

UNIVERSIDADE FEDERAL DE VIÇOSA

Effect of super-absorbent polymer on irrigated kidney beans under greenhouse conditions

Abdulrahman Ndagi
Magister Scientiae

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Dissertation submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Catariny C. Aleman Pina

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ABSTRACT

NDAGI, Abdulrahman, M.Sc., Universidade Federal de Viçosa, July, 2026. **Effect of super-absorbent polymer on irrigated kidney beans under greenhouse conditions.** Adviser: Catariny Cabral Aleman Pina.

Water scarcity and climate change are placing a serious strain on agricultural stability, particularly for shallow-rooted crops like kidney beans (*Phaseolus vulgaris* L.). This study investigated how different application rates of the commercial SAP hydrogel "HIDROSILO" affect the growth and yield of irrigated kidney beans under greenhouse conditions. Two experimental trials were conducted at the Federal University of Viçosa (UFV) in Brazil. The first experiment lasted for 63 days in Spring 2025 while the second experiment lasted for 57 days in Summer 2026, using a completely randomized design with five replicates. The kidney beans were grown in pots containing 10 kg of soil and treated with six SAP concentrations: 0 g (control), 10 g, 12 g, 14 g, 16 g, and 18 g. Morphological and yield traits were monitored and analyzed using the UFV statistical system. The regression models showed a significant effect on plant height, leaf count, node addition, and stem diameter across both trials ($P < 0.01$ and $P < 0.1$). Moderate doses of the polymer (7–14 g) enhanced structural development and accelerated node emergence. However, higher doses led to growth inhibition due to soil over-saturation, decreased air-filled porosity, and root hypoxia. The total biomass and plant weights followed a parabolic trend. In the second experiment, the model indicated that the optimal dry plant weight was 16.05 g (a 45.3% increase compared to controls) at 7.42 g of SAP. Total dry biomass ranged from 30.67 g to 31.71 g with SAP dosages of 7.5–8.2 g. Interestingly, reproductive metrics peaked at lower SAP rates than those for vegetative growth. The ideal dry seed weight was found to be 4.74 g per plant at 6.96 g of SAP, while dry pod weight stabilized between 7.12 g and 7.54 g. The harvest index (HI) reached its highest point at 0.3461 with 6.31 g of SAP. The greenhouse conditions also played a role in how effective the polymer was. Lower SAP rates worked well during mild, humid periods, while higher rates were necessary in hotter, high-radiation conditions. Superabsorbent polymers are good subsurface hydro-buffers that help maintain cell turgor, enhance gas exchange, and boost resource-use efficiency. Therefore, for optimal bean crop development in the spring, the recommended hydrogel application rate is 7 to 14 grams per plant; for early summer, 7 to 12 grams per plant for pot-grown kidney beans under greenhouse conditions.

Keywords: irrigation management ; water retention; grain; morphological

components.

RESUMO

NDAGI, Abdulrahman, M.Sc., Universidade Federal de Viçosa, julho de 2026. **Efeito do polímero superabsorvente em feijoeiro comum irrigado sob condições de casa de vegetação.** Orientadora: Catariny Cabral Aleman Pina.

A escassez de água e as mudanças climáticas estão colocando uma pressão séria sobre a estabilidade da agricultura, especialmente para culturas de raízes rasas como o feijão-carioca (*Phaseolus vulgaris* L.). Este estudo investigou como diferentes taxas de aplicação do hidrogel comercial SAP "HIDROSILO" afetam o crescimento e o rendimento do feijão-carioca irrigado em condições de ambiente protegido. Dois ensaios experimentais em casa de vegetação foram conduzidos na Universidade Federal de Viçosa (UFV), no Brasil. O primeiro experimento durou 63 dias na primavera de 2025, enquanto o segundo durou 57 dias no verão de 2026, usando um delineamento completamente casualizado com cinco repetições. Os feijões vermelhos foram cultivados em vasos contendo 10 kg de solo e tratados com seis concentrações de SAP: 0 g (controle), 10 g, 12 g, 14 g, 16 g e 18 g. As características morfológicas e de rendimento foram monitoradas e analisadas usando o sistema estatístico da UFV. Os modelos de regressão mostraram um efeito significativo na altura das plantas, número de folhas, adição de nós e diâmetro do caule em ambos os experimentos ($P < 0,01$ e $P < 0,1$). Doses moderadas do polímero (7–14 g) melhoraram o desenvolvimento estrutural e aceleraram o surgimento dos nós. No entanto, doses mais altas levaram à inibição do crescimento devido à saturação excessiva do solo, diminuição da porosidade preenchida com ar e hipóxia nas raízes. A biomassa total e o peso das plantas seguiram uma tendência parabólica. No segundo experimento, o modelo indicou que o peso seco ideal da planta era de 16,05 g (um aumento de 45,3% em comparação aos controles) com 7,42 g de SAP. A biomassa seca total variou de 30,67 g a 31,71 g com doses de SAP entre 7,5 e 8,2 g. Curiosamente, os indicadores reprodutivos atingiram o pico com taxas de SAP menores do que as para o crescimento vegetativo. O peso seco ideal de sementes foi de 4,74 g por planta com 6,96 g de SAP, enquanto o peso seco das vagens variou de 7,12 g a 7,54 g. O índice de colheita (HI) atingiu seu valor mais alto de 0,3461 com 6,31 g de SAP. As condições do viveiro também influenciaram na eficácia do polímero. Taxas mais baixas de SAP funcionaram bem durante períodos amenos e úmidos, enquanto taxas mais altas eram necessárias em condições mais quentes e com alta radiação. Polímeros superabsorventes são bons hidro-amortecedores subterrâneos que ajudam a manter o turgor celular,

melhoram a troca gasosa e aumentam a eficiência no uso de recursos. Portanto, para o desenvolvimento ideal da cultura de feijão na primavera, a taxa recomendada de aplicação de hidrogel é de 7 a 14 gramas por planta; para o início do verão, 7 a 12 gramas por planta para feijão vermelho cultivados em vasos sob condições de ambiente protegido.

Palavras-chave: gestão da irrigação; retenção de água; grãos; componentes morfológicos

LIST OF TABLES

Table 1 - Soil Physical and Chemical Characteristics for Both Experiment.....	17
Table 2 - Characteristics of Superabsorbent Polymer (HIDROSILO)	18
Table 3 - Total Volume (L) of Irrigation Water for the First Experiment.....	20
Table 6 - Water Productivity in g/L for the Second Experiment.....	21
Table 7 - Presentation of the Morphological Parameter Regression Model for the First Experiment	22

SUMMARY

1.	INTRODUCTION.....	11
1.1.	OBJECTIVES.....	12
1.1.1.	General Objective.....	12
1.1.2.	Specific Objectives.....	12
2.	GENERAL OVERVIEW.....	13
3.	MATERIAL AND METHODS.....	16
3.1.	Study Area.....	16
3.2.	Methodology.....	16
3.3.	Morphological and Yield Measurements.....	19
3.4.	Statistical Analysis.....	19
4.	RESULT.....	20
4.1.	Morphological Component.....	21
4.1.1.	Plant Height.....	23
4.1.2.	Number of Leaf.....	23
4.1.3.	Number of Node.....	24
4.1.4.	Plant Diameter.....	24
4.2.	Yield Component.....	25
4.2.1	Number of Pod.....	25
4.2.2.	Fresh Pod Weight.....	27
4.2.3.	Dry Pod Weight.....	28
4.2.4.	Pod Moisture Content.....	29
4.2.5.	Fresh Plant Weight.....	31
4.2.6.	Dry Plant Weight.....	32
4.2.7.	Number of Seeds.....	33
4.2.8.	Dry Seed Weight.....	35
4.2.9.	Harvest Index.....	36
4.2.10.	Total Biomass Yield.....	37
4.2.11.	Water Productivity.....	38
4.3.	Discussion of Results.....	39
5.	CONCLUSION.....	44
	REFERENCES.....	45

1. INTRODUCTION

Global water demand is increasing rapidly, and climate change is intensifying pressure on water resources, resulting in shortages across arid, semi-arid, and other regions. Competition for limited water supplies among urban, industrial, and agricultural sectors accounts for over two-thirds of global freshwater consumption (OLADOSU et al., 2022). The Food and Agriculture Organization of the United Nations (FAO 2016) projects that food production must rise by more than 70% to meet future demand, as the global population is expected to reach 9.1 billion by 2050. Water scarcity has strongly required new strategies for designing efficient irrigation systems in agriculture. The water management cycle could be improved through measures to increase soil moisture retention capacity and water-use efficiency. Consequently, new management techniques are being investigated to stimulate food production and address these challenges.

Kidney beans (*Phaseolus vulgaris* L.) are extensively cultivated and consumed legumes, recognized for their anti-obesity, antioxidant, and cardioprotective properties in humans (WANG et al., 2020). Common varieties include white, black, and red kidney beans. The protein isolate from kidney beans, comprising approximately 22 to 27% of the seed weight, possesses a favorable amino acid profile and aligns with the FAO-recommended protein pattern (YAN et al., 2023).

Kidney bean production, a vital global source of plant-based protein, faces growing threats from rising temperatures and unpredictable rainfall patterns (DAVE et al., 2024; MLADENOV et al., 2023). As kidney beans are predominantly cultivated under rain-fed conditions by smallholder farmers, their yield stability is highly susceptible to climatic variability, which disrupts metabolic processes and traditional cropping schedules (AKINYEMI, 2017).

Beans are an important food in Brazilians culture, and they represent a mandatory component of the population's diet. It is a very widespread crop throughout the national territory, known as a subsistence crop for small producers. However, it has been gaining ground in recent years among producers of other social classes who use new agricultural technologies. (GANASCINI et al, 2019)

Different physiological changes have been observed under moisture-stress conditions, like reduction in water potential and morphological rate, and thus declined yield and quality of the plant by restricting overall plant growth. Moisture stress conditions also lead to the formation of reactive oxygen species (ROS) which cause cellular damage under drought conditions, prompting increased antioxidant production as a defense mechanism. Antioxidants

enable organisms to mitigate oxidative stress resulting from free-radical damage. (PATRA et al, 2022)

The recent advancements in modern microirrigation technologies, such as low-pressure micro-sprinklers and drip irrigation systems, along with optimal irrigation scheduling in addition to plastic mulching, can solve these problems by drastically reducing the consumption of irrigation water consumption and improving water-use efficiency. Therefore, these high-tech systems are explicitly employed in high-value crops and require a sufficiently large capital investment, recurring operational expenditure, and farmers' expertise skills of the farmers (KEIVANFAR et al.,2019). However, the solution to these issues is to explore alternative irrigation technologies that use highly swellable polymer materials to overcome soil moisture stress and increase production. Superabsorbent polymer increases the efficiency of rainfall (or irrigation water) use by reducing water losses and, consequently, decreasing irrigation requirements of the crop.

Super Absorbent Polymers (SAPs) possess hydrophilic functional groups (-OH, -SO₃H, -NH₂) that enable their cross-linked macro- and micro-molecular networks to interact with soil pores. These substances can absorb substantial quantities of liquid and retain it for prolonged periods, (OLADOSU et al., 2022).

Therefore, their impact on soil moisture content and water retention will differ significantly. Moreover, soil composition and amount, the amount of clay in various soil textures, and plant type are also effective in evaluating the efficiency of SAP polymers, (YU et al., 2017). One of the main uses of SAHs in agriculture is as carriers for slow-release fertilizers (SRFs). Once fertilizers are mixed into the hydrogel matrix, they can gradually be released, giving plants a steady supply of nutrients. This controlled-release fertilizer hydrogel (SRFH) not only prevents fertilizer from leaching and running off but also cuts down on how often you need to fertilize, all while boosting plant growth.

