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RESEARCH ARTICLE

# Psyllium husk mucilage as a novel seed encapsulant for agriculture and reforestation

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## Abstract

**Introduction:** An efficient, economical, and flexible reforestation system capable of uncrewed aerial vehicle (UAV) deployment is a global necessity. Hydrogels have been previously investigated for their use in agriculture, however, research is limited in terms of UAV deployment. Psyllium Husk Mucilage (PHM) a natural hydrogel seed mucilage, has been previously investigated in other agricultural settings and shows promise in fulfilling the needs of UAV seeding.

**Materials and Methods:** A greenhouse trial was conducted under controlled laboratory conditions using two soil conditions 50% and 90% field capacity. PHM and bentonite clay blends containing dextran (DEX) and sodium alginate (SA) were tested for efficacy for two agricultural crops Green beans (*Phaseolus vulgaris*) and Lebanese cucumber (*Cucumis sativus*), as well as three Australian native species *Acacia stenophylla*, *Cymbopogon refractus*, and *Eucalyptus coolabah*. Agricultural Trials were conducted across a 4-week period, whilst *A. stenophylla* was 8 weeks, and *C. refractus* and *E. coolabah* was 12 weeks.

**Results:** Utilisation of PHM had varying effectiveness based on seed and soil moisture. In nonagricultural seed trials, PHM hydrogel succeeded with *A. stenophylla* but dried out and rotted in the extended trials with *C. refractus* and *E. Coolabah*, leading to plant death. The encapsulated agricultural seeds were largely outperformed in growth trials by C-Planted at 50% FC, and C-Surface at 90% FC.

**Conclusion:** PHM exhibits potential for successful UAV seeding in low-moisture agricultural conditions and is promising for fast-germinating plants or other riverbank species with high water content requirements. Without extending degradation time PHM is not suitable for slow-growing species.

KEYWORDS

agriculture, dextran, hydrogel, Psyllium Husk Mucilage (PHM), seed encapsulant, sodium alginate, reforestation, uncrewed aerial vehicle (UAV)

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## 1 | INTRODUCTION

In recent years, there's been a rising preference for direct seeding over seedling planting, driven by the global demand for reforestation, which has increased by an average of 41 million hectares per decade since 1990 (Grossnickle & Ivetić, 2017). Despite reforestation efforts, natural regeneration has decreased significantly, leading to an estimated annual loss of about 5 million hectares of forest (Global Forest Resources Assessment, 2023; Ritchie et al., 2021). While temperate forests have seen a net increase in coverage, tropical and subtropical forests continue to decline (Ritchie et al., 2021). Additionally, crop production has surged by 60% in the last two decades, challenging sustainable agricultural practices and facing threats of droughts and soil desertification (Liu et al., 2020; Skrzypczak et al., 2022). Prioritizing efficient seed use is crucial to maximize output, reduce resource wastage, and minimize stress on seedbanks (Hosonuma et al., 2012; Mather, 1992).

To meet this demand, avoid wastage, fulfill output needs, and meet required establishment rates, a new efficient system must be developed. Direct seeding, which involves planting seeds directly into the soil without prior growth in nurseries or greenhouses, has been favoured in reforestation practices due to cost savings and potentially faster natural plant establishment. However, challenges include low germination rates, poor plant survival, weed competition, and vulnerability to adverse weather conditions and predators (Engel & Parrotta 2001). As such, an efficient direct seeding method is crucial to meet global demand, requiring control over pH, moisture, air access, temperature, light, nutrients and soil microbiome for optimal seed germination and growth. A specially designed seed encapsulant using absorbent polymer compounds (hydrogels) holds promise in addressing these needs, utilising hydrogel properties like air permeability, water retention, adjustable pH and the capability to contain and release fertilizers and antipredation additives.

