on hydrogen bonding with water. Therefore, the observed increase in swelling correlates directly with higher AA content, highlighting the essential role of ionic functionality in hydrogel expansion.

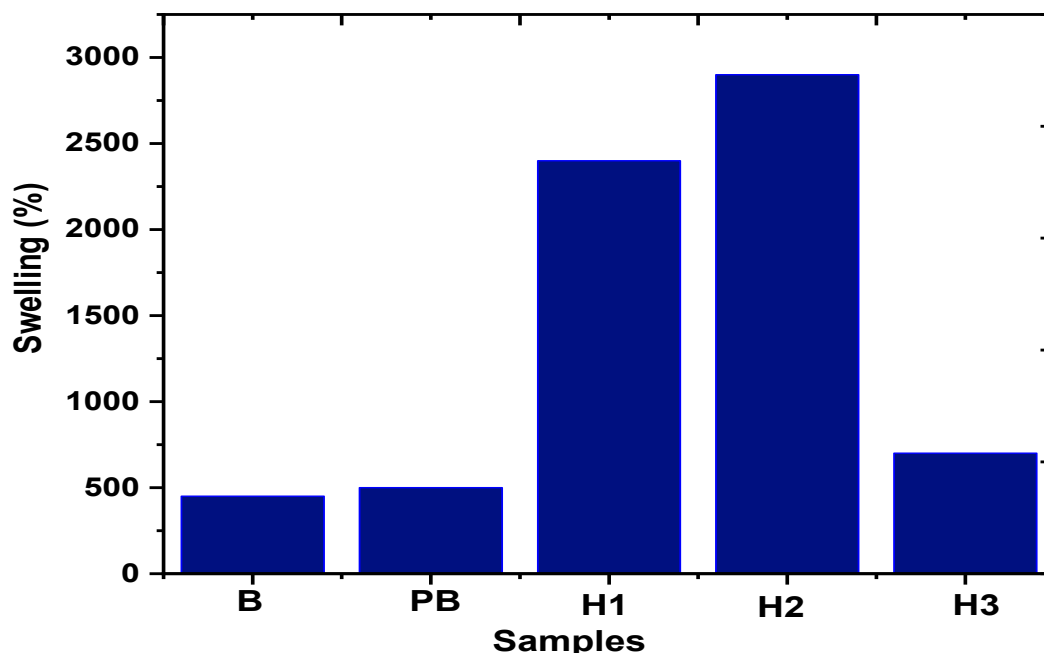


**Figure 3.** Swelling behavior of B, PB, H1, H2, and H3.

### Morphological Study

The morphological characteristics of the bagasse-based hydrogels were examined using SEM micrographs (**Figure 4**). These micrographs correspond to PB blended with AM and AA at 2:1 and 1:1 ratios, and to PB with AM, respectively. The comparative analysis shows distinct differences in the surface architecture, which can be directly attributed to the compositional variations. The micrograph of H1 (PB/AM: AA 2:1) shows a relatively smooth, striated surface with layered features. This surface pattern suggests that when the proportion of AM is greater than that of AA, the result is a compact, ordered structure. This compactness reduces particulate deposition and the formation of voids. The observed smoothness is associated with improved mechanical stability in cellulose-polymer hydrogel. In contrast, H2 (PB/AM/AA 1:1) displays a fibrous matrix interspersed with spherical or crystalline particulates. The balanced AM:AA ratio appears to favor heterogeneous nucleation, leading to a dual-phase morphology. The micrograph

of H3 (PB/AM) shows a highly irregular, porous surface with granular formations. Without AA, the matrix destabilizes, leading to roughness and pore formation. Porosity, which refers to the presence of many small holes, increases surface area. The sequence from H1 to H3 highlights the role of AA in stabilizing the hydrogel. Increasing AA content promotes smoother, more ordered surfaces, whereas its absence results in porous, degraded morphologies.

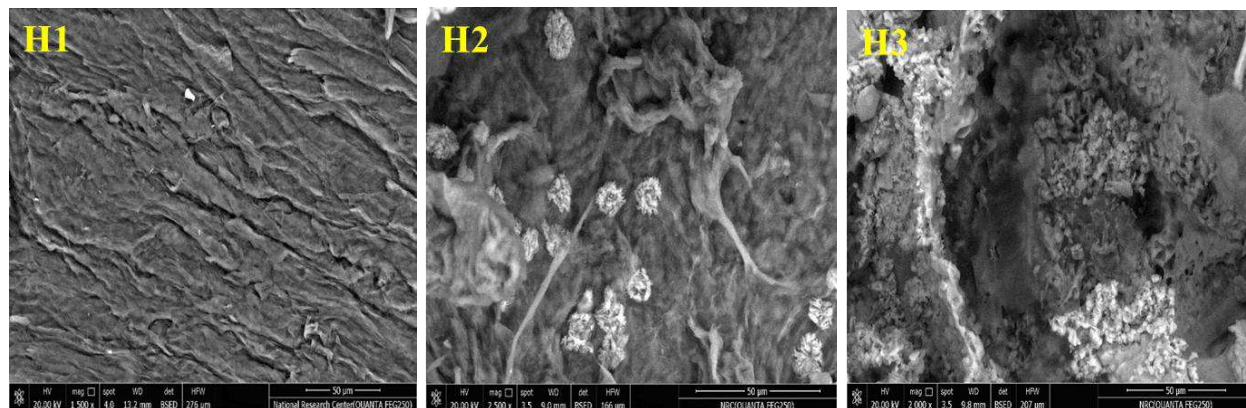


**Figure 4:** SEM image of H1, H2, and H3.

### Biodegradation study in soil

**Figure 5** illustrates the biodegradability of the hydrogels in soil for 4 weeks. The sample of free of bagasse fibers (AA/AM) observed a low degradation rate [41]. The biodegradation rate in the first week was  $1.33 \pm 0.577$  %, and in the fourth week, it was  $4 \pm 1$  %. Herein, the addition of bagasse fibers (H1) increases biodegradability to about  $4.66 \pm 1.53$  % in the first week, and the degradation rate increases to  $22 \pm 2$  % after four weeks. The role of AA was determined by the degradation rate of H2 hydrogel, with an increase in the AA ratio enhancing the degradation rate to  $7.67 \pm 1.528$  % and  $25 \pm 1$  % for the first and fourth weeks, respectively. The absence of AA in the hydrogel H3 led to a decrease in the biodegradation rate to  $2.33 \pm 0.578$  % and  $16 \pm 1$  % for the first and fourth weeks, respectively. Overall, these results show that adding bagasse fiber to the hydrogels increases the rate of biodegradation in soil. Moreover, AA increases the biodegradation

rate, and these results align with the hydrogels' swelling behavior. Accordingly, lignocellulosic fibers increase the biodegradability of the hydrogels due to their high polysaccharide content, which is characterized by rapid biodegradation [42]. Additionally, the AA increases the biodegradation rate via the carboxylic acid groups ( $-\text{COOH}/-\text{COO}^-$ ), which increase hydrophilicity and swelling, which can improve water diffusion and microbial access to the polymer network and thereby slightly promote physical–enzymatic degradation [43]. The results show that H2 hydrogel is the most biodegradable formulation because it has both lignocellulosic reinforcement and higher hydrophilicity because of AA. On the other hand, AA/AM is the least biodegradable because its synthetic polymer network is more stable. The biodegradation behavior of the prepared hydrogels was significantly influenced by their composition. This trend shows that bagasse fibers help biodegradation by giving it a natural phase that can break down, and that higher AA levels speed up degradation even more by making it more hydrophilic, swelling, and easier for microbes to attack.