1.1 OBJECTIVES

1.1.1. General Objective

To determine the morphology and yield of beans using different levels of superabsorbent polymer under greenhouse conditions.

1.1.2 Specific Objectives.

To assess the impact of SAP on the morphological attributes of beans.

To determine the impact of SAP on bean yield components, such as pod number, seed weight, and total biomass.

2. GENERAL OVERVIEW

Irregular rainfall and climate change pose serious threats to global food security, particularly by disrupting legume production, such as kidney beans (*Phaseolus vulgaris* L.). The challenges of bean cultivation are on the rise, primarily due to water scarcity, which is a major issue given the plant's shallow root system, making it particularly vulnerable to drought.

According to (PONCE et al. 2024), water shortages hinder essential physiological processes in these crops, leading to significant yield losses. Legumes are known for their yield variability, largely because they are highly sensitive to weather conditions, especially soil moisture, as noted by (MALIK et al. 2022). The ongoing water scarcity underscores the urgent need for innovative strategies to create more efficient irrigation systems in agriculture. Enhancing soil moisture retention and improving water-use efficiency could greatly benefit the water management cycle, as suggested by SATRIANI et al. (2018).

Climate change exacerbates these issues by increasing the frequency of droughts and creating unpredictable rainfall patterns. For kidney beans, water shortages during critical growth stages such as germination, vegetative growth, flowering, and pod formation—can lead to significant drops in productivity (ALOTAIBI et al., 2024). The reproductive phase is especially delicate; when daytime temperatures exceed 30°C or nighttime temperatures go above 20°C, it can lead to serious yield losses due to flower abortion, reduced pollen viability, and impaired seed filling. In extreme heat conditions, reductions in grain yield can surpass 80% (VARGAS et al., 2021).

Moreover, climate change is expected to push average temperatures beyond the optimal levels for legume cultivation by 2050, which could result in bean yields dropping by 10% to 49% if no adaptation measures are taken. The specific temperature thresholds for various legumes are as follows: chickpea 15 to 30 °C, common bean 20 to 24 °C, cowpea 18 to 28 °C, faba bean 25 °C, groundnut 30 to 35 °C, lentil 15 to 30 °C, lupins 20 to 30 °C, mung bean 28 to 35 °C, pea 15 to 25 °C, pigeon pea 18 to 30 °C, soybean 23 to 26 °C, and urd bean 25 to 35 °C (DAVE et al., 2024).

Three-dimensional cross-linked hydrophilic polymer networks are great at soaking up water and holding onto it, but they do lose moisture over time. Think of hydrogels as tiny water reservoirs that change in size based on physical and chemical triggers influenced by their surroundings (AHMED, 2015).

Superabsorbent polymers (SAPs) are designed to soak up and keep water from irrigation or rainfall in farming areas, which helps cut down on water loss from drainage and

evaporation. When the soil starts to dry out, SAPs slowly release the water they've stored through diffusion, helping to maintain soil moisture for longer periods. Adding SAPs to the soil not only boosts its volume but also enhances porosity and improves the oxygen supply to plant roots (OLADOSU et al., 2022).

When plants face drought stress or limited water, they experience oxidative stress and increased lipid peroxidation, leading to stunted growth, smaller leaves, and damaged leaf structures, as noted by ESSAWY et al. (2016). A new hydrogel polymer called CTS, made from chitosan, enhances the soil's ability to hold water and helps with nutrient release. SAPs also retain essential nutrients for plants and release them gradually, which ultimately supports better crop growth (ZHENG et al., 2023).

According to (YU et al. 2017), superabsorbent hydrogels have a significant impact on various soil characteristics, including permeability, density, structure, texture, evaporation, and water infiltration rates. These hydrogels help reduce how often irrigation is needed and minimize soil compaction, while also preventing erosion and water runoff. They enhance soil aeration and support microbial activity. Additionally, they act as slow-release systems, holding onto certain nutrients and gradually releasing them, which allows plants to access fertilizers over a longer period, ultimately boosting their growth and performance, as noted by (ABD EL-REHIM et al. 2004).

In a study analyzing five different hydrogel polymers, it was found that adding these materials increases soil water retention and decreases evaporation, especially in those with larger particle sizes. (SATRIANI et al. 2018) investigated the use of cellulose hydrogel polymers in bean cultivation under drought conditions in southern Italy, testing the polymer at 0, 5, and 10 grams mixed into the soil. Their findings revealed a significant increase in the water use efficiency (WUE) index with the polymer compared to the control group.

(SITU et al. 2023) explored how different doses of three superabsorbent polymers affected the growth of soybean and corn, as well as root development and nutrient uptake. They discovered that while plant roots could absorb water directly from the hydrogels, the overall effect of superabsorbents on moisture-related growth factors was minimal under non-drought conditions, in which soil water potential remained constant. However, applying a small amount of superabsorbent (0.2 wt%) enhanced soil physical properties by increasing porosity due to the swelling of the hydrogel after absorbing water. Although the general trend for superabsorbents was positive, the extent of improvement varied among different crops, likely influenced by their specific water needs and the functionality of the superabsorbent

polymers. The vegetable group showed the most significant yield increase, while the tuber group demonstrated the greatest improvement in water-use efficiency (WUE).

There is a need for more research on how much water-use efficiency (WUE) can actually be improved in beans when grown under various conditions. Several studies have examined the effects of superabsorbent polymers (SAPs) on plant yield. It's also worth mentioning that these hydrophilic polymers have different water-absorption and storage abilities, which can vary depending on how they are made and their chemical makeup.

In the world of legume farming, SAPs play a crucial role as soil conditioners, helping to counteract the challenges posed by unpredictable rainfall and drought. When mixed into the soil, they function like tiny reservoirs, soaking up excess water and gradually releasing it to the roots of kidney bean plants through osmotic pressure differences (SATRIANI et al., 2018; MALIK et al., 2022). This steady supply of moisture is vital for essential physiological processes like photosynthesis and helps keep cellular metabolism stable during those dry spells (ALOTAIBI et al., 2024).

Hydrogels have improved soil water-holding capacity (WHC) which has resulted in a delayed permanent wilting point under intense evaporation. It also absorbs and retainsswater at 171–402%, mass per mass (m/m), 80–180 times, m/m , and 67–376 times, m/m under laboratory conditions. Therefore, the water runoff losses were reduced whereas infiltration rates were enhanced; thus, the improved soil moisture retention enhanced crop biomass yield under rainfed conditions (RAJANNA et al, 2021).

Hydrogel improved the hydro-physical and chemical conditions of soil through an increase in water-stable soil aggregates and retention pores, decreasing transmission pores, and lowering soil penetration resistance, leading to hydrogel effects. Besides the sustained release of water, hydrogels have also been reported to influence nutrient-use efficiency (NUE) by trapping nutrients in the swollen mass and reducing their losses. The performance of hydrogels depends on the soil and crop types (NARJARY et al, 2014).

As reported by (ZHENG et al, 2023) SAP showed significant positive effects on yield and water productivity for different crops, indicating the wide applicability of SAP. However, the positive effects of SAP vary with the crop type, perhaps as a result of different water demand patterns and the functional characteristics of SAP used.

3. MATERIAL AND METHODS

3.1. Study Area

The experiment was conducted in the Irrigation Experimental Greenhouse of the Agricultural Engineering Department at the Federal University of Viçosa, Brazil (20° 45' 35" S; 42° 52' 28" W).

3.2. Methodology

Soil was collected from the irrigation experimental area. Physical properties were analyzed in the Hydraulic Laboratory of Agricultural Engineering, and chemical properties were analyzed in the Soil Science Laboratory, both at UFV, as shown in Tables 1, respectively. Also, soil field capacity was determined in a pot for each treatment as describe by (MATEMA 2019), which was used for irrigation management. Also, soil analyses were conducted for both untreated soil and soil treated with super-absorbent polymer (HIDROSILO) at 0% (control), 0.1%, 0.12%, 0.14%, 0.16%, and 0.18% by soil weight after the harvest and the analytical results are presented in Table 3 and 4 below.

Table 1. Soil Physical and Chemical Characteristics for Both Experiment.

Characteristics	Value for 1° Exp	Value for 2° Exp.
pH _{H2O}	5.62	5.48
P (mg/dm ³)	2.2	7
K (mg/dm ³)	14	41
Ca ²⁺ (cmol _c /dm ³)	1.09	1.74
Mg ²⁺ (cmol _c /dm ³)	0.44	0.55
H+Al	1.57	3.4
SB	----	2.4
T (cmol _c /dm ³)	3.97	5.8
V %	39.5	41.4
Mo dag/kg	1.22	1.87
P-Rem (mg/l)	16.5	25.3
Cu (mg/dm ³)	2.59	3.92
Mn (mg/dm ³)	19.6	72.7
Fe (mg/dm ³)	37.3	108.8
Zn (mg/dm ³)	1.97	5.09
FC %	28.87	29.64
PWP %	21.36	21.45

FC = Soil Feed Capacity in % , PWP = Permanent Wilting Point of the soil in %

The experiment followed a completely randomized design (CRD) with five replicates per treatment in a greenhouse measuring 7.3 m by 8.0 m. Each pot served as a replicate, with the appropriate amount of commercial superabsorbent polymer (HIDROSILO) added to the soil, except for the control pot. A precisely weighed quantity of commercial super-absorbent polymer (HIDROSILO) was measured to 0.1 g accuracy for each measured gram; that is, 250 ml of water per gram of HIDROSILO mixed with soil at room temperature. The mixture was allowed to reach maximum swelling within 30 minutes. The mixture of superabsorbent polymer (HIDROSILO) with water was incorporated into 10 kg of dry soil in a pot. The characteristics of the commercial HIDROSILO are presented in Table 2 below, in accordance with the manufacturer's specifications. Three bean seeds were hand-sown in each pot

containing a mixture of super-absorbent polymer hydrogel and 10 kg of soil on October 17, 2025 (spring), and January 15, 2026 (summer). After sowing, the soil was irrigated to the field capacity specified for each treatment. Three days after emergence, bean seedlings were thinned to one plant per pot. At the vegetative stage, NPK fertilizer was applied based on the soil properties according to (FOA 2006).

Table 2. Characteristics of Superabsorbent Polymer (HIDROSILO)

Variable	Specification
Absorption (g H ₂ O/g SAP)	200 - 400
Absorption Time (min)	30
Soil Toxicity	None under normal conditions of use
Dry Product Shelf Life	5 years
UV Stability	High resistance to UV rays
Average Product Stability in Soil (years)	3 - 5 years
Acrylamide Residual (ppm)	< 10
Acrylicacid Acid Residual (ppm)	<10
Potassium Concentration (%)	25
Nitrogen (%)	10
Specific Density (g/cm ³)	1.1
Appearance	Yellowish to orange granular

3.4. Morphological and Yield Measurements

Morphological and yield parameters were recorded for all treatments, including the control plant. The observations included plant height, stem diameter, the number of nodes per plant, the number of leaves per plant, and the number of pods per plant, bioyield, and harvest index. The harvest index was calculated as the ratio of seed yield to total biological yield. The plant height was measured with measuring tape in centimeter while the stem diameter was measured with digital caliper millimeter. All morphological parameters were evaluated weekly. Meanwhile, the yield parameter was evaluated during the harvest through wet weight and dry weight after oven drying.

3.5. Statistical Analysis

The collected data were analyzed using a completely randomized design (CRD) with five replicates per treatment. Regression analysis was conducted using the UFV System Software to evaluate the effects of super-absorbent polymer levels on kidney bean morphological and yield parameters. When significant differences were observed, Tukey's Honestly Significant Difference (HSD) test (HERVE et al., 2010) was applied to separate means at the 10%, 5%, and 1% significance levels.