Hydrogels are three-dimensional polymeric networks prepared from super absorbent polymers (SAPs) capable of absorbing large quantities of water (Peppas et al., 2012). Hydrogels structures are formed through a variety of interactions, such as covalent cross-linking, chain entanglements and ionic interactions, and can be classified by their physical properties, nature of swelling and materials source (Dingley et al., 2024; Peppas & Hoffman, 2020; Ullah et al., 2015). In order for a hydrogel material to be an effective seed encapsulant in the environment, key features include being, (i) comprised of a sustainable material, (ii) complete biodegradability, (iii) high water absorbance and retention, (iv) cost-effectiveness, (v) durability in environment, (vi) nontoxicity, (vii) rewetting capabilities and advantageously and (viii) can be prepared on-site (Supare & Mahanwar, 2022). SAPs have been used for agricultural applications since the 1960s when the first functional synthetic polymers were being produced, for soil conditioning applications (Abdel Hakiem et al., 2022; Sikder et al., 2021). Recent agricultural studies on SAPs aim to minimise water and nutrient loss, crucial for mitigating crop dehydration and moisture stress, especially in semi-arid and arid climates where effective water management is vital for sustainable farming (Abdel Hakiem et al., 2022; Behera & Mahanwar, 2020; Elshafie & Camele, 2021; Jahan & Nassiri Mahallati, 2020). SAPs offer benefits beyond seed germination, including reducing water scarcity and waste from inefficient direct watering systems for crops. They also eliminate the need for expensive targeted sprinkler systems, which are financially impractical for many rural farmers worldwide (Skrzypczak et al., 2021). SAPs have been shown to provide higher and faster germination rates, enhanced root and plant growth, and increased crop yields (Montesano et al., 2015; Pathak & Ambrose, 2020; Patil et al., 2011; Yang et al., 2020). Some studies have also demonstrated the effect of SAPs on enhancing the activity of microorganisms, both delivered and naturally occurring to encourage germination and plant growth (Hernández et al., 2017; Merino et al., 2021; Patil et al., 2011; Riseh et al., 2021; Vinceković et al., 2016).

While most research focuses on agricultural applications, such as thin seed-coatings made from materials like alginate, starch, cellulose, and chitosan, these coatings are unsuitable for UAV deployment due to their limited nutrients, minimal environmental protection, and poor delivery efficiency (Faqir et al., 2021; Martínez-Cano et al., 2022; Supare & Mahanwar, 2022; Zainul Armir et al., 2021). Moreover, Studies on various plants have shown promise in using natural hydrogels like alginate, carboxymethyl cellulose (CMC), and carrageenan as foliage or soil additives (Akalin & Pulat, 2019; Dingley et al., 2024; Jiménez-Arias et al. 2023; Thye et al., 2022). However, research on seed encapsulation with these materials is limited. A recent study found that alginate-coated seeds can slowly deliver encapsulated nutrients, improving cucumber fresh weight (FW) and root length (Skrzypczak et al., 2021). Therefore, an in-depth study on an innovative hydrogel encapsulant suitable for UAV deployment, prepared on-site, to enhance growth and germination conditions is expected to fill a gap in this space.

In nature, seed mucilages which are primarily composed of pectins and hemicelluloses, swell when hydrated, aiding seed hydration and germination. They enhance seedling emergence, decrease mortality rates, and vary in function depending on plant species and environment. Additionally, they reduce predation through soil adherence and promote seed dispersal by attaching to animals (Liu et al., 2021; Pan et al., 2021; Western, 2012). Previous studies investigating the role of mucilages in plant germination under drought stress show that mucilages positively influence germination and germination rate (Geneve et al., 2017; Yang et al., 2012; Zhao et al., 2021).

The material must meet key criteria like deployability, nontoxicity, biodegradability and affordability. Moreover, it should be easily prepared on-site without complex equipment and ready for use promptly to ensure practicality. Psyllium is a general term for plants of the genus of the Plantago variety, which has more than two hundred species worldwide (Monge Neto et al., 2021). The seeds of the *Plantago ovata* are the most commonly extracted seed for PHM (Monge Neto et al., 2021). PHM has found use in the food industry as a stabilising and gelling agent, which similarly has led to extended research into water remediation (Thakur & Thakur, 2014). PHM composition varies naturally depending on the seed source, mainly comprising xylose and arabinose,

with traces of aldobiuronic acid, arabinoxylan, arabinoxylans, galacturonic acid, and possibly pectins (~3%). Its high-water holding capacity and retention make PHM a novel choice for seeding applications. Moreover, PHM properties and extraction efficiency can be modified through different gel extraction methods, particularly by using alkaline materials and varying temperatures. We hypothesise that PHM and its blends have the potential to support seed germination and growth in addition to ease of processing for delivery at remote sites with the help of UAV. Although, there are published research in use of PHM as seed encapsulant, the current research is unique as it aims to assess PHM and its various blends for use in remote area reforestation for specific tree species.