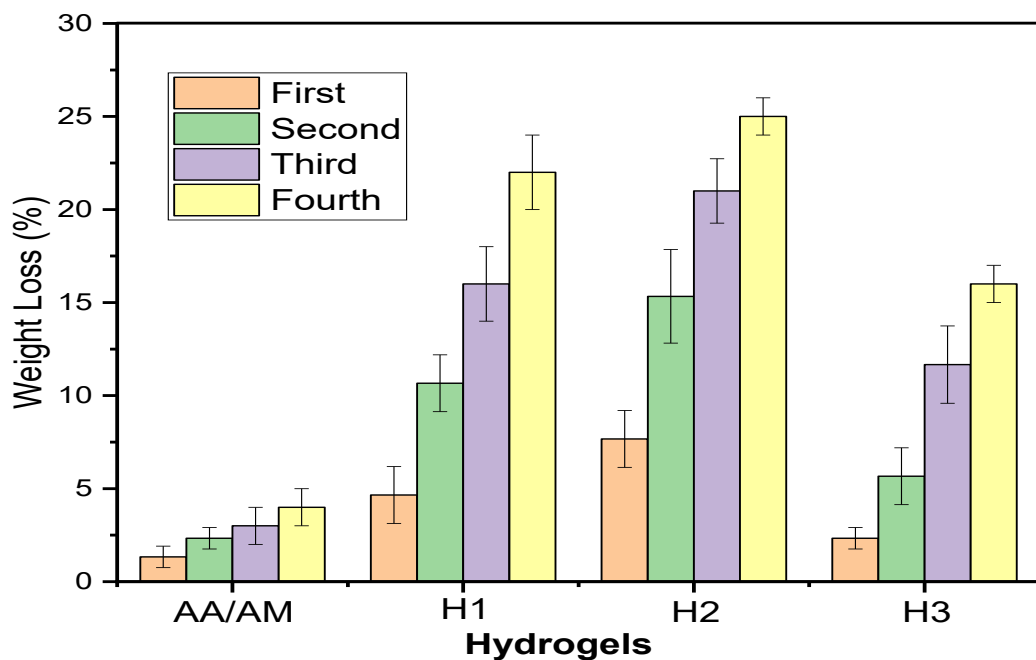


**Figure 5.** Biodegradation behavior of the prepared hydrogels, H1, H2, and H3 for 4 weeks.

## Elemental analysis

The elemental composition of the B, PB, and prepared hydrogels (H1, H2, and H3) (**Table 1**) provides important insights into the impact of phosphorylation of B and grafting of AM and AA onto PB. The nitrogen (N), phosphorus (P), and potassium (K) contents varied significantly among the different formulations. This variation reflects both the chemical nature of the grafted monomers and the efficiency of the modification process. The N content increased markedly after grafting, rising from 1960 mg/kg in B and 1560 mg/kg in PB to 52080, 35280, and 78400 mg/kg in H1, H2, and H3, respectively. This sharp increase results from incorporating AM, which introduces amide groups into the polymer matrix, thereby increasing N content. The highest N content in H3 demonstrates that with only AM present, N enrichment is at its maximum; in contrast, adding AA in H1 and H2 lowers the N proportion by diluting the effect of AM. These results clarify the causal role of AM in enhancing N functionality, which underpins applications such as nutrient-retentive hydrogels and agricultural soil conditioners [44].

P levels were highest in PB because the phosphorylation treatment introduces phosphate groups into the bagasse backbone. However, subsequent grafting with AM and AA reduced P concentrations to 108, 99, and 60 mg/kg in H1, H2, and H3, respectively. This reduction occurs because the grafted polymers partially mask or dilute the phosphate groups, particularly in AM-rich formulations. Thus, phosphorylation enhances initial P incorporation, while grafting alters the elemental balance, potentially affecting the material's nutrient-release profile.

K concentrations also increased significantly after grafting, rising from 34 mg/kg in B and 6 mg/kg in PB to 1400, 2080, and 1100 mg/kg in H1, H2, and H3, respectively. This increase in K levels in the grafted samples likely results from ionic interactions that occur between the grafted

polymer chains and residual salts present during synthesis. The highest K enrichment observed in H2 (PB/AM: AA 1:1) indicates that when both AM and AA are present, the polymer structure formed is more conducive to K retention or incorporation than when only AM is used.

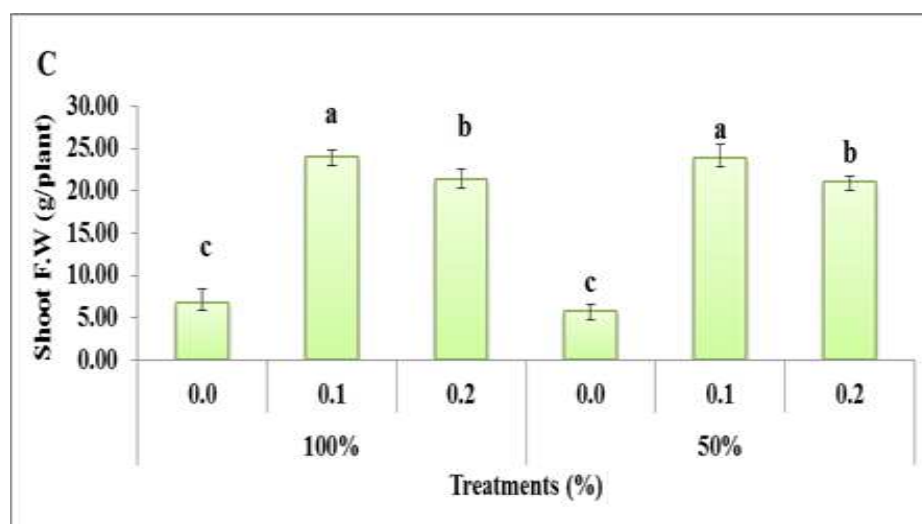
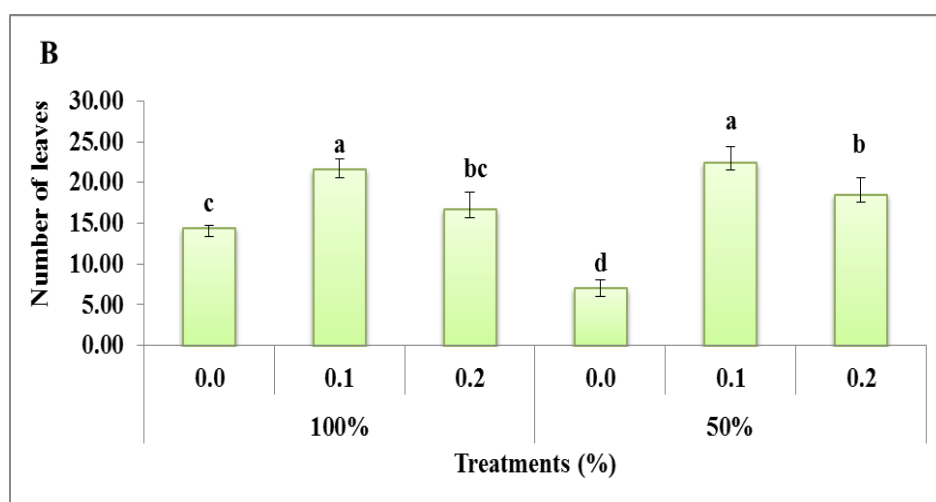
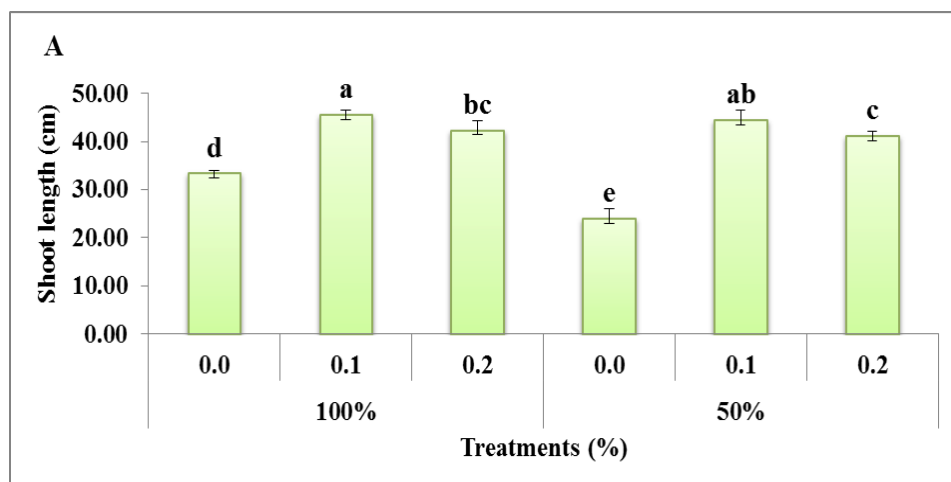
**Table 1.** NPK analysis of B, PB, H1, H2, and H3.