4. RESULT

Tables 3 and 4 present the total irrigation depth in litres per plant for the first and second experiments. This was based on the soil feed capacity in the pot for each treatment, while Tables 5 and 6 present the water productivity for both experiments.

Table 3. Total Volume (L) of Irrigation Water for the First Experiment

Hydrogel (g)	0	10	12	14	16	18
Rep1	10.79	10.21	10.89	10.03	10.59	10.93
Rep2	10.32	8.99	10.16	9.66	10.60	10.75
Rep3	9.60	9.42	9.18	8.82	10.93	9.06
Rep4	9.32	7.92	9.54	9.25	9.13	8.17
Rep5	8.90	9.41	8.79	8.84	6.47	5.99
Average Volume (L)	9.78	9.19	9.71	9.32	9.54	8.98

Rep1-Rep5 = number of replications

Table 4. Total Volume (L) of Irrigation Water for the Second Experiment

Hydrogel (g)	0	10	12	14	16	18
Rep1	7.86	10.01	10.03	9.09	8.69	0.00
Rep2	9.93	9.58	9.84	11.28	9.36	0.00
Rep3	10.37	10.57	10.83	8.25	7.19	8.11
Rep4	7.81	10.41	9.48	8.59	8.72	0.00
Rep5	9.13	8.04	9.08	7.70	6.72	0.00
Average Volume (L)	9.02	9.72	9.85	8.98	8.14	8.11

Rep1-Rep5 = number of replications

Table 5. Water Productivity in g/L for the First Experiment

Hydrogel (g)	0	10	12	14	16	18
Rep1	0.54	0.33	0.57	0.34	0.72	0.58
Rep2	0.49	0.33	0.51	0.78	0.67	0.50
Rep3	0.41	0.53	0.60	0.58	0.68	0.20
Rep4	0.57	0.27	0.66	0.20	0.57	0.15
Rep5	0.45	0.79	0.82	0.33	0.00	0.00
Average(g/L)	0.49	0.45	0.63	0.44	0.53	0.35

Rep1-Rep5 = number of replications

Table 6. Water Productivity in g/L for the Second Experiment

Hydrogel (g)	0	10	12	14	16	18
Rep1	0.00	0.42	0.63	0.36	0.51	0.00
Rep2	0.52	0.00	0.62	0.61	0.65	0.00
Rep3	0.68	0.59	0.32	0.00	0.17	0.35
Rep4	0.37	0.50	0.52	0.69	0.67	0.00
Rep5	0.27	0.18	0.33	0.10	0.00	0.00
Average Depth (g/L)	0.37	0.34	0.48	0.35	0.40	0.35

Rep1-Rep5 = number of replications

4.1 Morphological Component

Tables 7, and 8 present the model regression analysis for both experiments, detailing the morphological parameters. All morphological parameters increased generally linearly over time. In relation to hydrogel dosage, each parameter increased at lower concentrations but decreased at higher concentrations. Regression analysis of the morphological parameters showed statistical significance at the 1% level for the first experiment and at both the 1% and 10% levels for the second experiment. For yield measurements, no statistically significant results were observed at the 1% and 5 % levels in the first experiment for all measured yield traits. In the second experiment, fresh pod weight, dry pod weight, and number of seeds were significant at the 10% level, while fresh plant weight, dry plant weight, plant moisture content, dry seed weight, and biomass yield were significant at the 5% and 10% levels.

Table 7. Presentation of the Morphological Parameter Regression Model for the First Experiment

Variable	Regression Model Equation $\hat{Y}_i$	R ²	Adj R ²
Height (cm)	$\hat{Y}_i = -2.1318 + 118.921^{**}\text{Dose} - 721.71^{**}(\text{Dose})^2 + 0.69915^{**}\text{Day}$	0.8771	0.8674
Number of Leave	$\hat{Y}_i = -7.4704 + 122.319^{**}\text{Dose} - 649.873^{**}(\text{Dose})^2 + 0.4125^{*}\text{Day} + 0.00609^{*}(\text{Day})^2$	0.8852	0.8728
Number of Node	$\hat{Y}_i = -3.1029 + 54.222^{**}\text{Dose} - 288.95^{**}(\text{Dose})^2 + 0.248040^{**}\text{Day}$	0.8930	0.8846
Diameter (cm)	$\hat{Y}_i = 0.647 + 1.5433^{**}\text{Dose} - 10.7242^{**}(\text{Dose})^2 + 0.010756^{**}\text{Day} + 0.0002039^{**}(\text{Day})^2$	0.7064	0.6748

Sig. At 1% (**) and 10% (*) Probability Test.

Table 8. Presentation of the Morphological Parameter Regression Model for Second Experiment

Variable	Regression Model Equation $\hat{Y}_i$	R ²	Adj R ²
Height (cm)	$\hat{Y}_i = -4.0517 + 307.641^{**}\text{Dose} - 2220.79^{**}(\text{Dose})^2 + 1.00461^{**}\text{Day}$	0.7753	0.7543
Number of Leave	$\hat{Y}_i = -10.1527 + 300.416^{**}\text{Dose} - 1898.29^{**}\text{Dose}^2 + 0.8297^{**}\text{Day}$	0.8344	0.8189
Number of Node	$\hat{Y}_i = -1.9612 + 111.35^{**}\text{Dose} - 717.239^{**}(\text{Dose})^2 + 0.25904^{**}\text{Day}$	0.8292	0.8133
Diameter (cm)	$\hat{Y}_i = 0.230838 + 4.9581^{**}\text{Dose} - 33.584^{**}(\text{Dose})^2 + 0.0058118^{**}\text{Day}$	0.6055	0.5686

** Sig. At 1% Probability Test.

4.1.1 Plant Height

The regression analytical results showed that hydrogel applications had a significant impact on plant height at the 1% confidence level in both experiments, as illustrated in Tables 9 and 10. However, the sensitivity to changes and the ideal dosage levels varied between the two.

Both experiments were well represented by second-order polynomial (quadratic) regressions (Table 7 and 8). In the first experiment, the quadratic model had a coefficient of determination ($R^2 = 0.8771$), meaning that about 88% of the variation in bean height is attributed to SAP dosage and the duration of the experiment, with a strong model fit of 0.8674. The second experiment had a slightly lower R^2 value of 0.7753, but it still showed a strong fit (0.7543), explaining 77.53% of the variance in plant height. Interestingly, the primary linear coefficient for dosage was higher in the second experiment (307.641) compared to the first (118.921), indicating that the plants in the second trial were more responsive to initial increases in hydrogel dosage and showed a quicker growth rate in height during the early stages. Both experiments revealed a parabolic relationship between hydrogel dosage and plant height, supported by negative quadratic coefficients for dosage (-721.71 in the first experiment and -2220.79 in the second). These results suggest that there is an optimal dosage threshold of 8.24 g for the first experiment and 6.97 g for the second; beyond these points, adding more hydrogel actually leads to a decrease in plant height.

4.1.2. Number of Leaf

In the first experiment, the relationship between hydrogel dosage and time was non-linear, with a coefficient of variation of ($R^2 = 0.8852$) that is 88.52 % variation is attributed to SAP dosage and time duration of the experiment and also a strong fitness model of 0.8728 for the quadratic model as shown in Table 7 and 8. On the other hand, the second experiment showed a non-linear relationship for hydrogel dosage but a linear one for time, with a slightly lower coefficient of variation ($R^2 = 0.8344$) and a closed fitness model of 0.8189 respectively. Interestingly, both models produced negative quadratic coefficients for dosage (-649.873 and -1898.29), indicating that too much hydrogel can actually hinder vegetative growth. The optimal hydrogel dosages for the first experiment were 9.41 g and 7.91 g for the second. In both scenarios, using a moderate amount of hydrogel led to a higher leaf count than using none (control) and to a higher hydrogel concentration which led to a lower leaf count.

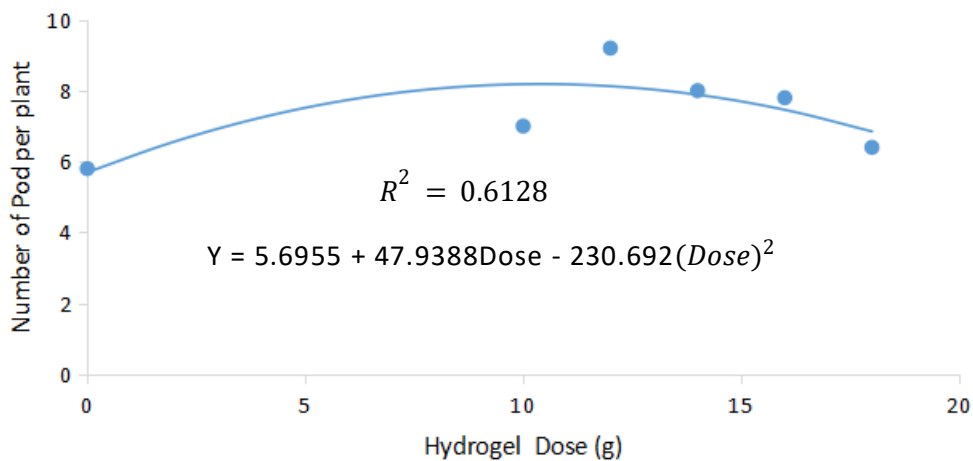
4.1.3. Number of Node

The number of nodes is an important morphological indicator in bean plants (*Phaseolus vulgaris* L.), acting as vital attachment points for leaves, lateral branches, and future flowers. In Table 7 and 8 above, both experiments were analyzed using second-order polynomial (quadratic) regressions, and the first experiment showed stronger predictive power ($R^2 = 0.8930$) compared to the second ($R^2 = 0.8292$). This variation is likely attributed to slightly lower temperatures and higher relative humidity, especially during the early phases of the second experiment. Meanwhile, the two model equations reveal a strong model fitness at 0.8846 and 0.8133 for both first and second experiment respectively. The optimum hydrogel dosages were found to be 9.38 g for the first experiment and 7.76 g for the second. Even though there were minor differences in how well the models fit, both trials displayed a consistent parabolic trend. Proper hydrogel dosages enhanced rhizosphere hydro-buffering, while too much application led to root hypoxia.

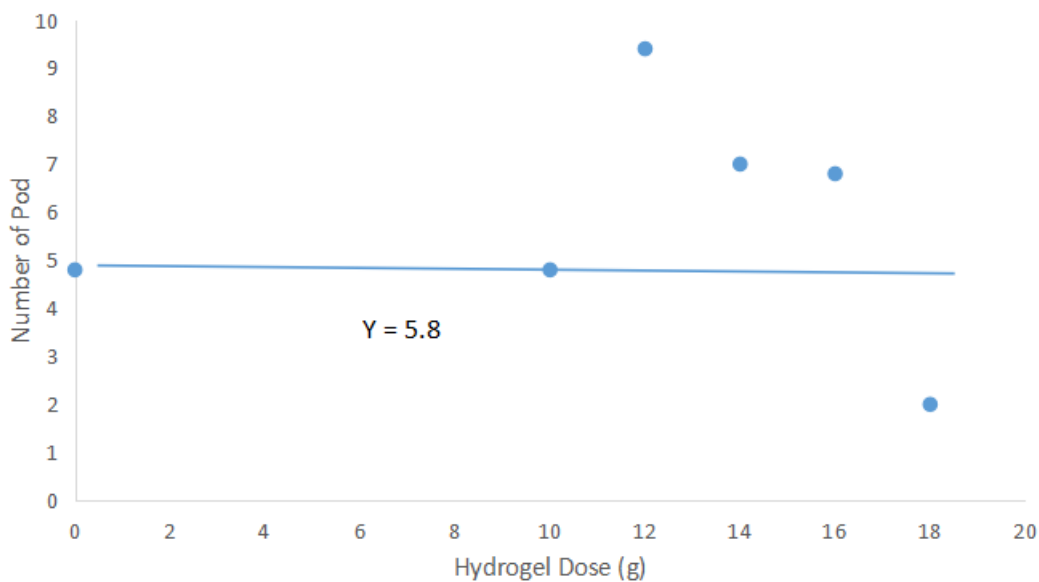
4.1.4. Plant Diameter

The regression analysis shown in Table 7 and 8, that the first experiment produced an R^2 value of 0.7064, meaning that about 70.64% of the variance can be explained by the model. On the other hand, the second trial had a lower coefficient of variation R^2 of 0.6055 (60.55%). Meanwhile, the fitness models for both experiments are 0.6748 and 0.5686 and these indicate that the diameter had a good model fit in the regression analysis. Both models were statistically significant across the two trials at ($p \leq 0.01$), with the optimum hydrogel dosages being 7.20 g for the first experiment and 7.38 g for the second. Interestingly, the negative quadratic term in the model suggests that as the hydrogel concentration increases beyond the optimal level, the plant diameter tends to decrease. The regression model also suggests that, in the first experiment, the optimal diameter was achieved at 26 days, while, in the second experiment, the diameter increased steadily by 0.0058 cm each day.