To be viable in industrial applications, the encapsulant needed to meet specific deployment criteria, including a minimum deployment height of 3 m and a processing time limited to 5 h with minimal equipment. PHM-polysaccharide blends, show promise in modifying the viscosity, yield stress and gelation properties to meet these criteria. These additions bind to water in the matrix, reducing its availability for PHM. The reduction varies with the molecular weight of the additives; lower molecular weight polysaccharides like maltodextrin reduce viscosity less than higher molecular weight ones like locust bean gum or gum Arabic (Kale et al., 2016).

Dextran (DEX), is an exopolysaccharide synthesised by lactic acid bacteria or their enzymes in the presence of sucrose and is biocompatible and biodegradable (Díaz-Montes, 2021). Commonly used in the food industry, dextran serves as a gelling, suspending, thickening, stabilising and moisturising agent, found in various products like breads, pastries, ice cream, sweets, meats and vegetables. Its molecular weight varies widely, from 2000 to 440 MDa, affecting solubility and chemical interactions (Díaz-Montes, 2021; Sigma-Aldrich, 2022). Dextrans above 40 kDa are termed dextrans, while those below are called oligodextrans; oligodextrans above 10 kDa exhibit highly branched behaviour (Sigma-Aldrich, 2022).

Sodium alginate (SA) is also a water-absorbing polysaccharide additive, which offers higher initial viscosity than dextran. PHM-SA beads have previously been crosslinked in calcium chloride solution, to enhance viscosity, water uptake, and encapsulation efficiency in hydrogel beads (Belščak-Cvitanović et al., 2015; Lotfipour et al., 2012). However, this reduces water access and oxygen permeability (Belščak-Cvitanović et al., 2015). SA has been used in soil amendment, seed coating, and crop protection applications (Dingley et al., 2024). Alginate-based bio-composites efficiently remove contaminants, exhibit high absorbance capacities, and enhance soil health and plant growth under drought stress (El Idrissi et al., 2023; Hu et al., 2021; Li et al., 2023, 2022; Liu et al., 2023; Merino et al., 2021; Saberi Riseh et al., 2021). SA serves as an emulsifier and thickener in crop protection, enhancing sustained release (Du et al., 2023; Ma et al., 2023; Patel et al., 2018; Ren et al., 2023; Sarma et al., 2023; Wang et al., 2020). Challenges include hindered seed development and storage issues in seed coating, impacting practicability. While some studies show positive outcomes, further research is needed for scalability and uniform nutrient distribution (Chin et al., 2021; Dutra et al., 2023; Fu et al., 2022; Jarecki, 2022; Skrzypczak et al., 2021; Trica et al., 2023; Trică et al., 2023). SA's versatile properties in agriculture make it a promising candidate for exploration and optimisation.

Bentonite clay is commonly utilised as a low-cost, nontoxic viscosity enhancer and binding agent (Kangsopa et al., 2018; Medha et al., 2023; Murray, 2006; Xie et al., 2023). It enhances mechanical and thermal capabilities, acts as a filler and adsorbent, and improves cation exchange capacity and nutrient retention and delivery efficiency in agriculture (Chaudhuri et al., 2022; Kirsh & Chutkina, 2011; Satriananda et al., 2018). When wet, its crystalline sheets swell and adhere, increasing viscosity, especially when chemically crosslinked (Chaudhuri et al., 2022; Chen et al., 2022; Zhumagaliyeva et al., 2017). Studies suggest concentrations over 5% wt. reduce swelling ratio (Chaudhuri et al., 2022).

To assess the suitability of PHM blends as a seed encapsulant, properties such as the gelation point (GP) and droplet sizing are investigated. Due to the gelation process of PHM occurring across many hours a processing window (PW) was also defined as the point at which the material had stabilised, that is, reached its GP. Within this PW the material had to meet certain criteria such as sufficient cohesiveness to survive impact from aerial seeding, while not excessively exceeding this as this would impact seed growth, as well as motor parameters required for extrusion on a lightweight UAV system.