| Code      | N (mg/Kg) | P (mg/Kg) | K (mg/Kg) |
|-----------|-----------|-----------|-----------|
| <b>B</b>  | 1960      | 5         | 34        |
| <b>PB</b> | 1560      | 395       | 6         |
| <b>H1</b> | 52080     | 108       | 1400      |
| <b>H2</b> | 35280     | 99        | 2080      |
| <b>H3</b> | 78400     | 60        | 1100      |

### **Lupine Growth Parameters**

Applying NPK hydrogel in soil at 0.1 and 0.2 % improved all lupine growth parameters (shoot length, number of leaves, and F.W and D.W of lupine shoot) as compared with stressed and unstressed conditions. Low level of hydrogel (0.1 %) showed maximum increase in shoot length (45.54 cm), number of leaves (21.66), shoot F.W (24.06 g /plant), and shoot D.W (8.70 g/plant) at 100 % FC. Under drought stress (50 % Fc), 0.1 % hydrogel demonstrated a significant enhancement in shoot length (44.42 cm), number of leaves (22.50), shoot F.W (23.92 g/plant), and shoot D.W (8.32 g/plant) as compared to the control. The Enhancement in lupine growth through the application of hydrogel could be due to its role in increasing water retention capacity and increasing soil moisture availability. Furthermore, hydrogel plays a significant role in the absorption and subsequent gradual release of water and nutrients, thereby increasing biomass production and reducing ROS accumulation [16]. The reduction in lupine growth may be due to

467 decreased gas exchange, altered water relations, loss of turgidity, deterioration in relative water  
468 content, declines in cell division and elongation, and reductions in net CO<sub>2</sub> assimilation rate,  
469 stomatal conductance, and transpiration rate [19]. Talbi et al. [45] stated that a reduction in biomass  
470 accumulation in tobacco plants may be attributed to the limitations imposed on photosynthesis.  
471 Our results are similar to those reported by Sadak and Ramadan [46], who found that water stress  
472 at 75 and 50 % FC caused a significant decrease in growth and photosynthetic pigments of *Lupinus*  
473 *termis* L. compared with 100 % irrigation. According to Tawfik et al. [20], reducing irrigation  
474 water to 75% and 50% decreased all growth traits in oat. Albalasmeh et al. [22] demonstrated that  
475 the use of hydrogel (0.27 and 0.33 %) enhanced the soil water content of corn plants by 35% and  
476 49%, respectively. Additionally, water use efficiency improved by 28% and 32% in sandy and  
477 silty clay loam soils, respectively. The same result was obtained by Elsayed et al. [23], who found  
478 that application of HPMC-Xanthan gum hydrogel at all concentrations significantly increased  
479 growth parameters of soybean plants under different irrigation regimes. The addition of a hydrogel  
480 polymer and zeolite to soil significantly improved vegetative growth attributes and yield of  
481 common bean plants compared with the control [15]. According to Javed et al. [21], soil  
482 amendment with plant-based hydrogels, potato peel powder-chitosan (PPPC), cellulose-based  
483 (CL), and gum arabica (GA) improved drought resilience and increased growth and yield of rice.



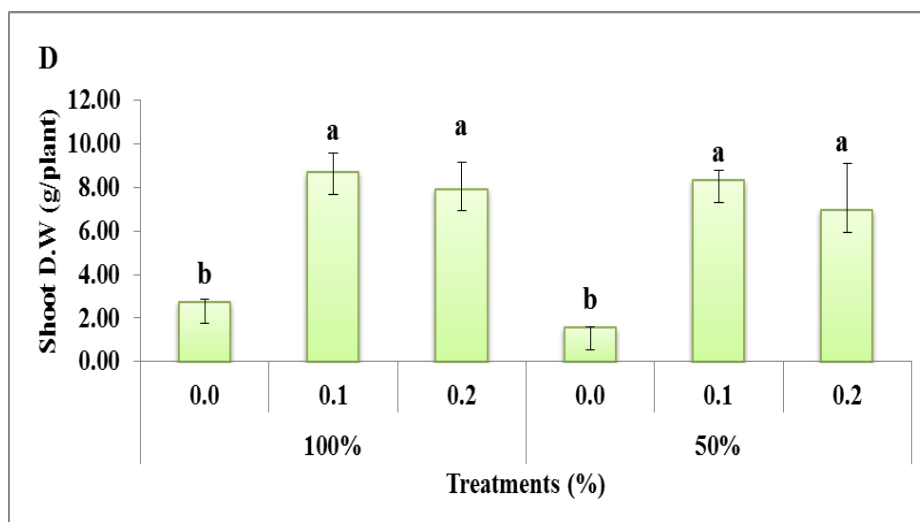


**Figure 6.** Effect of different ratios of soil applied hydrogel, H1 (0, 0.1, and 0.2 %) on vegetative growth criteria of lupine plants (A) shoot length (cm), (B) number of leaves, (C) shoot F.W (g/plant) and (D) shoot D.W (g/plant) exposed to drought stress (100 and 50 % FcC). Bars indicated standard deviation ( $\pm$ SD). Similar letters indicate non-significant variations at 0.05 level.

### Photosynthetic Pigments

In this study, we examined how amendment of soil with H1 hydrogel affects photosynthetic pigments (mg/g F.W), including chlorophyll a (Chl a), chlorophyll b (Chl b), and carotenoids (Car), in lupine plants exposed to drought stress (**Figure 7**). Drought stress (50 % FC) reduced the content of Ch a to 1.603, Ch b to 0.643, and Car to 0.091 mg/g F.W, as related to the corresponding control. Decline in Ch a, Ch b, and Carotenoids of lupine leaves under stress may be attributed to stomatal closure [16], chlorophyll degradation, and the transformation of Chl b into Chl a, leading to an increase in the Chl a/b ratio [47]. The reduced chlorophyll content in lupine leaves under water stress may be linked to the overproduction of reactive oxygen species (ROS), which subsequently damage the photosynthetic machinery, inhibit enzymes responsible for chlorophyll biosynthesis, and trigger the activation of the chlorophyllase enzyme. Additionally, the enhanced biosynthesis of carotenoids in response to water scarcity indicates that lupine plants possess an