4.2. Yield Component



(a)



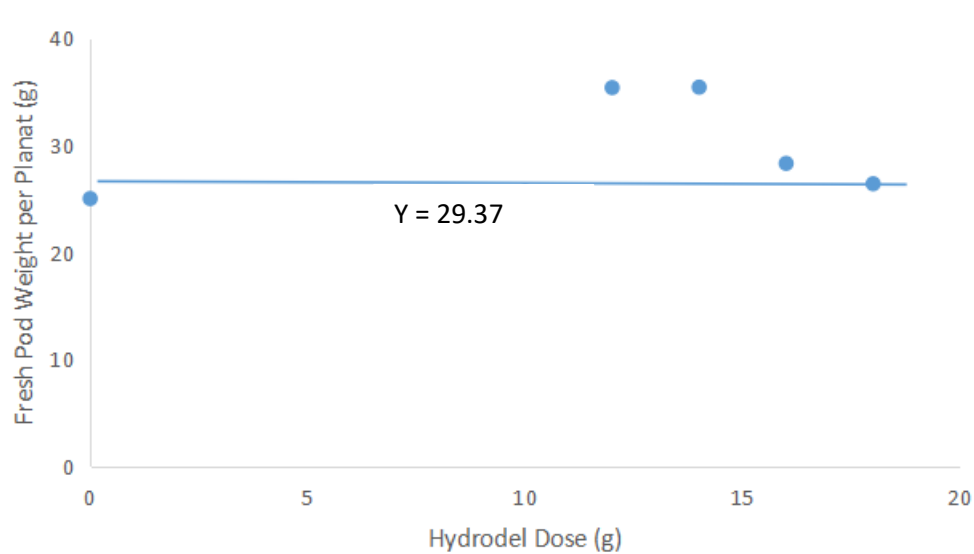
(b)

Fig. 4.5. Effect Hydrogel on the Number of Pod

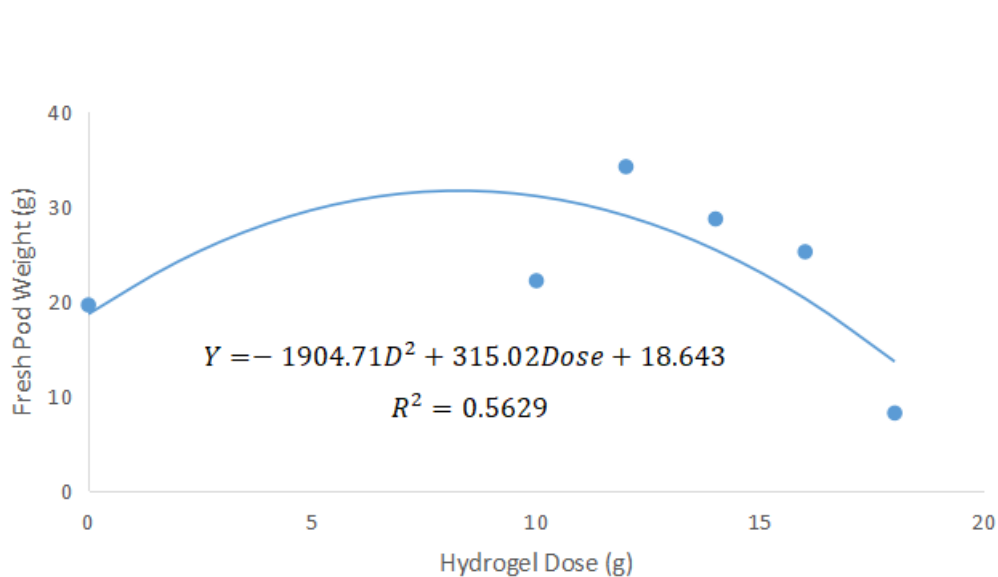
4.2.1. Number of Pod

The reproductive performance of kidney beans (*Phaseolus vulgaris* L.) "Evaluated by the number of pods, showed a notable quadratic response to the application of super-absorbent

polymer (hydrogel) in the first experiment. As illustrated in Fig. 4.5 (a), the R^2 value of 0.6128 suggests a 61% fit for the model, with an optimal yield of 8.0 pods per plant reached at a hydrogel dosage of 10.4 g. In the second experiment, the number of pods remained steady at an average of 5.8 pods per plant, with no significant quadratic or linear regression detected across the various polymer rates. However, the regression curves in Fig. 4.5 (b) reveal that the peak pod number was found between hydrogel dosages of 12 g and 14 g, aligning with the findings reported by LOPES et al. (2017).



(a)

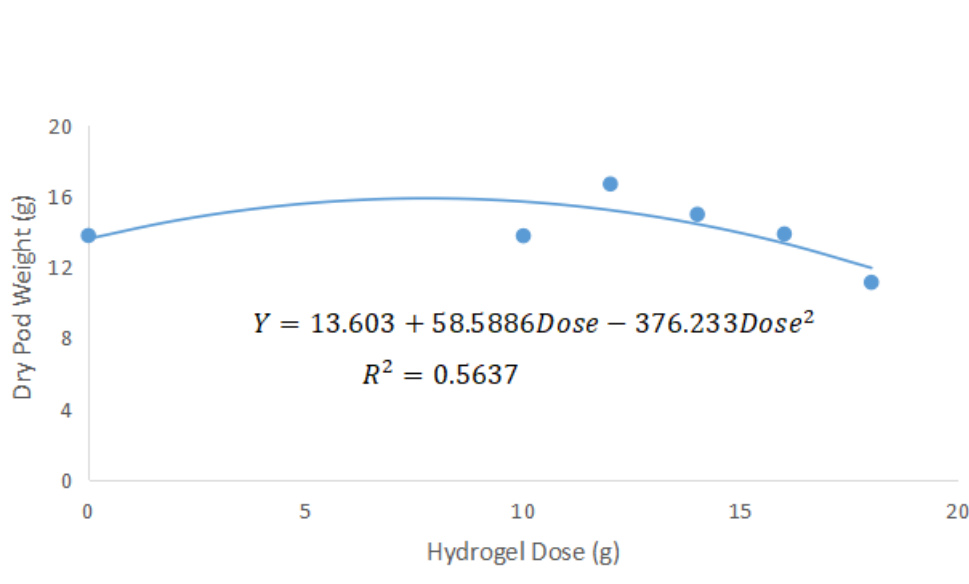


(b)

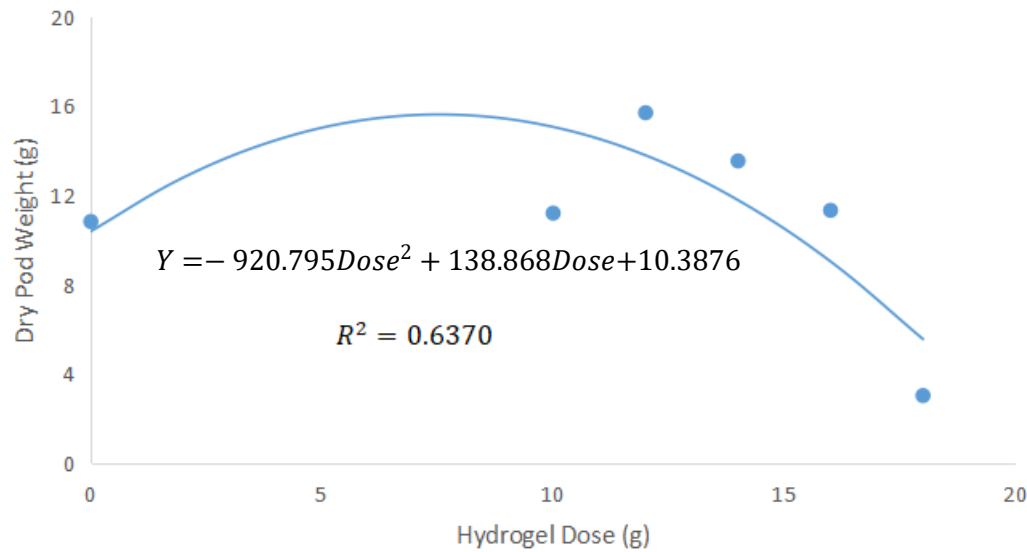
Fig. 4.6. Effect of Hydrogel on Fresh Pod Weight

4.2.2 Fresh Pod Weight

In the first experiment, regression analysis revealed a constant mean fresh pod weight of 29.58 g. The highest fresh pod weight recorded was 37.9 g per plant, achieved with a hydrogel dosage of 14 g, as shown in Fig. 4.6 (a). On the other hand, the second experiment shows a clear quadratic response, illustrated in Fig. 4.6 (b), with a coefficient of determination (R^2) of 0.5629 (56.29%). The optimal fresh pod weight reached 31.67 g per plant at a hydrogel dosage of 7.54 g, as depicted in Fig. 4.6 (b). Fresh pod weight serves as a key indicator of both structural tissue buildup and temporary water storage in the plant. The quadratic peak observed in the second experiment suggests that a particular hydrogel dosage fosters ideal root conditions. This optimal range helps maintain a high xylem water potential during pod elongation while also preventing the soil from becoming over-saturated.