The investigation encompasses various PHM blends with DEX and SA, with bentonite clay as a viscosity enhancer. Suitability of encapsulants shall be assessed using GP and deployment testing. Successful e encapsulants shall be assessed for UAV seeding potential for two common agricultural crops, beans (*Phaseolus vulgaris*) and Lebanese cucumber (*Cucumis sativus*), as well as three Australian native seeds: *Acacia stenophylla*, *Cymbopogon refractus*, and *Eucalyptus coolabah*. All seeds underwent testing for germination, FW and dry weight (DW), moisture content (MC), root and shoot length, as well as leaf development properties to assess the efficacy of the encapsulant.

Consequently, this research aims to advance the use of hydrogels in agriculture, reforestation, and land revitalisation by utilising PHM and its blends as seed encapsulants for aerial delivery via UAVs. The study will focus on (i) determining the GP of PHM to establish a PW of less than 6 h for on-site preparation, (ii) evaluating deployment onto various surfaces from a height of 3 m to assess delivery success and (iii) analysing germination and growth across a range of agricultural and nonagricultural species to surpass traditional seeding methods. Achieving these objectives will provide valuable insights into the efficacy of hydrogel seed encapsulants and inform future advancements in this field.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials

Psyllium husk (95%) was obtained from Patel industries, Bentonite micro clay was obtained from 'Pure Wellness Australia', SA (99%) (MW 216.12) was sourced from Aus Chem Source, Dextran (99%)

(MW 18,100) was obtained from Sigma Aldrich, 'Seasol Trilogy Liquid Fertiliser', 'Osmocote' slow release fertiliser pellets, and the 'Garden Basics' garden soil utilised were sourced from Bunnings (2024). Agricultural seeds, green beans (*P. vulgaris*) and Lebanese cucumber (*C. sativus*) were sourced from Mr. Fothergill's seeds (Fothergill's, 2024). The native Australian seeds utilised are *A. stenophylla*, *C. refractus* and *E. coolabah*, sourced from 'BioBankSeed' (BioBankSeed, 2023).

## 2.2 | Preparation of hydrogel composites

5 w/v% bentonite micro clay water added to a solution comprising of Seasol Trilogy (0.4 v/v%) and deionised water while stirring on a magnetic hot plate at 1500 rpm and 25°C. After 5 min the solution became 'milky' and there were no aggregates present. Following this both psyllium husk and dextran/alginate were added in their defined quantities (Table 1) and mixed for a further 10 min before the stir plate was turned off. This mixture was then allowed to gel before adding and mixing in the slow-release fertiliser pellets and seeds (when applicable). For each blend, a total polymer concentration of 4% (A-4.x and D-4.x) or 5% (A-5.x and D-5.x) was considered. These blends were further distinguished by a secondary number (x), indicating the increasing substitution levels of psyllium for the alternate polysaccharide.

## 2.3 | Determination of hydrogel composite GP using yield stress

The proposed hydrogel can be defined as a structured fluid with complex thixotropic flow behaviour and multiphase structure (TA Instruments Understanding Rheology of Structured Fluids, 2016). As such the stability of the material is influenced by factors like viscosity of liquid phase, particle characteristics, and attractive forces between the particulate and continuous phase (TA Instruments Understanding Rheology of Structured Fluids, 2016). Shear thinning behaviour and yield stress ($\sigma_y$) are crucial for production applications, determining the point of flow through pipelines or vessel filling. Since the proposed deployment method of dispersal operates like extrusion from a large syringe, this point is crucial as it determines the stabilisation of material extrusion during deployment. As such, this point determines the maximum force and motor required for extrusion, as well as the time at which deployment should begin.

The stress sweep (0.1–10,000 Pa) is conducted using a TA Instruments HR-3 rheometer with a 20 mm parallel plate geometry, a 1 mm gap, and at a frequency of 10 rad/s. Measurements are taken at from 0.5 to 6 h as well as at 24 h (Rahman et al., 2022); the uncertainty is assumed to be the standard error across the samples for a specific time interval. The log of both the storage modulus (G′) and the Oscillation stress (Pa) is recorded using a stress sweep, where the onset point of the modulus curve determines $\sigma_y$ (Pa).