504 effective photo-protective defense mechanism against water stress. It is crucial for plants to  
505 mitigate ROS formation. Carotenoids play a role in reducing the production of singlet oxygen in  
506 photosynthetic tissues by quenching triplet chlorophyll [21]. However, applying NPK hydrogel in  
507 soil with varying ratios (0.1 and 0.2%) significantly enhanced Ch a, Ch b, and Car compared to  
508 control treatments. The most pronounced improvement was observed at the lowest hydrogel  
509 concentration (0.1%). Abd El-Aziz et al. [48] and Soliman et al. [49] found that the application of  
510 hydrogel increased the content of Ch a, Ch b, and carotenoids in leaves of *Calendula officinalis*  
511 plants. They stated that the effect observed in the performance of hydrogel polymers may be  
512 attributed to a decrease in chlorophyll degradation or an enhancement of its biosynthesis,  
513 facilitated by sufficient water (increased soil moisture) and nutrient availability for the plants.  
514 Kenawy et al. [19] indicated that soil amendment with superabsorbent nanocomposites (SANC)  
515 increased photosynthetic performance under water stress (40% FC). Elsayed et al. [23] found that  
516 HPMC-Xanthan gum hydrogel application increased photosynthetic pigments of soybean plants  
517 under different irrigation regimes. Ramadan et al. [16] verified that hydrogel amendment in sandy  
518 soil increased chlorophyll and carotenoid contents in faba bean plants under drought stress (50%  
519 FC).

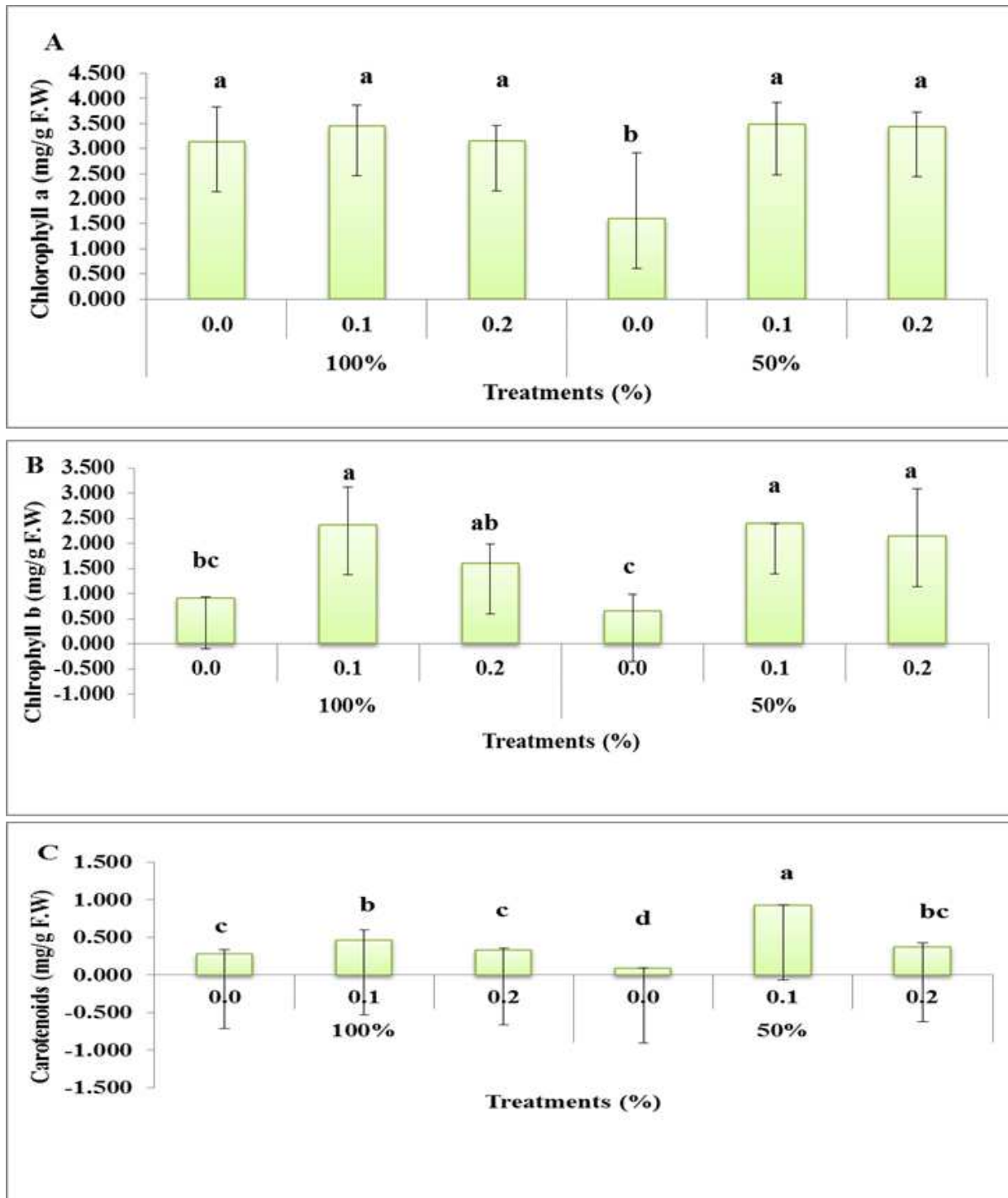


**Figure 7.** Effect of different ratios of soil applied hydrogel, H1, (0, 0.1 and 0.2 %) on photosynthetic pigments (Ch a, Ch b, and Carotenoids mg/g F.W) of lupine leaves exposed to

drought stress (100 and 50 % FC). Bars indicated standard deviation ( $\pm$ SD). Similar letters indicate non-significant variations at the 0.05 level.

## **Biochemical Analysis**

### **Osmolytes Accumulation**

**Figure 8** illustrates the effects of H1 hydrogel ratios (0, 0.1, and 0.2 %) and two levels of drought stress (100 and 50 % FC) on osmolyte constituents, such as proline (Pro) and total soluble sugars (TSS), in leaves of lupine plants, along with their interactions. Lupine plants subjected to 50 % FC showed a non-significant ( $P > 0.05$ ) increase in Pro and TSS levels compared to the control group. The rise was approximately 36.46 ( $\mu$ moles/g F.W) for Pro and 40.42 (mg/g D.W) for TSS relative to the control. The osmoprotectants were essential for carbon storage, osmotic adjustment, and enhanced radical scavenging under water stress [50]. The elevation of these components improved the cells' ability to respond to various stressors by increasing cytoplasmic osmotic pressure and stabilizing proteins and membranes, thereby preserving the relatively higher water content necessary for plant growth and cellular function [51]. Furthermore, it has been demonstrated that proline protects the cellular machinery from lipid peroxidation-induced dysfunction and detoxifies the membrane from harmful ROS [52]. They concluded that proline serves multiple functions, including increasing the rate of photosynthesis, interacting with various signaling molecules, such as plant growth regulators (IAA), activating stress signaling, and facilitating the upregulation of stress-related genes. Ashraf and Iram [53] noted that elevated proline levels in cowpea plants indicate high drought tolerance. Proline is also recognized as an antioxidant and helps maintain redox balance, thereby protecting plant cells from desiccation [23].

Under conditions of water deficit, soluble sugar content increased with increasing stress duration from three to nine days [54]. TSS acts as an osmolyte, protecting proteins from oxidative

damage caused by free radicals during water-deficient conditions [55]. The intracellular accumulation of TSS is crucial for osmoregulation, as it lowers cell water potential and retains more water within the cell to sustain appropriate turgor pressure during drought stress [56]. In conditions of water scarcity, TSS levels in plant tissues are altered, which affects the efficiency of photo assimilate translocation and, subsequently, plant growth and respiration [57]. Earlier research has emphasized the importance of these organic solutes in ensuring plant survival and in aiding osmotic adjustment [58]. Silva et al. [59] reported that under water restriction, cowpea plants can accumulate proline and TSS. Elevated concentrations of proline and TSS enhance cell turgor and boost the plant's defense systems against ROS [60].