(a)

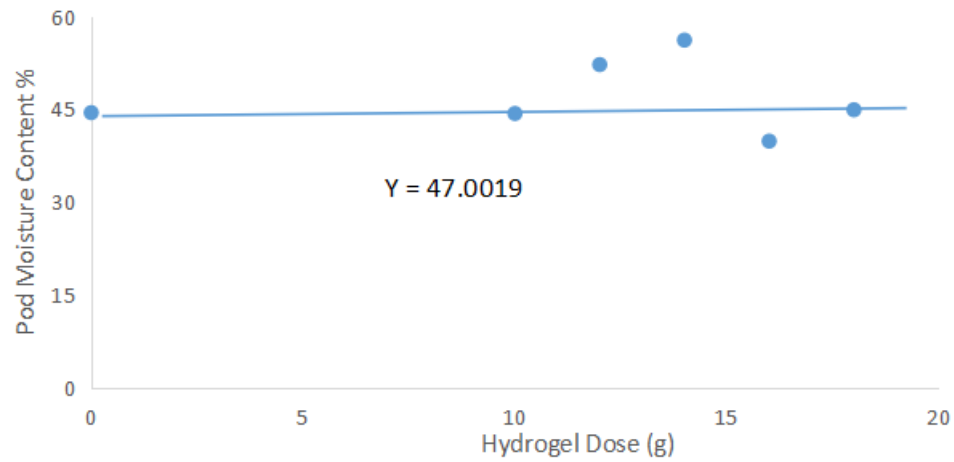


(b)

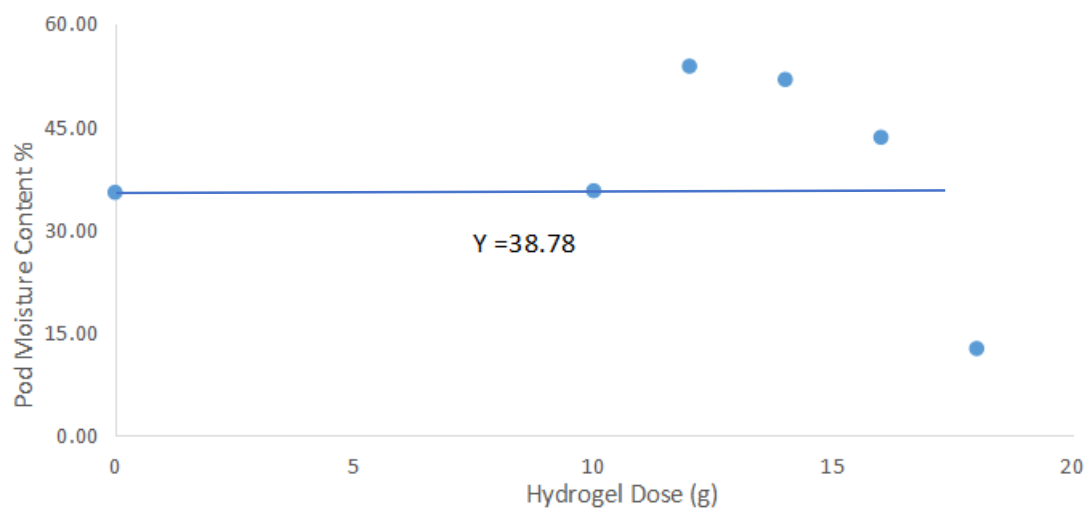
Fig. 4.7. Effect of Hydrogel on Dry Pod Weight

4.2.3. Dry Pod Weight

The first experimental trial shows a clear quadratic model equation that captures the relationship between dry pod weight, as shown in Fig. 4.7(a). With an R^2 value of 0.5637 (56.37%), it indicates a significant impact of hydrogel dosage on dry pod weight. The model predicts an optimal yield of 15.88 g at a hydrogel dosage of 7.12 g. In the second trial, the quadratic fit improved even more, boasting an R^2 value of 0.6370 (63.70%), which points to a very responsive yield curve (see Fig. 4.7(b)). The increased variation and better fit in this second experiment really emphasize how beans respond phenotypically when hydrogel matrices are fine-tuned in the rhizosphere.



(a)

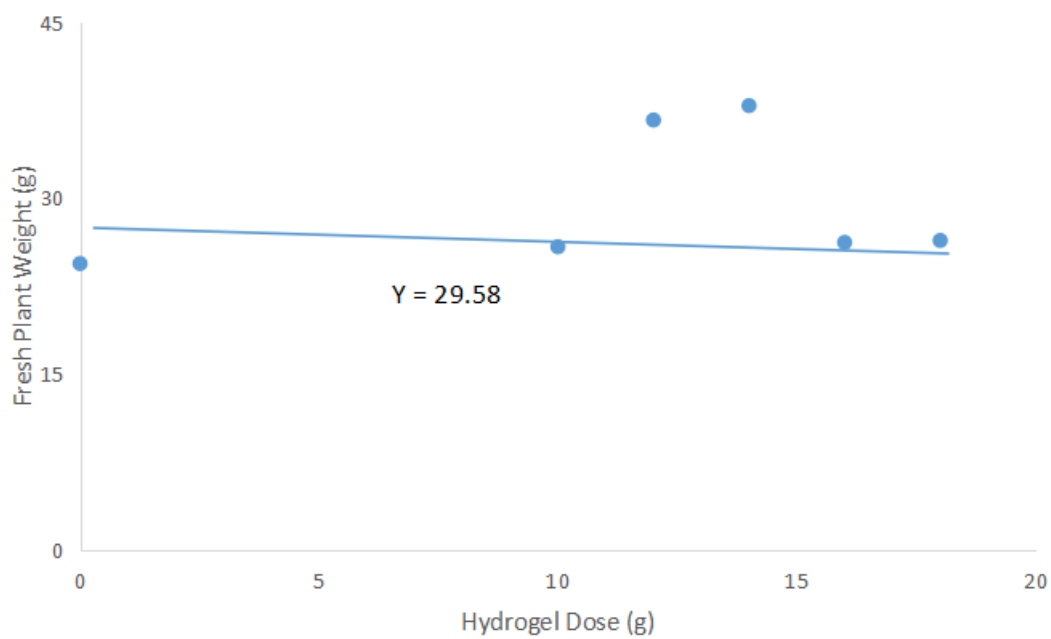


(b)

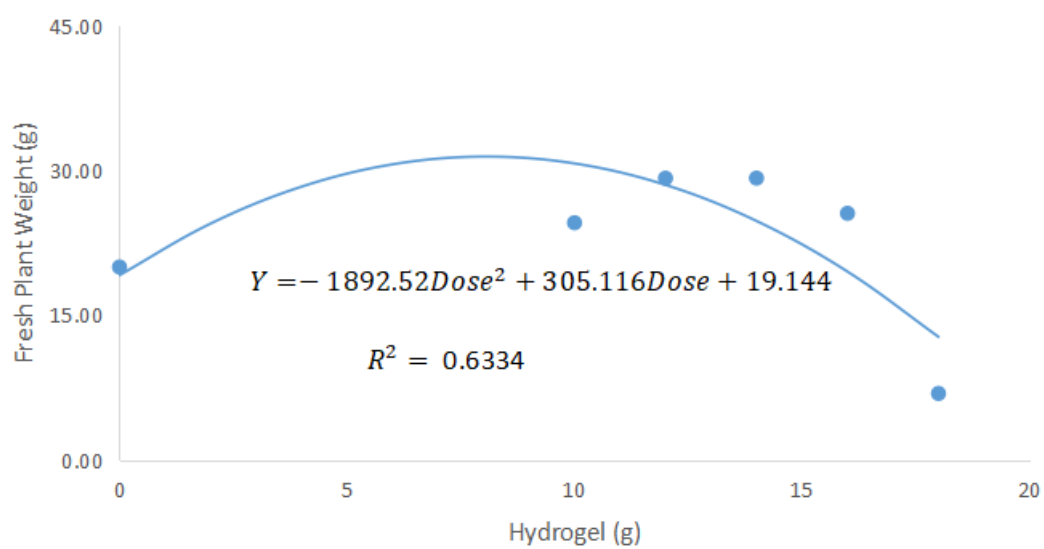
Fig. 4.8. Effect of Hydrogel on Pod Moisture Content

4.2.4. Pod Moisture Content

In the initial experiment, the statistical analysis showed that there was no significant change in response to different hydrogel treatments, with the pod moisture content remaining steady at an average of 47.0%. The second experiment followed suit, stabilizing at an average of 38.78%. As shown in Fig. 4.8 (a) and (b), the highest pod moisture levels in both trials were reached with hydrogel dosages ranging from 12 to 14 g.



(a)

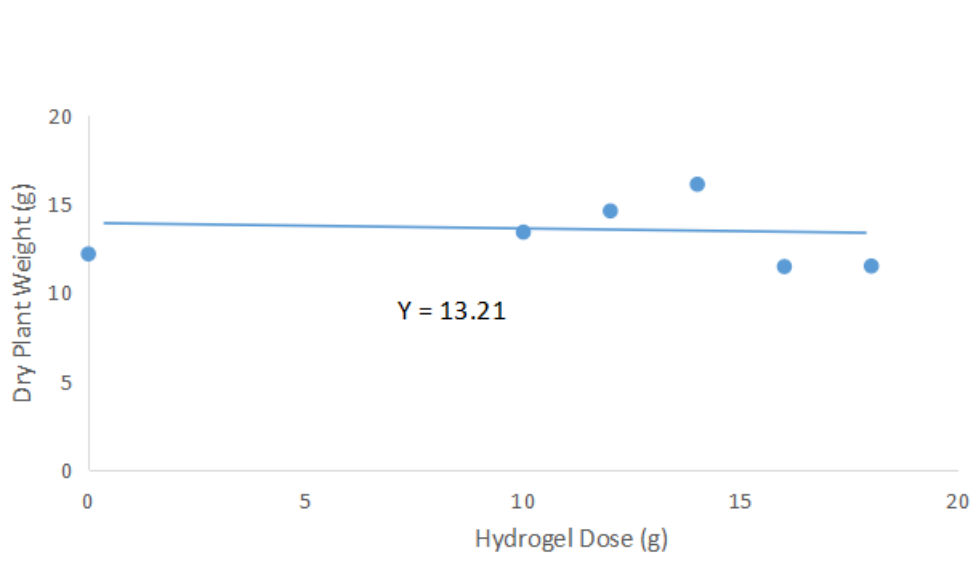


(b)

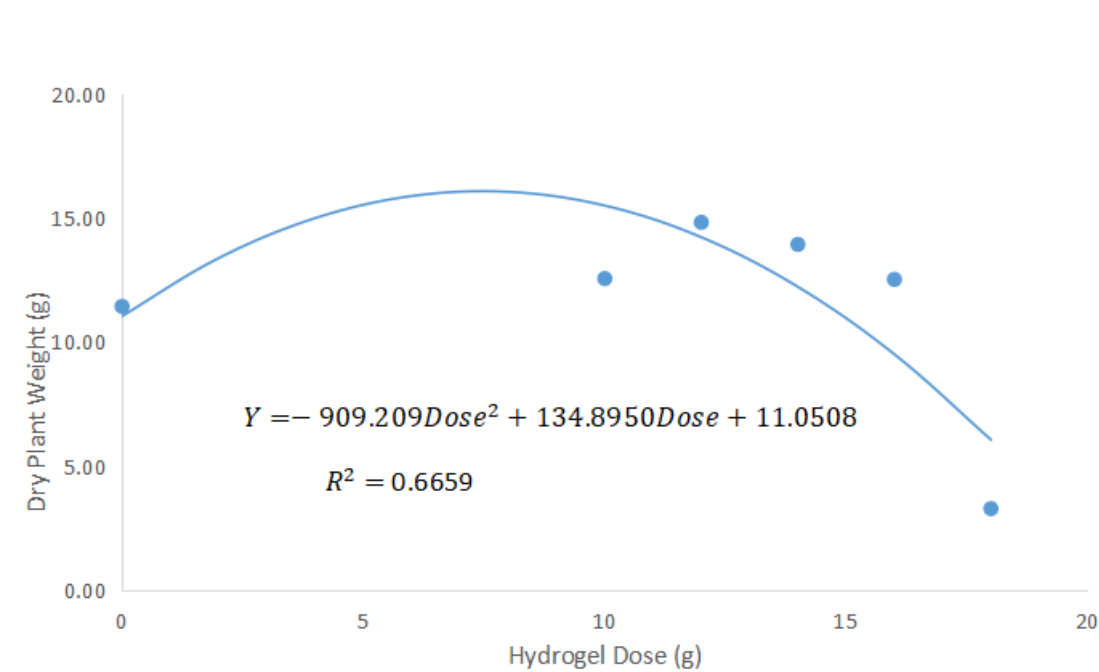
Fig. 4.9. Effect of Hydrogel on Fresh Plant Weight

4.2.5. Fresh Plant Weight

The first experiment showed that the fresh weight of bean plants did not indicate a statistically significant response to different amounts of hydrogel applied (0, 10 g, 12 g, 14 g, 16 g, and 18 g). The average fresh plant weight is 29.58 g (Fig. 4.9 (a)). However, the second experiment reveals a strong response to hydrogel application that follows a parabolic curve, as shown by a quadratic model (Fig. 5.0(b), $R^2 = 0.6334$). This regression model is statistically significant at the 5% level. The optimal fresh plant weight of 31.44 g was achieved with a hydrogel dosage of 8.06 g per plant. Interestingly, when the application rates exceeded 14 g, there was a drop in the fresh plant weight, suggesting that a high concentration of hydrogel led to soil over-saturation and diminishing returns in fresh plant weight.