**TABLE 1** Hydrogel composition.

| Sample name | Psyllium (w/v%) | Dextran (w/v%) | Sodium alginate (w/v%) | Bentonite micro clay (w/v%) | Osmocote fertiliser (w/v%) | Seasol fertiliser (v/v%) |
|---|---|---|---|---|---|---|
| *PHM Blends* | | | | | | |
| P-1 | 3 | - | - | 5 | 4.5 | 4 |
| P-2 | 4 | - | - | 5 | 4.5 | 4 |
| P-3 | 5 | - | - | 5 | 4.5 | 4 |
| *PHM-DEX Blends* | | | | | | |
| D-4.1 | 3.5 | 0.5 | - | 5 | 4.5 | 4 |
| D-4.2 | 3 | 1 | - | 5 | 4.5 | 4 |
| D-5.1 | 4.5 | 0.5 | - | 5 | 4.5 | 4 |
| D-5.2 | 4 | 1 | - | 5 | 4.5 | 4 |
| D-5.3 | 3 | 2 | - | 5 | 4.5 | 4 |
| *PHM-SA Blends* | | | | | | |
| A-4.1 | 3.5 | - | 0.5 | 5 | 4.5 | 4 |
| A-4.2 | 3 | - | 1 | 5 | 4.5 | 4 |
| A-5.1 | 4.5 | - | 0.5 | 5 | 4.5 | 4 |
| A-5.2 | 4 | - | 1 | 5 | 4.5 | 4 |
| A-5.3 | 3 | - | 2 | 5 | 4.5 | 4 |

## 2.4 | Deployment testing (Droplet Spread)

In this test, a 5 mL droplet of the PHM-Blends, incorporated with seeds and fertiliser pellets are dropped from 3 m, and their drop size is assessed using image analysing software. Each droplet will be analysed for area and maximum dimension. In this test, no droplet should exceed an area of 20 $cm^2$ (~2.5 cm radius), as after this point there would be a lack of encapsulant coating the seed with a 5 mL droplet.

## 2.5 | Soil field capacity (FC)

FC testing followed the Australian standard AS1289. This method involved preparing 20 samples, each with a volume of approximately 50 mL, filled with fully saturated soil. Fully saturated soil (100% FC) was obtained by initially oversaturating the soil and allowing it to gravity dry for 24 h. Subsequently, the samples were placed in an oven at 110°C for 24 h and then reweighed to determine FC using Equation (1).

$$FC\left(\frac{m^3H_2O}{m^3Soil}\right) = \frac{(m_w - m_d)}{\rho_{H_2O} \times V} \quad (1)$$

where,

$m_w$ = Mass of wet soil
$m_d$ = Mass of dry soil
$m_c$ = Mass of container
$\rho_{H_2O}$ = Density of water
V = Volume of soil in $m^3$

## 2.6 | Germination test

Both agricultural and native seeds underwent germination tests in two soil conditions, 50% and 90% FC. Agricultural seeds were observed over 3 weeks, while native seeds were monitored for 8 weeks (*A. stenophylla*) and 12 weeks (*C. refractus* and *E. coolabah*). Weekly watering-maintained soil moisture. Tests were conducted in enclosed growth trays at 23°C, 16 h of light, and 30% humidity. Each test included two psyllium encapsulants and two controls: surface-sown seeds (C-Surface) and seeds planted at the desired depth (C-Planted). Hydrogel conditions had two seeds per 5 mL, while controls had individual seeds. Tests were triplicated for each moisture condition, with eight seeds per sample. C-Planted seeds are considered germinated, but emergence from soil was observed for consistency.

$$GP(\%) = \frac{N}{T} \times 100 \quad (2)$$

where,

N = Number of germinated seeds
T = Total number of seeds tested = 24 Seeds




**FIGURE 1** Plant growth measurements.

## 2.7 | Growth test

Six parameters were measured in the plant growth evaluation study, which include shoot and root length, FW and DW, and leaf count and size, as shown in Figure 1. Agricultural seedlings that had germinated during the 21 days previous, were carefully extracted from the soil after 7 additional days (28 days total), given slower growth for *A. stenophylla* the total time was 8 weeks and *C. refractus* and *E. coolabah* was 12 weeks. Seedlings were then meticulously washed with DI water to remove excess material and were carefully patted dry not to damage the leaves, shoots, and roots. First, FW was recorded on a balance that was accurate to ±0.05 mg. This was followed by root length, stem length, and maximum leaf dimensions (length and width), which were measured using a micrometre, number of leaves was also measured. Lastly, DW was determined by oven-drying the samples at 60°C for 24 h, and this, along with FW, was used to calculate plant MC. These parameters serve as indicators of nutrient uptake efficiency, resource competition success, metabolic activity, structural integrity, and resource utilisation efficiency, which collectively provide insights into plant development, growth, and successful seedling establishment. It's important to note that not all germinated seeds were included in the plant growth results, with some data points omitted due to unsuccessful growth, defined as shoot and/or root length less than 30 mm or plants with zero leaves. Statistical significance was determined utilising a one-way analysis of variance (ANOVA) ($p < 0.05$) and Turkey's HSD.