Adding NPK hydrogel to the soil with 0.1 and 0.2 % boosted the accumulation of Pro (29.70  $\mu$ moles/g F.W) and TSS (30.58 mg/g D.W) in leaves of lupine plants at 100 % FC, while under stressed conditions (50 % FC), NPK hydrogel (0.1 and 0.2 %) reduced the accumulation of Pro (26.42  $\mu$ moles/g F.W) and TSS (32.87 mg/g D.W) compared to the corresponding control treatment. The most remarkable outcome was seen at 0.1%, as hydrogel functions as mini-reservoirs. It stores water in the root zone, or rhizosphere, and gradually releases it. The plant does not sense a water deficiency warning because it has a constant supply of moisture. As a result, the plant receives a consistent supply of moisture, preventing it from detecting a water deficit signal. Therefore, it does not need to initiate the costly production of osmolytes. The synthesis of proline and soluble sugars is considered metabolically expensive. The plant must utilize carbon and nitrogen that could otherwise contribute to the development of new leaves, stems, or roots. By employing a hydrogel to sustain soil moisture, the plant circumvents this metabolic burden. Rather than converting starch into TSS for survival, the plant can retain its carbon in the form of complex carbohydrates, promoting growth. This explains why plants treated with hydrogel frequently

exhibit lower levels of osmolytes but greater biomass in comparison to stressed plants lacking hydrogel. The decrease in TSS and proline serves as a physiological indicator that the hydrogel is successfully alleviating stress [61].

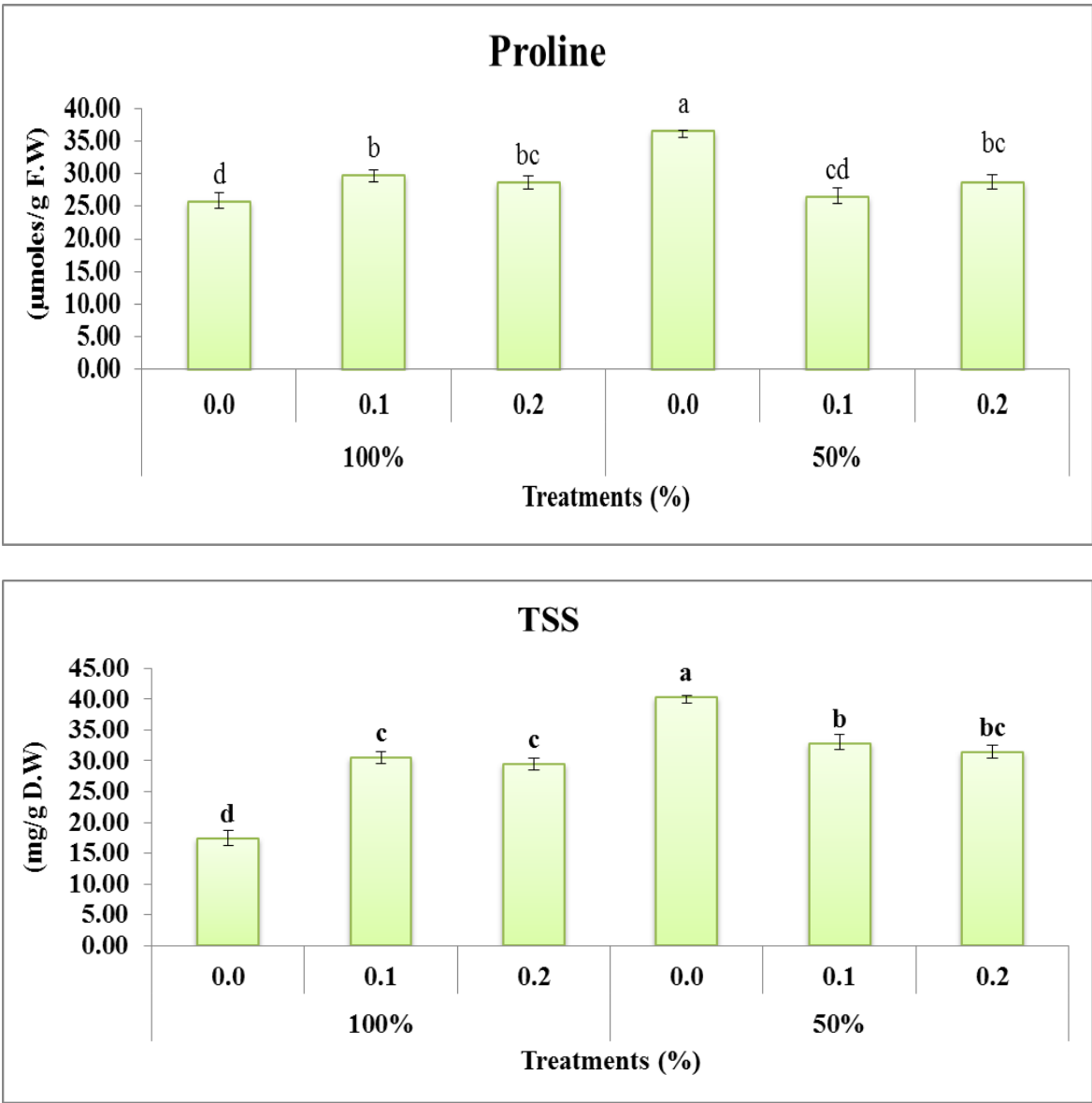


**Figure 8.** Effect of different ratios of soil applied hydrogel, H1 (0, 0.1, and 0.2 %), on proline ( $\mu\text{moles/g F.W}$ ) and total soluble sugar content ( $\text{mg/g D.W}$ ) of lupine leaves exposed to drought

stress (100 and 50 % FC). Bars indicated standard deviation ( $\pm$ SD). Similar letters indicate non-significant variations at the 0.05 level.

### **Total Phenolic and Flavonoid Compounds**

Data of the present study (**Figure 9**) indicated that both the drought stress and hydrogel application did not significantly affect ( $P > 0.05$ ) the content of the total phenolic (TPC) and flavonoid compounds (TFC) of lupine leaves. Drought stress applied at 50 % FC increased TPC (5.30 mg/ GAE g D.W) and TFC (5.91 mg/ QE g D.W) compounds in lupine plants compared with those subjected to 100 % FC. Water shortage led to disturbances in biochemical processes, resulting in heightened biosynthesis of phenolic compounds [62]. Phenolics are recognized for their role in plant processes, by oxidizing phenols and activating defense enzymes, which ultimately help to eliminate oxidative damage agents, such as  $H_2O_2$ . This compound initiates various physiological and molecular processes that indicate the synthesis of multiple defense components and enzymes [47]. Phenolic compounds play a crucial role as antioxidants in neutralizing ROS [63].

Applying lowest level of hydrogel (0.1 %) at 100 % FC caused more enhancement in both TPC and TFC (5.06 mg/ GAE g D.W, 4.79 mg/ QE g D.W, respectively) compared to untreated control (0 % hydrogel). Under water stress (50 % FC), addition of 0.1 % of hydrogel reduced the content of TPC (4.83 mg/ GAE g D.W) and TFC (4.73 mg/ QE g D.W) in lupine leaves. The marked decrease in TPC and TFC in hydrogel-treated groups during water-deficit conditions suggests a physiochemical buffering effect. Through improving the soil's ability to retain water and sustaining leaf Relative Water Content (RWC), the hydrogel reduces the build-up of ROS, thus avoiding the need for metabolic enhancement of the antioxidant phenylpropanoid pathway [64, 65]. This is contrary to what Soliman et al. [49] told; hydrogel treatments (0.4 and 0.6 %)

increased the contents of phenols in *Calendula officinalis* plants. Besharati et al. [66] showed that hydrogel treatments increased TPC and antioxidant activity in *Hibiscus sabdariffa* plants. Elsayed et al. [23] stated that all concentrations of HPMC-Xanthan gum hydrogel increased TPC and TFC in soybean leaves under drought stress. While, Ramadan et al. [16] indicated that the absence and presence of hydrogel in soil decreased TPC in faba bean plants.