(a)

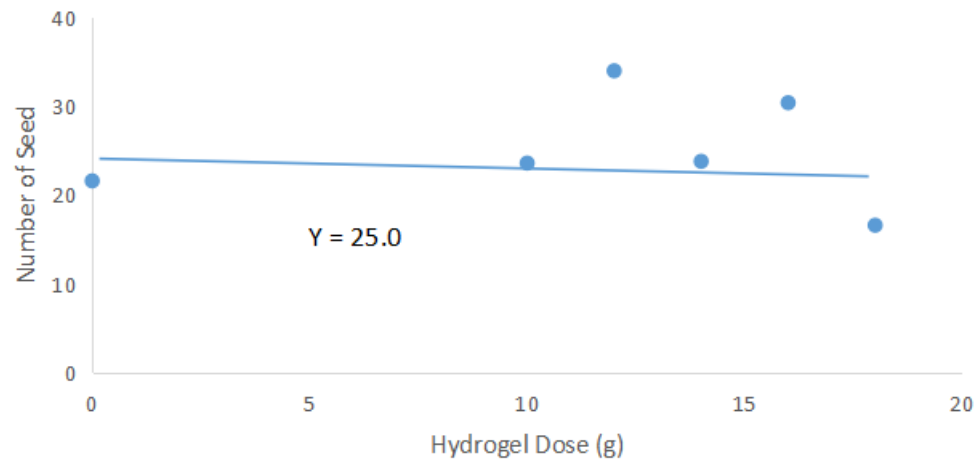


(b)

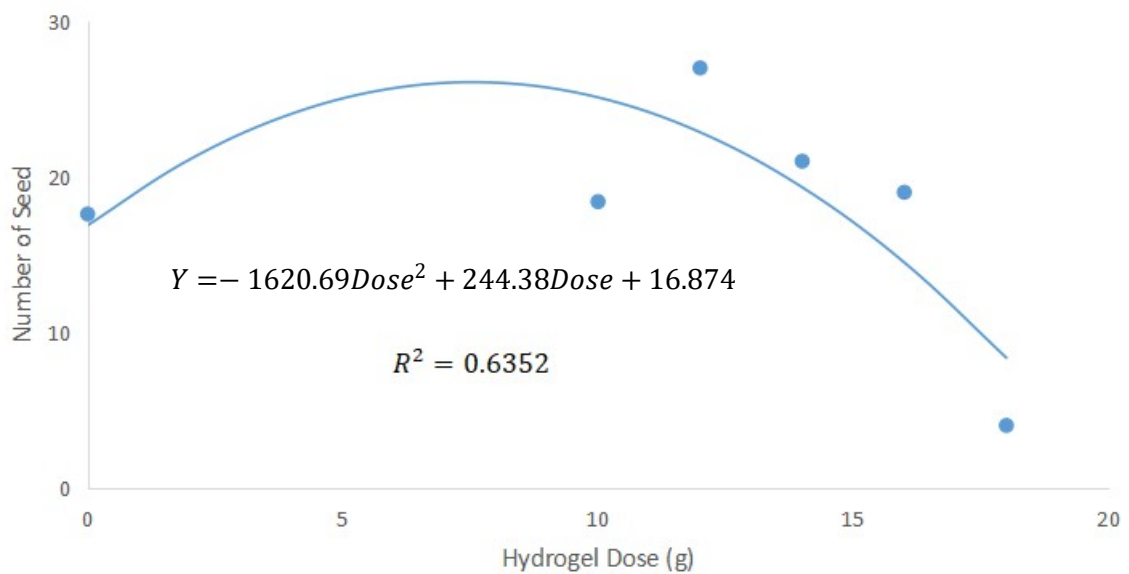
Fig. 4.10. Effect of Hydrogel on Dry Plant Weight

4.2.6. Dry Plant Weight

The regression analysis showed that hydrogel dosage did not have a significant impact on plant dry weight, which averaged 13.12 g, as shown in Fig. 4.10(a). The peak dry weight recorded was 16 g at a hydrogel dosage of 14. Interestingly, when there was enough moisture available, increasing the hydrogel concentration did not boost the dry biomass yield and, in some instances, even led to a decrease. In the second experiment, the model explained a considerable amount of variance ($R^2 = 0.6659$), suggesting that around 67% of the variation in dry biomass is linked to the hydrogel dosage, as illustrated in Fig. 4.10(b).



(a)



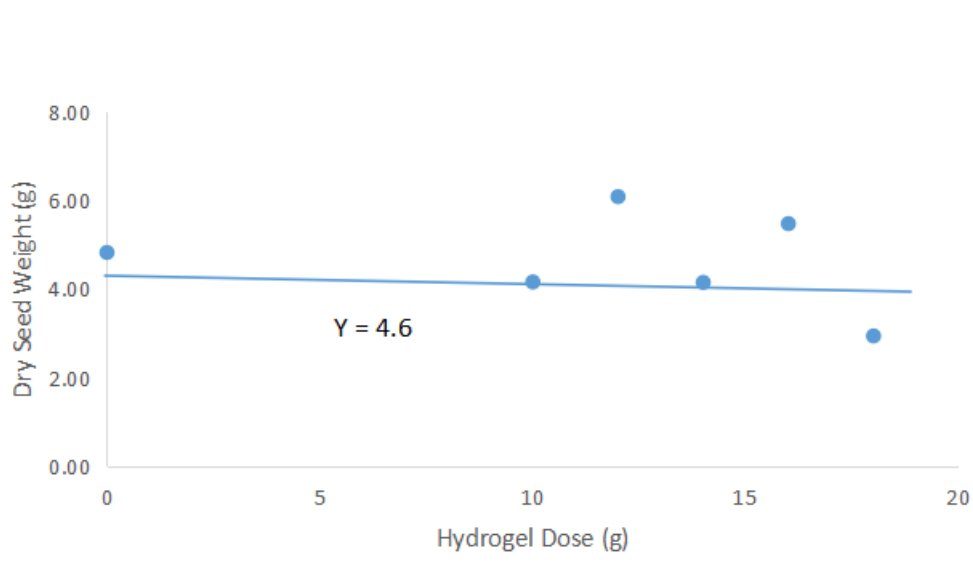
(b)

Fig. 4.11. Effect of hydrogel on the Number of Seed

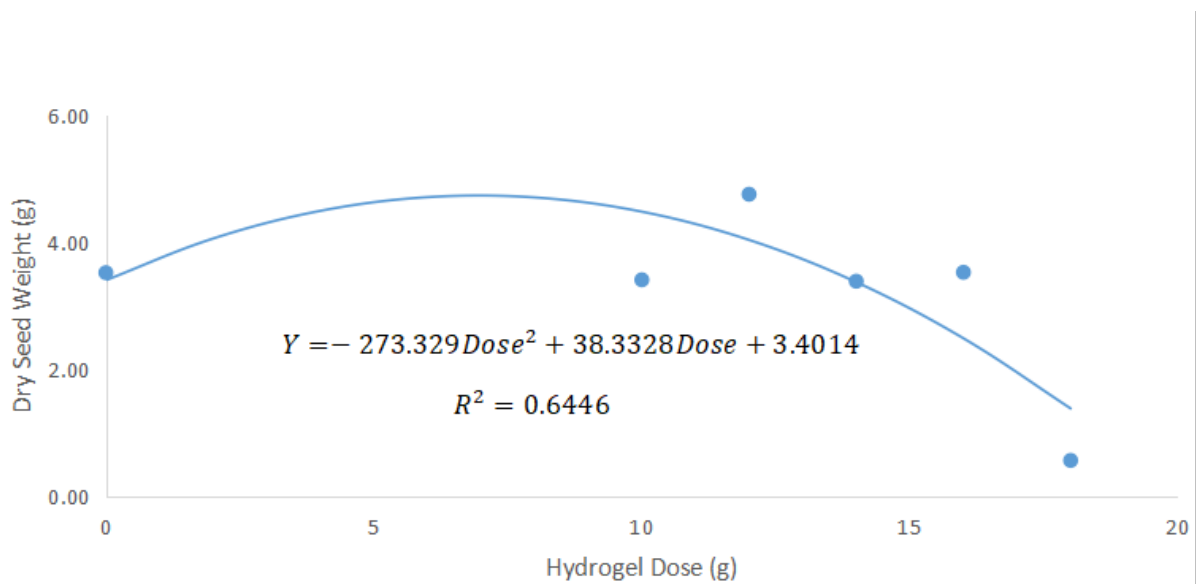
4.2.7. Number of Seeds

In the first experiment (Fig. 4.11a), changing the amounts of hydrogel didn't affect how many seeds each plant produced, with an average yield of 25.0 seeds. However, the second experiment (Fig. 4.11b) showed a clear response, highlighted by a significant quadratic fit (R^2

= 0.6352). This analysis indicates that 63.52% of the total variation in seed production per plant was linked to the ideal hydrogel dosage of 7.54 g, which led to an impressive yield of 26 seeds. These findings imply that the combination of soil moisture and growing medium created a perfect balance of moisture and nutrients. Since the soil water potential never dipped low enough to cause reproductive or stomatal stress, the plants were able to reach their full genetic potential for seed production under greenhouse conditions.



(a)

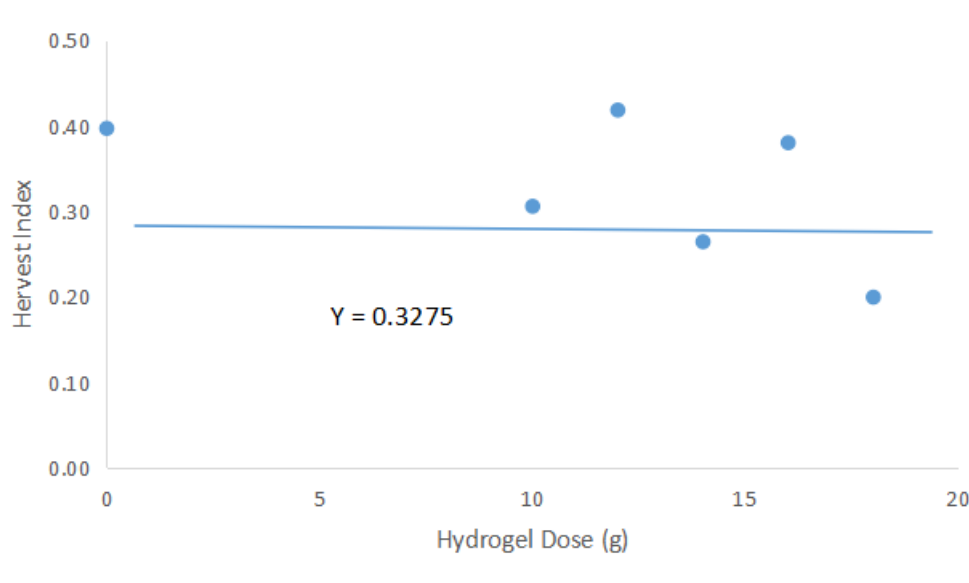


(b)