# 3 | RESULTS

## 3.1 | Determination of GP using yield stress

GP was assessed for the formulations in Table 1, excluding Osmocote and seeds. Increasing PHM concentration extended gel stabilisation

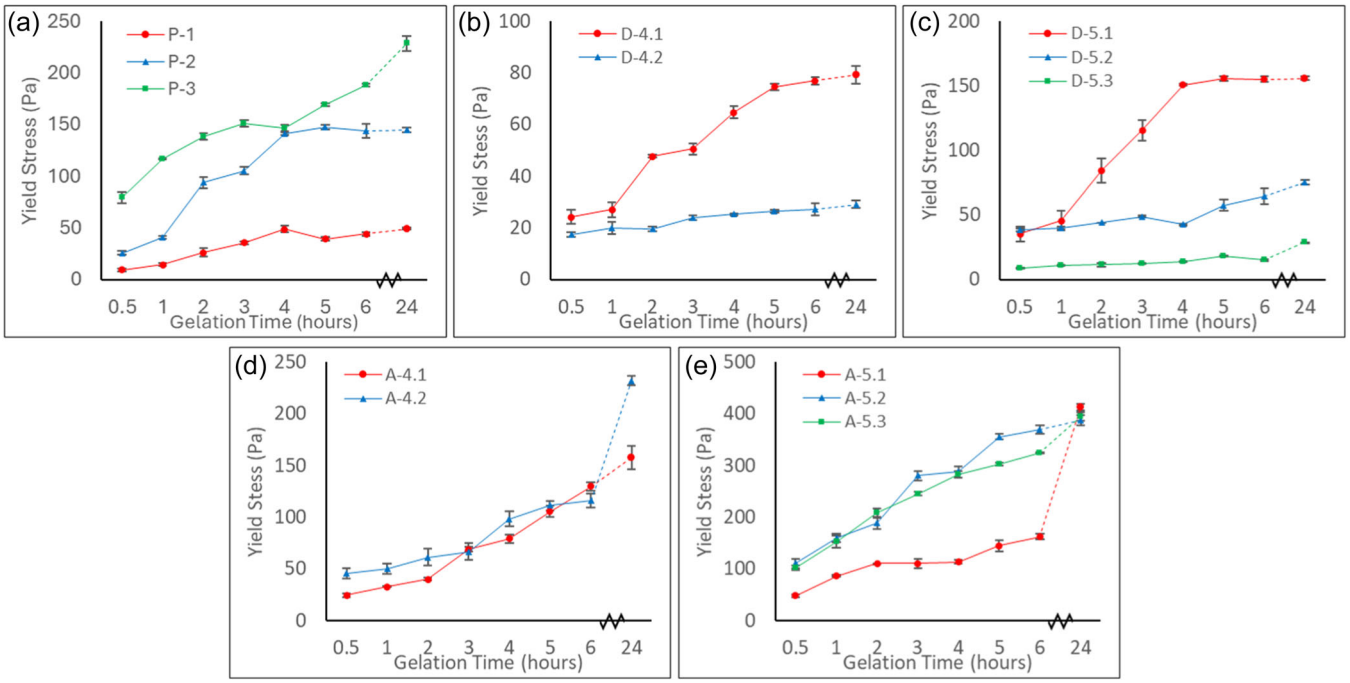



**FIGURE 2** Gelation time (h) versus yield stress (Pa), (a) psyllium blends, (b) 4% polymer dextran blends, (c) 5% polymer dextran blends, (d) 4% polymer alginate blends, (e) 5% polymer alginate blends.