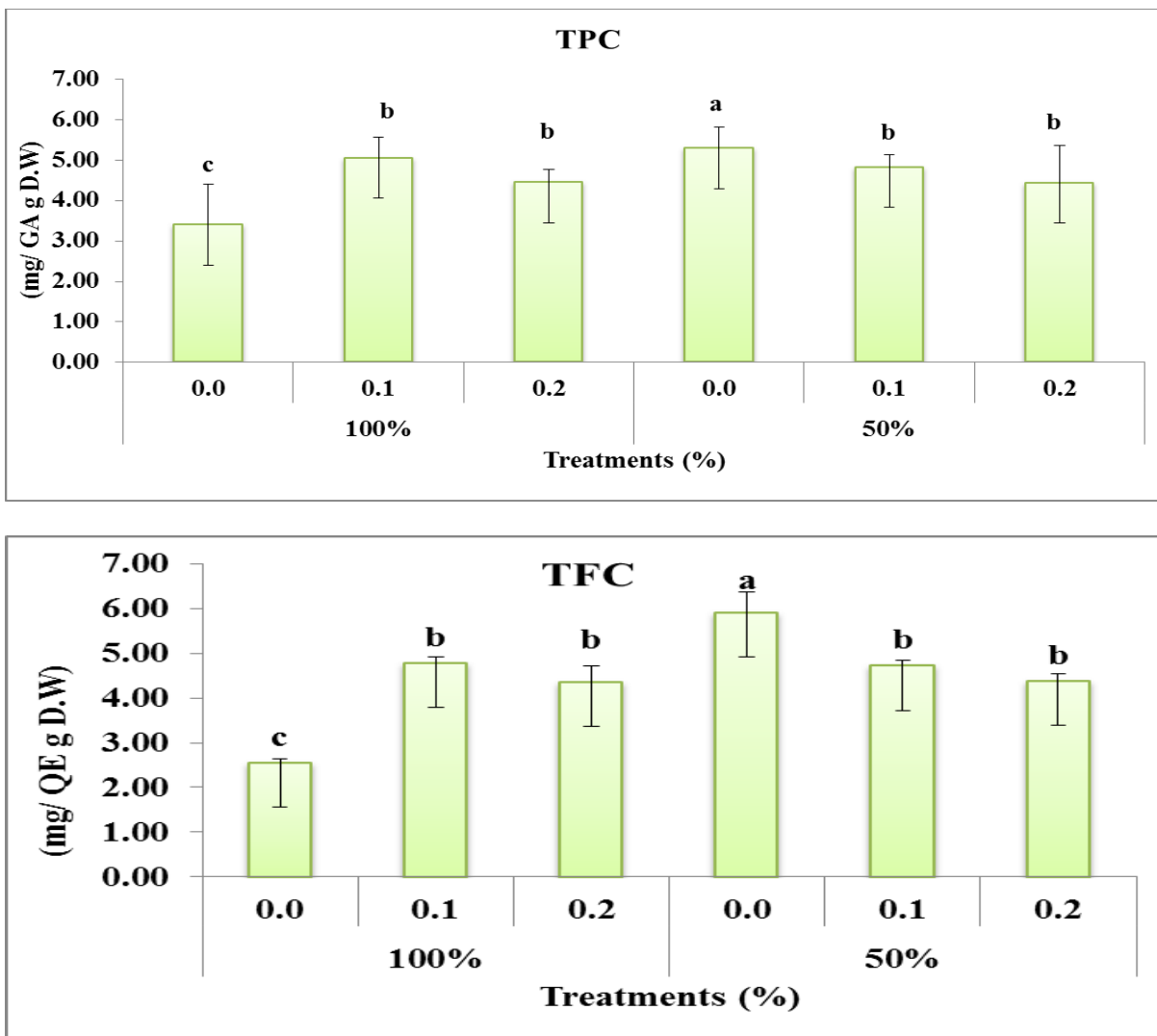


**Figure 9.** Effect of different ratios of soil applied hydrogel, H1, (0, 0.1 and 0.2 %) on TPC and TFC (mg/g D.W) of lupine leaves exposed to drought stress (100 and 50 % FC). Bars indicated standard deviation ( $\pm$ SD). Similar letters indicate non-significant variations at 0.05 level.

## **Lipid peroxidation (MDA) and Hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>)**

The findings showed that applying drought stress (100 and 50 % FC) combined with H1 hydrogel (0, 0.1 and 0.2 %) non-significantly raised ( $P > 0.05$ ) the MDA and H<sub>2</sub>O<sub>2</sub> (μmoles/g F.W) levels in lupine leaves. Effect of water restriction on malondialdehyde (MDA) as a product of lipid peroxidation and H<sub>2</sub>O<sub>2</sub> content as an oxidative marker in lupine plants is represented in **Figure 10**. Drought stress at 50 % FC led to a notable rise in MDA and H<sub>2</sub>O<sub>2</sub> in stressed plants compared to those none stressed. In conditions of water stress, oxidative damage caused by ROS often takes place, leading to membrane lipid peroxidation at both cellular and subcellular levels, which reduces growth, biomass production, and seed yield. The current study noted elevated levels of MDA and H<sub>2</sub>O<sub>2</sub> in lupine plants facing water stress, a finding consistent with other plant species such as wheat [67], mung bean [68], canola [69] and sugar beet [70]. Consequently, the increased levels of lipid peroxidation and H<sub>2</sub>O<sub>2</sub> result from heightened oxidative stress caused by the disruption in enzymatic responses in plants experiencing water stress [70].

Application of hydrogel mitigated this oxidative damage by decreasing MDA and H<sub>2</sub>O<sub>2</sub> levels than the untreated control. At 50 % FC, the application of 0.1 % hydrogel reduced MDA and H<sub>2</sub>O<sub>2</sub> levels to 27.62 and 19.63 μmoles/g FW, respectively compared to the drought-stressed control. The reduction of MDA and H<sub>2</sub>O<sub>2</sub> concentrations in lupine stressed plants treated with hydrogel are due to the beneficial effects of hydrogel in maintaining a favorable hydraulic condition within the rhizosphere of these stressed plants. Consequently, the activities of the antioxidative defense system, specifically APX, SOD, and PPO are believed to play a crucial role in the reduction of H<sub>2</sub>O<sub>2</sub> and MDA levels in water-stressed plants [19]. Our findings indicated that lupine plants treated with NPK hydrogel exhibited production of SOD alongside a corresponding down-regulation of H<sub>2</sub>O<sub>2</sub> and MDA synthesis. The incorporation of hydrogel enhanced the soil's

633 capacity for water retention, thereby mitigating water scarcity and fostering growth [70].  
634 Consequently, in conditions of elevated hyperosmotic concentrations, the addition of hydrogel  
635 would augment the water available to plants in the soil while simultaneously decreasing oxidative  
636 stress at the phyto-physiological levels, resulting in enhanced growth and increased biomass  
637 production [71]. Kenawy et al. [19] reported that using superabsorbent nanocomposites reduced  
638 MDA and H<sub>2</sub>O<sub>2</sub> levels in faba bean plants under water shortage (40 % FC). Elsayed et al. [23]  
639 informed that soil application with HPMC-Xanthan gum hydrogel declined the accumulation of  
640 MDA and H<sub>2</sub>O<sub>2</sub> in soybean plants under different irrigation regimes.