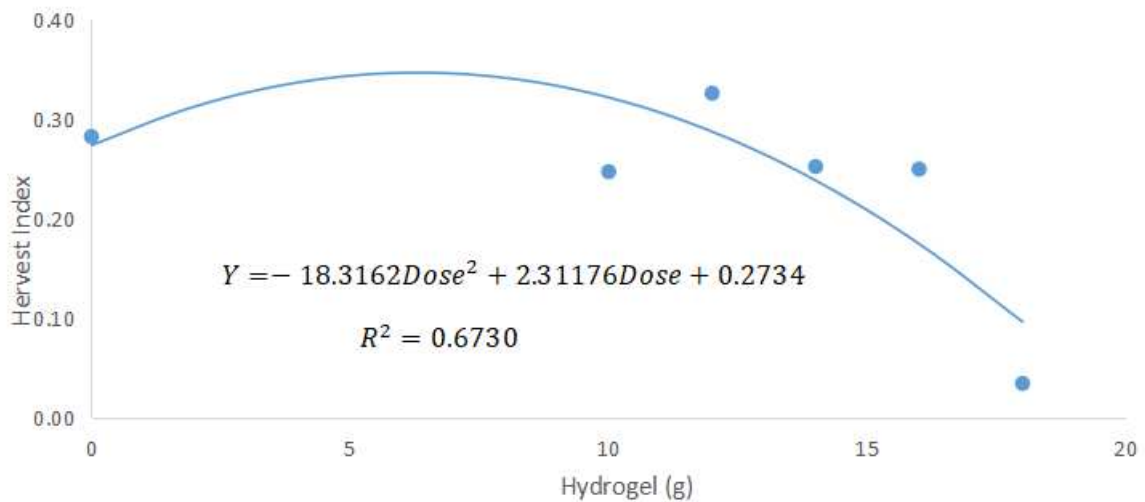
Fig. 4.12 Effect of Hydrogel on Dry Seed Weight

4.2.8. Dry Seed Weight

In the first experiment, regression analysis showed no significant treatment effect at the 5% significance level ($p < 0.05$), as illustrated in Fig. 4.12(a). The average dry seed weight was 4.60 g. However, the second experiment (Fig. 4.12b) revealed a significant quadratic relationship ($p < 0.05$), with hydrogel dosage playing a key role in explaining a substantial proportion of the variation in the final yield. The coefficient of determination (R^2) was 0.6446, meaning that 64.46% of the variation in bean dry seed weight was due to the parabolic response to the polymer dosage. The regression model produced an optimal seed weight of 4.74 g at a hydrogel dosage of 6.96 g, which represents a significant enhancement in grain filling and dry matter accumulation compared with the control under greenhouse conditions. This important finding from the second experiment at the 5% level highlights how crucial it is to use the right hydrogel dosage to keep soil moisture in the root zone during short spells of water deficit.



(a)

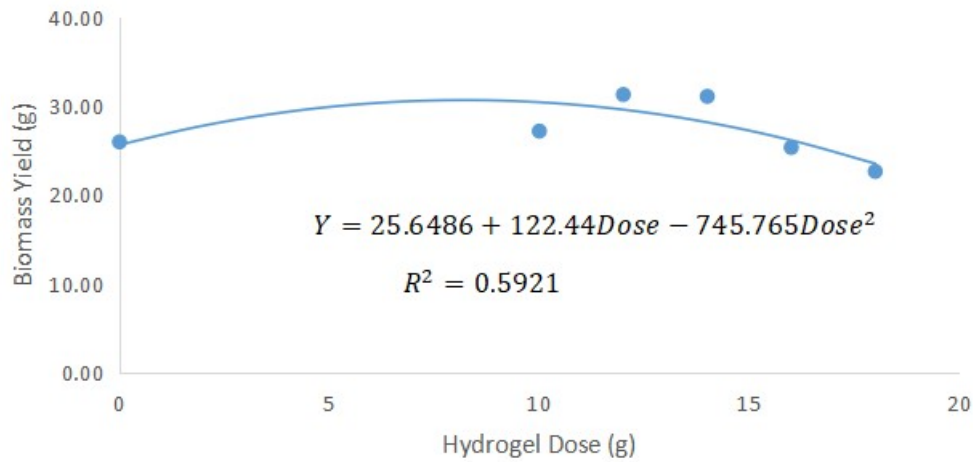


(b)

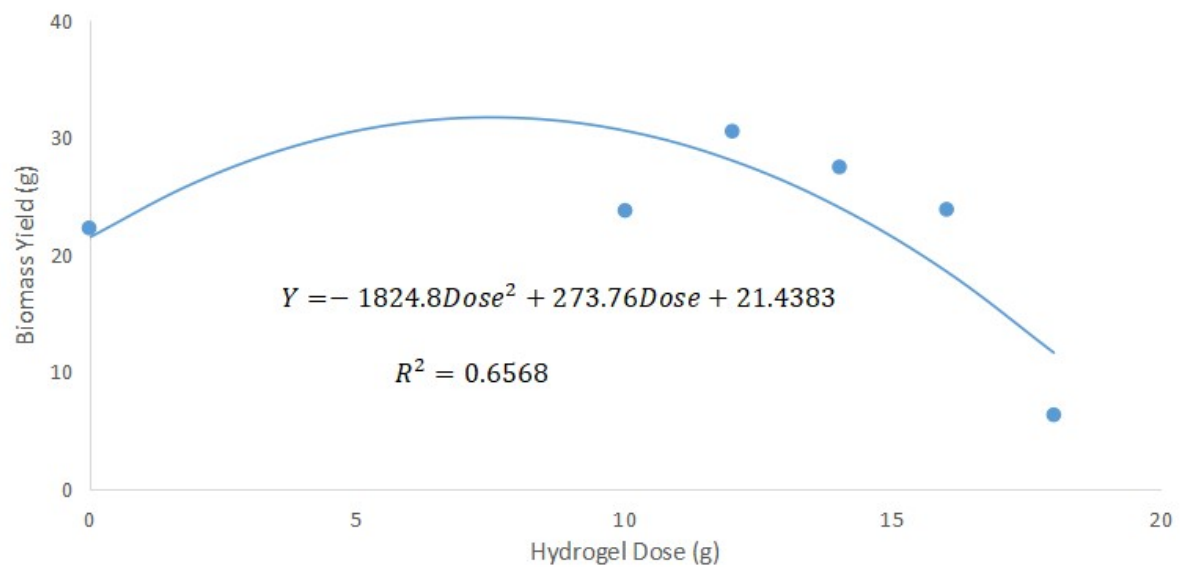
Fig. 4.13 Effect of hydrogel on Harvest Index

4.2.9. Harvest Index

In the first trial, the harvest index held steady at an average of 0.3275, showing no significant differences ($p < 0.05$) across the various hydrogel application rates. As shown in Fig. 4.13 (a), this indicates that when the soil moisture is adequate to meet the crop's evapotranspirational needs, using superabsorbent polymer (SAP) hydrogels doesn't really change how resources are allocated. On the other hand, the second experiment demonstrated a distinct quadratic relationship, as depicted in Fig. 4.13 (b). The model accounted for 67.30% of the total variance in the bean harvest index based on the hydrogel application rate. The peak harvest index of 0.3461 was reached with a hydrogel dosage of 6.31 g. This lower threshold for optimizing the harvest index compared to vegetative traits highlights a key limitation in resource allocation, as vegetative growth like leaves and stems still responds to more conservative soil moisture levels.



(a)



(b)

Fig. 4.14 Effect of Hydrogel on Biomass Yield

4.2.10. Total Biomass Yield

Both experiments showed notable quadratic responses to the treatments with superabsorbent polymers, revealing consistent performance trends across the trials, as illustrated in Fig. 4.14 (a) and (b). In the first experiment, the quadratic fit ($R^2 = 0.5921$) accounted for 59.21% of the total biomass accumulation linked to the polymer treatment, optimal at a yield of 30.67 g

when applying 8.2 g of the polymer. The second experiment showed a similar response and an even stronger quadratic relationship ($R^2 = 0.6568$) and explaining 65.68% of the total biomass variation. Under these conditions, the bean plants reached an impressive dry biomass yield of 31.71 g with a hydrogel dosage of 7.5 g. The close correlation between these independent experiments underscores a reliable response pattern. In both trials, the optimal biomass yield consistently fell within a tight range of 30.67 to 31.71 g, corresponding to hydrogel dosages between 7.5 and 8.2 g.

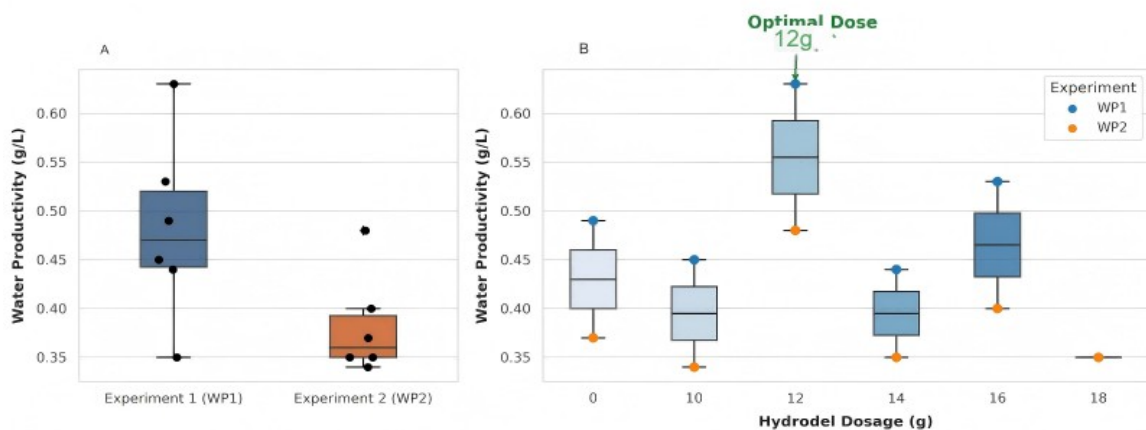


Fig. 4.15. Water Productivity for Both the First and Second Experiment

A: Comparison of Water Productivity Between Both Experiments

B: Water Productivity Distribution for the First (WP1) and Second Experiment (WP2) by Hydrogel Application Rate.

4.2.11. Water Productivity

The water productivity was evaluated from seed yield per plant (g) to the total irrigation volume (L) which increases as SAP treatment levels increase from the untreated plant to the optimal plant dosage. Beans plants treated with SAP produce more seed yield per plant, per unit volume of applied irrigation water, as shown in Fig. 4.15 (B), Control treatments under deficit irrigation typically show greater variability in yield and productivity. SAP applications narrow irrigation water variation by providing consistent volumetric soil water content, reducing crop response variability across individual plants. The box plot indicates the first experiment at higher boundaries and the second experiment at lower boundaries of water productivity while Fig. 4.15 (A) illustrates the comparison of water productivity between the first and second experiments, showing higher water productivity for the first experiment and lower productivity for the second, demonstrating the variation between the seasons.

4.3 Discussion of Results

Regression analysis models show that crops respond with a non-linear quadratic response to SAP application. All the morphological parameters measured were significantly affected as the moisture in the rhizosphere shifted into physical limitations in the root zone. The growth rate exhibited a clear quadratic response to the concentration of hydrogel, but this effect was influenced by the microclimates within the greenhouse. In both experiments, it was observed that a strong negative quadratic effect indicated an optimal response between 6.31 and 9.41 grams per plant. Interestingly, the first experiment had a gentler curve, with positive height responses continuing even at higher doses of the polymer. This difference suggests that the greenhouse's ambient conditions, especially seasonal changes in solar radiation, temperature, and humidity, play a crucial role in how effective the hydrogel is.