time (Figure 2a), with P-1 and P-2 stabilising after 4 h, while P-3 failed to stabilise within 6 h. Higher psyllium concentration prolonged gel stabilisation, emphasizing the need for more water to solubilise greater psyllium concentrations. P-2 emerged as a better candidate than P-1, demonstrating improved cohesion suitable for aerial deployment. The addition of DEX (Figure 2b,c) delayed gel stabilisation by hindering PHM water uptake. Moreover the 4% polymer blends failed to achieve sufficient viscosity for UAV dispersal. Addition of ALG (Figure 2d,e) increased material yield stress, however, resulted in unsuitable stabilisation properties. Hence, 5% DEX blends (Figure 2c) were deemed more favourable than ALG blends due to improved stabilisation properties and easier preparation. Consequently, encapsulants P-2, D-4.1 and D-5.1 were selected for further assessment.

## 3.2 | Deployment testing

Drop testing a gel intended for UAV deployment is crucial to ensure its resilience and stability under real-world conditions. UAVs often face dynamic scenarios involving rapid acceleration, deceleration, and sudden impacts on a variety of surfaces during deployment. By subjecting the hydrogel to drop tests, we simulate the challenges posed by two surfaces: a piece of cardboard on concrete floor and a softer agricultural-like soil. Both surfaces represent surfaces the encapsulant may encounter during use; examples of deployed hydrogels are shown in Figure 3b,d. This testing will give insights into the materials ability to maintain its integrity by measuring the spread of PHM encapsulant. Deployment testing included the materials P-2, D-4.1 and D-5.1, identified as the best materials from the GP investigation. Analysis of droplet diameter (Figure 3a) revealed that, on average, P-2 had the largest diameter, followed by D-4.1 and D-5.1. However, due to the slight difference between P-2 and D-5.1, it can be concluded that D-5.1 produces a smaller diameter than both P-2 and D-4.1. For hard surface data, D-5.1 yielded the best results, followed by D-4.1 and P-2. All PHM hydrogels met the maximum area requirement (20 $cm^2$) after their respective gelation time. Thus, these results suggest that at a height of 3 m, these gels meet the requirements for harder surfaces. However, if the height is increased to 5 m, P-2 may not fulfill this requirement. In terms of droplet diameter, a similar trend to hard surfaces persisted in soft surface tests (Figure 3c), with P-2 having the largest droplet diameter, followed by D-4.1 and D-5.1. This pattern also held true for droplet area. The difference between soil and cardboard surfaces significantly influenced droplet size, resulting in a notable reduction in all droplet averages. Hence, it is more likely that on softer surfaces, such as tilled agricultural soil or sandy soils, droplets could be dispensed from greater heights. The results also reveal that, despite an additional hour for stabilization, D-4.1 does not yield the smallest droplet size in either condition. Consequently, the material testing results conclude that D-5.1 and P-2 are the most suitable materials to continue germination and growth experiments.

## 3.3 | Agricultural seed testing

The material analysis identified hydrogels D-5.1 and P-2 as optimal encapsulants for testing agricultural crop growth and germination, specifically beans (*P. vulgaris*) and Lebanese cucumber (*C. sativus*).