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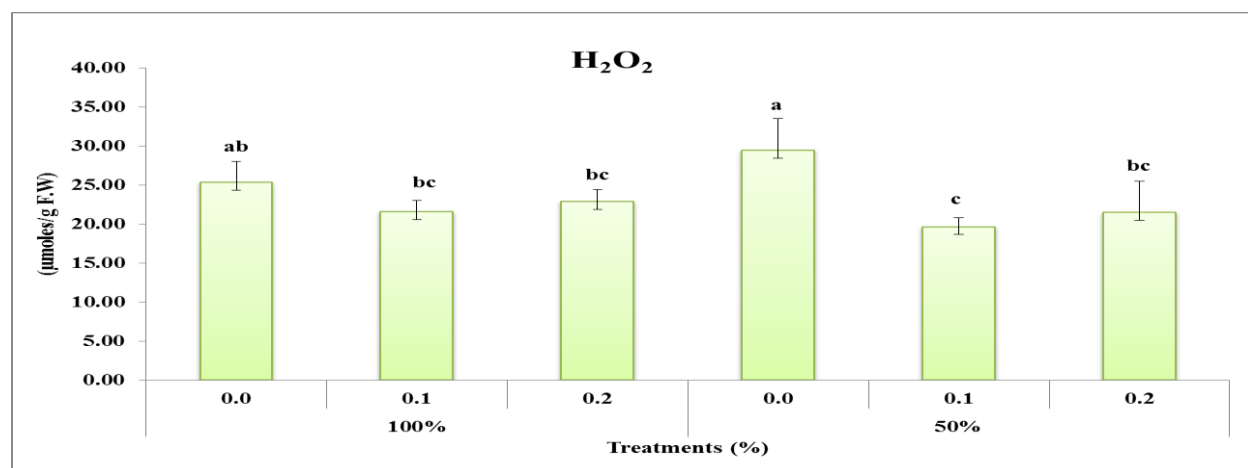
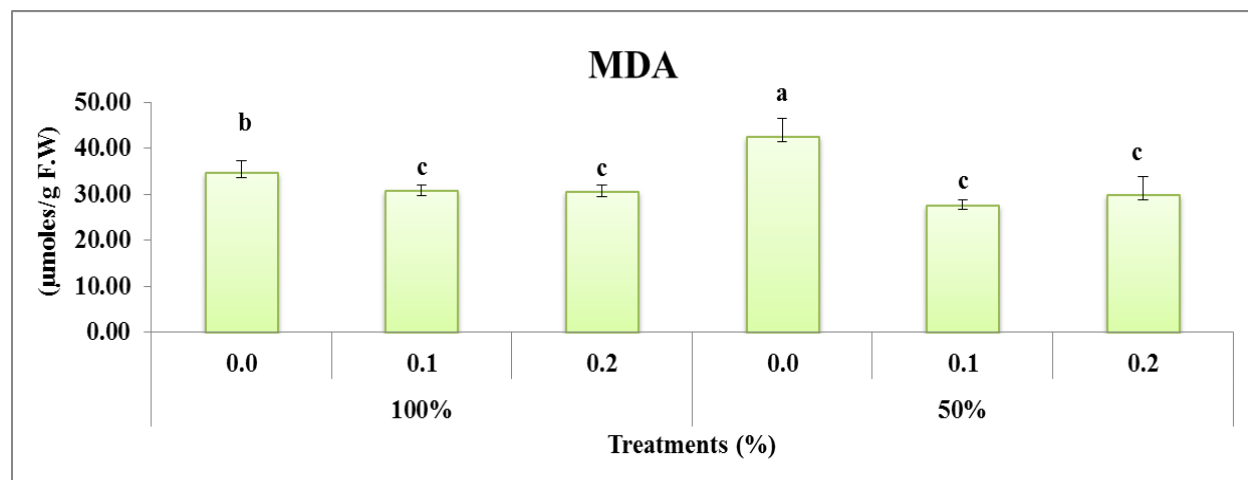


**Figure 10.** Effect of different ratios of soil applied hydrogel, H1, (0, 0.1 and 0.2 %) on MDA (μmoles/g F.W) and H<sub>2</sub>O<sub>2</sub> (μmoles/g F.W) of lupine leaves exposed to drought stress (100 and 50 % FC). Bars indicated standard deviation (±SD). Similar letters indicate non-significant variations at 0.05 level.

### Antioxidant enzyme activities

Impact of soil amendment with H1 hydrogel on the activity of antioxidant enzymes (SOD, CAT, and POX) of drought-stressed (50 %) lupine plants is represented in **Figure 11**. As shown from data, drought stress caused an increase in SOD (72.67 u/mint/g F.W), CAT (90.81 u/mint/g F.W), and POX (70.99 u/mint/g F.W) activities as compared with the non-stressed control.

Antioxidant enzymes are produced to combat oxidative stress in order to protect plants from the harmful effects of abiotic stressors [72]. The increase in SOD activity is essential for the transformation of  $O_2^-$  radicals into  $H_2O_2$  and  $O_2$ , acting as the primary defense mechanism against oxidative harm to cells [73]. Additionally, CAT facilitates the conversion of  $H_2O_2$  into  $H_2O$  and is necessary for plant metabolism and signal reception [74]. Gharache et al. [75] demonstrated the increased activities of SOD that promote the elimination of ROS, thereby providing greater drought resistance to plants. Sadak et al. [76] indicated that the rise in SOD and POX activity is associated with shielding against oxidative damage caused by drought stress in flax cultivars. The heightened activity of CAT demonstrated drought resistance in certain canola varieties [77]. Fiaz et al. [78] validated our findings, demonstrating that drought stress (60 % FC) increased the levels of antioxidant enzymes catalase, peroxidase, and superoxide dismutase by 40, 13, and 30 %, respectively. Alencar et al. [79] discovered that the SOD level rose in cowpea plants under water stress.

Concerning the addition of H1 hydrogel to soil (0.1 and 0.2 %), it decreased the activity of antioxidant enzymes in lupine leaves. Ramadan et al. [16] indicated that hydrogel amendment to sandy soil under drought conditions (50 % FC) positively affected the activities of antioxidant enzymes that enabled faba bean plants to tolerate drought. Soliman et al. [49] found that hydrogel (0.6 % w/w) increased the antioxidant enzyme activity (Catalase, Superoxide dismutase, and Peroxidase) with or without stress. Elsayed et al. [23] found that application of HPMC-Xanthan gum hydrogel decreased antioxidant enzymes (SOD, CAT, and POX) in soybean plants under drought stress. The application of hydrogel reduced oxidative stress, improved crop biomass production under drought conditions, and maintained soil moisture and nutrients while allowing easy access for plants. Moreover, in situations of extreme water shortage, hydrogel significantly

enhanced plant growth, chlorophyll content, photosynthetic effectiveness, and relative water levels. They also improved the functions of antioxidant enzymes, such as SOD and POD [80].