In the first experiment, which had milder and more resource-intensive conditions, higher doses of the polymer to meet the plants' transpiration needs. On the other hand, the second experiment showed that lower SAP rates were more efficient, particularly in the early stages when temperatures were cooler and humidity was high. Going beyond the optimal SAP levels led to noticeable decreases in plant height in both experiments. The hydrogel application actually boosted plant height by stabilizing moisture levels and acting as a hydro-buffer, which helps maintain high turgor pressure and encourages cell elongation. This finding is consistent with the research by (CZOPEK, K. 2026), who noted that Faba bean and pea plants grew significantly taller after hydrogel application.

When hydrogel is applied in high concentrations, it can actually inhibit growth. This mainly happens because the soil becomes oversaturated, which limits the air-filled spaces, disrupts gas exchange, and can lead to localized root hypoxia. Interestingly, the positive linear relationship with time seen in both experiments shows that hydrogel application has significant benefits, especially as the crops mature between Days 40 and 50. This advantage allows the treated plants to keep growing quickly during peak transpiration, while the control plants face temporary moisture shortages. The development of the leaf canopy relies heavily on consistent water availability in the root zone. The benefits of superabsorbent polymers (SAPs) are dynamic and increase with the plant's leaf area and its need for transpiration. As bean plants hit their peak vegetative growth phase (Days 40 to 57), the cumulative benefits of water retention and nutrient preservation from the hydrogel become clear. Control plants struggle with moisture fluctuations that can cause temporary stomatal closure and slow down leaf emergence. In contrast, plants treated with 7-14 grams of hydrogel maintain cell turgor

and the metabolic processes needed to increase leaf counts. Using hydrogel doses below this optimal range can lead to water stress and growth inhibition, while going overboard can risk root suffocation. These findings underscore the importance of applying hydrogel precisely to prevent phytotoxicity and oversaturation, ensuring efficient resource use, as noted by (SITU et al. 2023).

The development of stem nodes over time showed significant variation between the experiments. In the first experiment, the linear effect of time was found to be statistically independent of hydrogel dosage, suggesting that node development isn't just a straightforward function of time but is greatly influenced by the moisture-buffered environment created by the hydrogel. SAPs help minimize rapid evaporation and localized drying by absorbing moisture and gradually releasing it into the rhizosphere, as highlighted by (ALOTAIBI et al. 2024).

This guarantees that moisture is readily available and helps reduce micro-drought stress between irrigation cycles. As a result, superabsorbent polymers (SAPs) play a crucial role in maintaining cell turgor, optimizing stomatal conductance, and encouraging cell division, all essential for rapid leaf growth during the peak vegetative phase. In the second experiment, the addition of nodes progressed linearly over time but showed a distinct negative quadratic trend as the crop neared maturity. This decline in node development in the later stages signifies the physiological shift from the vegetative to the reproductive phase, a typical transition for determinate leguminous crops approaching maturity, as noted by (MALIK et al. 2022).

In both trials, applying moderate rates of hydrogel (7–14 g) led to a significant increase in node counts compared with the control and higher-dose treatments. For example, on Day 57 of the first experiment, the 14 g treatment resulted in 16 nodes per plant, while the control group only averaged 9 nodes. This remarkable increase highlights the strong positive interaction coefficient seen in the first experiment, suggesting that the polymer speeds up daily node development by reducing the plastochron, which is the time interval between successive node appearances. The impact of SAPs on total vegetative mass is closely tied to their ability to stabilize moisture in the rhizosphere. The notable fresh weight response observed in the second experiment indicates that the physical properties of the root zone, optimized by the polymer, created a hydro-buffered condition that provided consistent moisture during critical growth phases, as discussed by (AGBNA & ZAIDI 2025).

(AGBNA & ZAIDI 2026) also noted that adding polymers helps to alleviate micro-drought cycles, ensuring that plant tissues maintain a high relative water content. This

consistent hydration is crucial for maintaining the turgor pressure needed for quick leaf expansion, which in turn boosts the leaf area index and improves the plant's ability to capture light for photosynthesis.

When crops aren't stressed for moisture, they can effectively convert photoassimilates into structural tissue, leading to a significant increase in fresh weight by the time of harvest. This connection is supported by the mathematical model from the second trial, illustrated in Fig. 4.10 (b) for dry plant weight. The model's intercept (11.0508 g) predicts the dry weight under control conditions (0 g hydrogel), while a steep positive linear coefficient shows a rapid initial increase in biomass with hydrogel application, confirming that low-to-moderate doses improve soil moisture availability. However, the negative quadratic term indicates that biomass starts to decline when the dosage exceeds a certain threshold. The model suggests an optimal dry plant weight of 16.0542 g, which is a 45.3% increase compared with untreated plants. This optimization highlights how a hydrogel-enhanced rhizosphere microclimate stabilizes photosystem efficiency and gas exchange under greenhouse conditions. When application rates go beyond 14 g, the hydrogel can overly expand the soil matrix, which reduces aeration porosity, limits root respiration, and temporarily traps nutrient-rich water within the polymer network. This explains the observed drop in biomass at higher application rates, as noted by (AGBNA & ZAIDI 2025).

Total biomass yield provides insight into fresh weight, total dry plant, leaves and pods productivity throughout the entire lifecycle of the crop, but pod moisture content is influenced by a different physiological process. During the active vegetative and early reproductive stages, the amount of soil moisture plays a crucial role in regulating stomatal conductance. While total biomass yield reflects net productivity over the crop lifecycle, pod moisture content is driven by a separate physiological mechanism. At early stages, the availability of soil moisture is key to regulating stomatal conductance, transpiration, and the dynamics of grain filling (GELETA et al., 2024). Once the crop reaches physiological maturity, dry matter accumulation comes to a halt. At this stage, the vascular connections of both phloem and xylem that supply the pod walls begin to break down and undergo abscission, effectively isolating the pod from the plant's hydraulic system. This ensures that the final drying phase happens naturally, without being influenced by any leftover soil hydrogel moisture. The number of pods is mainly determined by how many flowers are retained during the early reproductive phases. In the first experiment, applying hydrogel helped alleviate moisture stress during anthesis, which prevented flower abortion and boosted the final pod counts. On

the other hand, in the second experiment, pod counts remained fairly stable at lower treatment levels but dropped sharply once the dosage exceeded 12 g. This trend indicates that the greenhouse conditions during early growth in the second trial provided enough ambient moisture, reducing the crop's dependence on the hydrogel until higher dosages began to interfere with root function. Notably, the optimal dry pod weights of 15.62 g and 15.88 g were recorded at hydrogel dosages of 7.12 g and 7.54 g, respectively. This consistency reinforces the idea that the dry pod weight of beans responds predictably to hydrogel amendments, as supported by (ABDELFATTAH & MOSTAFA 2024).

When hydrogel is applied beyond the optimal range of 7.12–7.54 g, it can significantly reduce the weight of dry pods. Using too much superabsorbent polymer in the root zone can cause the soil to become over-saturated, which restricts aeration, hinders root respiration, and traps vital micronutrients within the polymer structure. This ultimately results in a decrease in yield, as noted by (ALI et al. 2022).

The weight of dry seeds is a direct indicator of reproductive efficiency and the final harvest index. In these trials, the highest dry seed weights were achieved with moderate hydrogel concentrations, while higher concentrations led to a noticeable decline. Interestingly, under optimal resource conditions, adding more hydrogel did not improve yields. The crucial phase for dry matter accumulation relies on two main carbon sources: the current photoassimilates produced after flowering and the remobilization of stored non-structural carbohydrates from parts of the plant like stems and leaves, as highlighted by MIGUEL et al. (2023).

As reported by (FAROOQ et al., 2017; KHATUN et al., 2021) in their study, during periods of water stress in the reproductive stage, legumes often show decreased stomatal conductance, reduced net CO₂ assimilation, and quicker leaf aging, which shortens the time available for grain filling. Therefore, the second experiment suggests that the optimal hydrogel application is around 7 g, which helps stabilize seeds by creating small water reservoirs in the rhizosphere. These polymers soak up nearby water and release it slowly as the soil dries out, helping to maintain leaf moisture and keep stomata open. This ongoing physiological process ensures a consistent supply of sucrose to developing ovules, enhancing starch production and boosting individual seed weight, as reported by (ALOTAIBI et al. 2024). Additionally, the harvest index (HI) reflects how efficiently a crop converts total photoassimilates into harvestable parts, such as seeds, rather than just growing more vegetative matter. For In the production of *P. vulgaris*, it's crucial to ensure that effective

allocation of dry matter to reproductive organs is more valuable than maximizing absolute vegetative growth. The two greenhouse experiments revealed contrasting resource allocation strategies based on baseline moisture conditions:

When the use of hydrogel goes beyond the optimal threshold for reproductive allocation, the extra moisture encourages bean plants to focus on extended vegetative growth. This leads to a larger leaf surface area, excessive stem elongation, and more tillering (ALOTAIBI et al., 2024). The surplus canopy growth traps non-structural carbohydrates in structural tissues such as cellulose and lignin. Consequently, fewer nutrients are redirected to developing pods during the crucial post-anthesis grain-filling phase, which diminishes reproductive efficiency and ultimately lowers the final harvest index (CERASOLA et al., 2022). From a vegetative standpoint, total biomass peaks at a higher hydrogel concentration than the harvest index, as vegetative growth relies on consistent moisture to keep leaf relative water content (RWC) and stomatal conductance stable throughout the plant's lifecycle (MALIK et al., 2022). In the dosage range of 7.5 to 8.2 grams, hydrogel establishes a reliable subsurface moisture buffer that mitigates temporary water stress, allowing the plant to enhance structural dry matter accumulation (ABOU-BAKER et al., 2020). However, surpassing this optimal range causes the over-hydrated polymer to expand within the confined space of pots, filling soil macropores, limiting root-zone aeration, and leading to temporary hypoxia. This root stress and the resulting nutrient transport issues can cause a significant drop in biomass yield beyond the ideal dosage. Meanwhile, SAP improves soil water retention; box plots in Fig. 4.15 reveal low to moderate SAP dosage shows significant statistical gains in water productivity due to reduced water stress. While excessive SAP application lead to a decline in water productivity. With higher application of superabsorbent polymer which reduce soil macroporosity, restricting root aeration and inducing temporary anaerobic conditions irrigation events.

These insights suggest that applying hydrogel within the optimal dosage range is a reliable and sustainable approach to optimizing both the morphological development and the overall yield of bean crops in greenhouse conditions

5. CONCLUSION

Adding the superabsorbent polymer (SAP) "HIDROSILO" to the soil had a significant impact on the growth of kidney beans (*Phaseolus vulgaris* L.). Every morphological parameter measured showed a significant effect. Crop development is influenced by the amount of hydrogel used, as it affects the balance between vegetative growth and reproductive output.

The total dry plant weight increased by as much as 45.3% compared with the controls that did not receive any amendments, particularly at moderate application rates of up to 14 grams per plant. This influence was largely due to improved conditions in the rhizosphere. Interestingly, the optimal reproductive efficiency was observed at lower concentrations. The harvest index peaked at 6.31 grams, with dry seed weight averaging around 6.96 grams, and dry pod weight ranging from 7.12 to 7.54 grams. Therefore, for optimal bean crop development in the spring, the recommended hydrogel application rate is between 7 and 14 grams per plant, while for early summer in greenhouse conditions, it should be between 7 and 12 grams. This dosage range helps maintain a stable moisture level in the soil, which in turn maximizes resource efficiency and strengthens plant structure. However, if application rates exceed 12 to 14 grams, the soil can become over-saturated, expanding in the limited space of the pots, clogging soil macropores, leading to prolonged vegetative growth, reduced aeration in the root zone, and ultimately causing temporary hypoxia and yield loss.

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