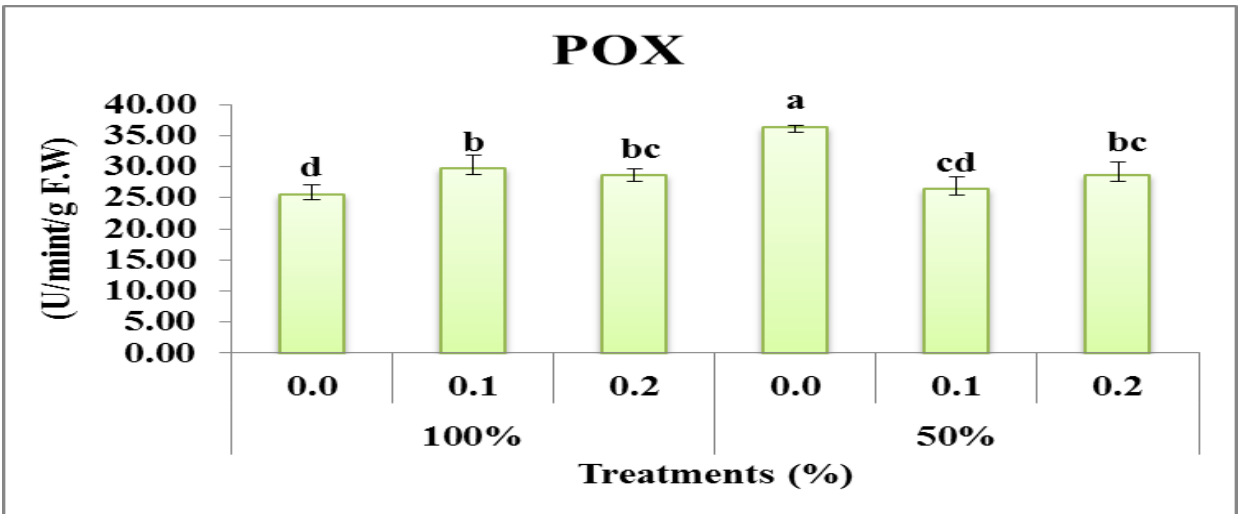
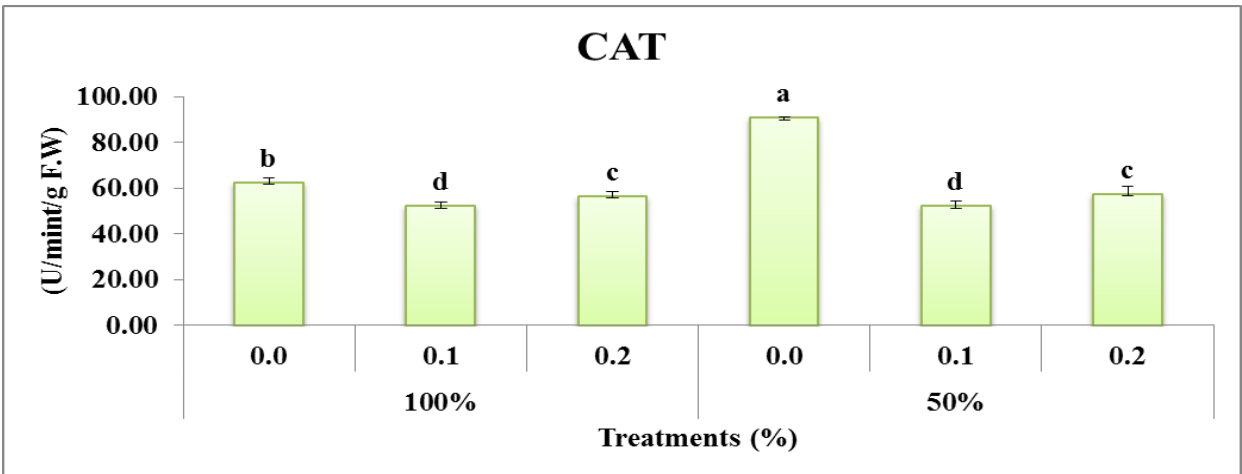
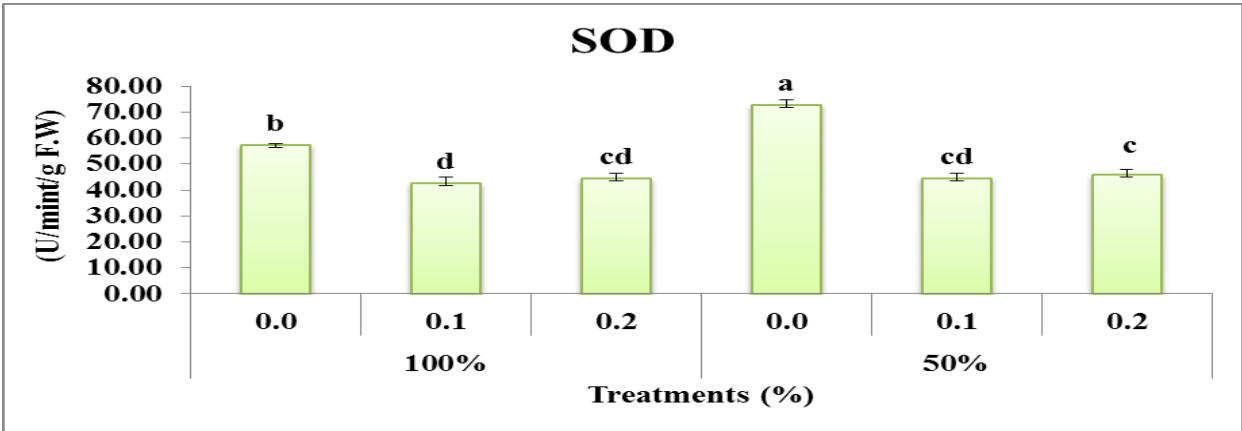


**Figure 11.** Effect of different ratios of soil-applied H1 hydrogel (0, 0.1, and 0.2 %) on antioxidant enzyme activities (SOD, CAT, and POX  $\mu\text{moles/g F.W}$ ) of lupine leaves exposed to drought stress (100 and 50 % FC). Bars indicated standard deviation ( $\pm\text{SD}$ ). Similar letters indicate non-significant variations at the 0.05 level.

## **Conclusion**

This work demonstrates how a biodegradable NPK hydrogel fertilizer derived from sugarcane bagasse can be successfully developed, offering a sustainable alternative to traditional mineral fertilizers. Multifunctional hydrogels with adjustable swelling, biodegradability, and nutrient release characteristics were created by phosphorylating bagasse and then grafting it with acrylamide and acrylic acid. The H2 hydrogel (AM: AA = 1:1) had the maximum water uptake ( $\approx 2900\%$ ) and biodegradability (25% after 4 weeks) among the formulations, demonstrating the complementary roles of carboxyl functionalities and lignocellulosic reinforcement. Significant nitrogen, phosphorus, and potassium enrichment was verified by elemental analysis, guaranteeing agronomic significance. Hydrogel supplementation enhanced growth characteristics, chlorophyll content, and drought tolerance under both full and deficit watering regimes, according to pot studies with lupine plants. This work enhances circular economy methods and offers a scalable route toward environmentally friendly fertilizer solutions by combining regulated nutrient delivery with agricultural waste valorization. The results highlight the potential of waste-based hydrogels to improve fertilizer usage efficiency, lessen environmental effects, and promote sustainable agricultural output by bridging laboratory innovation with field implementation. In order to expedite the use of such biodegradable hydrogel fertilizers in various agricultural systems, future research should concentrate on long-term field experiments, cost-benefit evaluations, and scaling techniques.

706 **Declarations**

707 **Authors' contributions**

708 All authors contributed equally to writing the manuscript. All authors have approved the final  
709 version of the manuscript.

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712 **Ethics approval and consent to participate**

713 Not applicable.

714 **Consent for publication**

715 Not applicable.

716 **Data Availability**

717 All original data supporting the findings of this study are provided within the article.

718 **Competing interests**

719 The authors declare no competing interest.

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