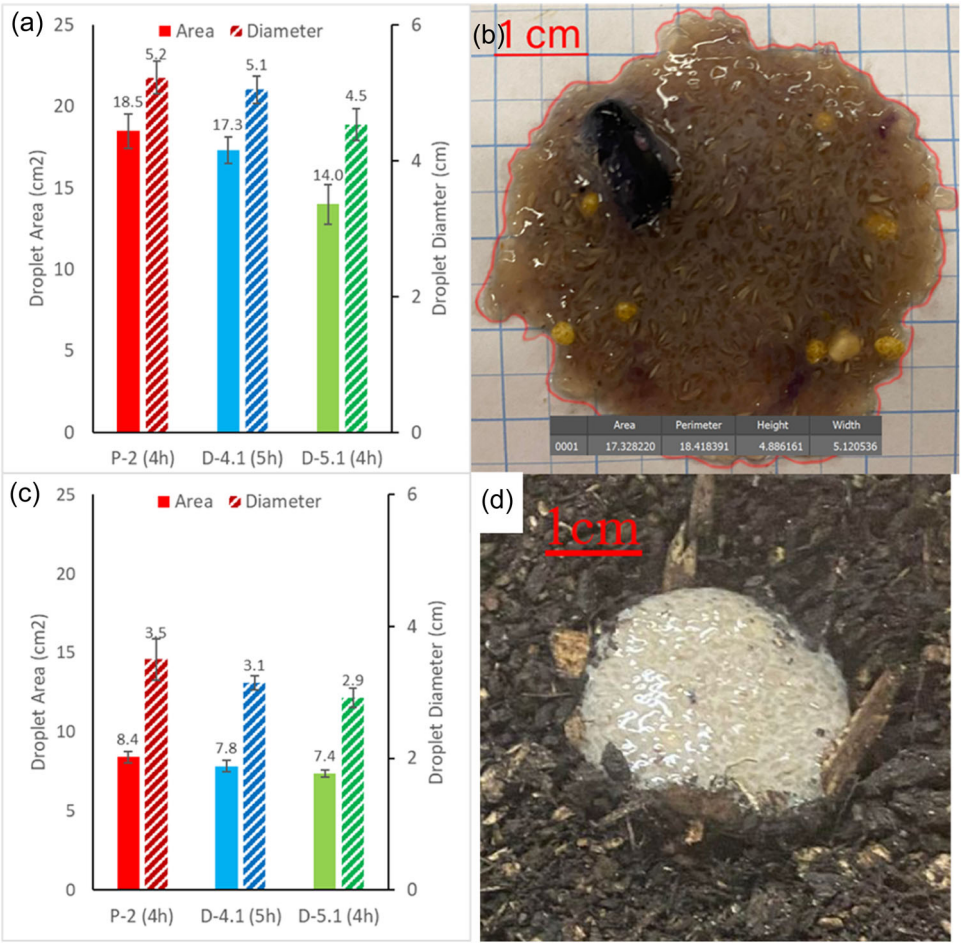



**FIGURE 3** (a) Droplet size for hard surface, (b) P-2 (Hard) Droplet containing 'Osmocote' and beans, (c) droplet size for soft (soil) surface, (d) D-5.1 (Dirt) droplet containing 'Osmocote' and beans.

Germination percentage and six growth criteria were used to assess encapsulant effectiveness compared to control conditions (C-Planted and C-Surface); namely, FW and DW, MC, root and shoot length, and leaf count and size.

As shown in Figure 4a,c, in drier conditions PHM encapsulants improved the germination rate of both beans and cucumbers compared to C-Surface seeds, suggesting a preference for arid environments. PHM showed potential for faster germination than C-Planted in drier conditions, though this might be influenced by C-Planted seed emergence timing. However, PHM blends consistently underperformed compared to C-Planted at 50% FC (Figure 4a,c) and C-Surface at 90% FC (Figure 4b,d). Addition of dextran hindered germination for both crops, indicating a need for alternative blends. Fungal growth was observed on most non-germinated beans in PHM blends, likely due to oversaturation and PHM providing a conducive environment for fungi. Addressing this issue is crucial for improving germination success. While PHM may be more useful in well-saturated environments, C-Surface planting showed better germination but is vulnerable to seed predation and environmental factors. Real-world conditions often result in seed predation rates exceeding 90%, making exposed seeds impractical (Dalling et al., 2010).

PHMs had no significant impact on bean plants' FW and DW, or MC at 50% FC in both ANOVA and Turkey's HSD (Table S1). At 90% FC encapsulants significantly increased the FW of beans, compared to C-Surface. In terms of DW and MC there was no significant difference observed (Figure 5a). Analysis of bean root length revealed that at 50% FC, there was a significant difference between encapsulants (D-5.1 and P-2) but not between the encapsulants and the controls given the large degrees of variation. In contrast at 90% FC, D-5.1 maintained its root length whereas all other conditions drastically reduced their average root length, thus it had a significantly larger root length than C-Surface (Figure 5b). Analysis of bean shoot length concluded that at 50% FC, D-5.1 produced beans with significantly shorter shoots than C-Planted, and P-2 produced significantly shorter shoots than all other conditions (Figure 5c). Total length analysis of beans showed that at 50% FC D-5.1 was significantly smaller than C-Planted, no significant results were observed at 90% FC. Analysis of bean plant leaf size and count showed no significant results at 50% FC. However, at 90% FC, D-5.1 produced both longer and wider leaves than C-Surface, whereas P-2 only produced significantly longer. Furthermore, P-2 also produced significantly more leaves than C-Surface at 90% FC (Table S3) Analysis of

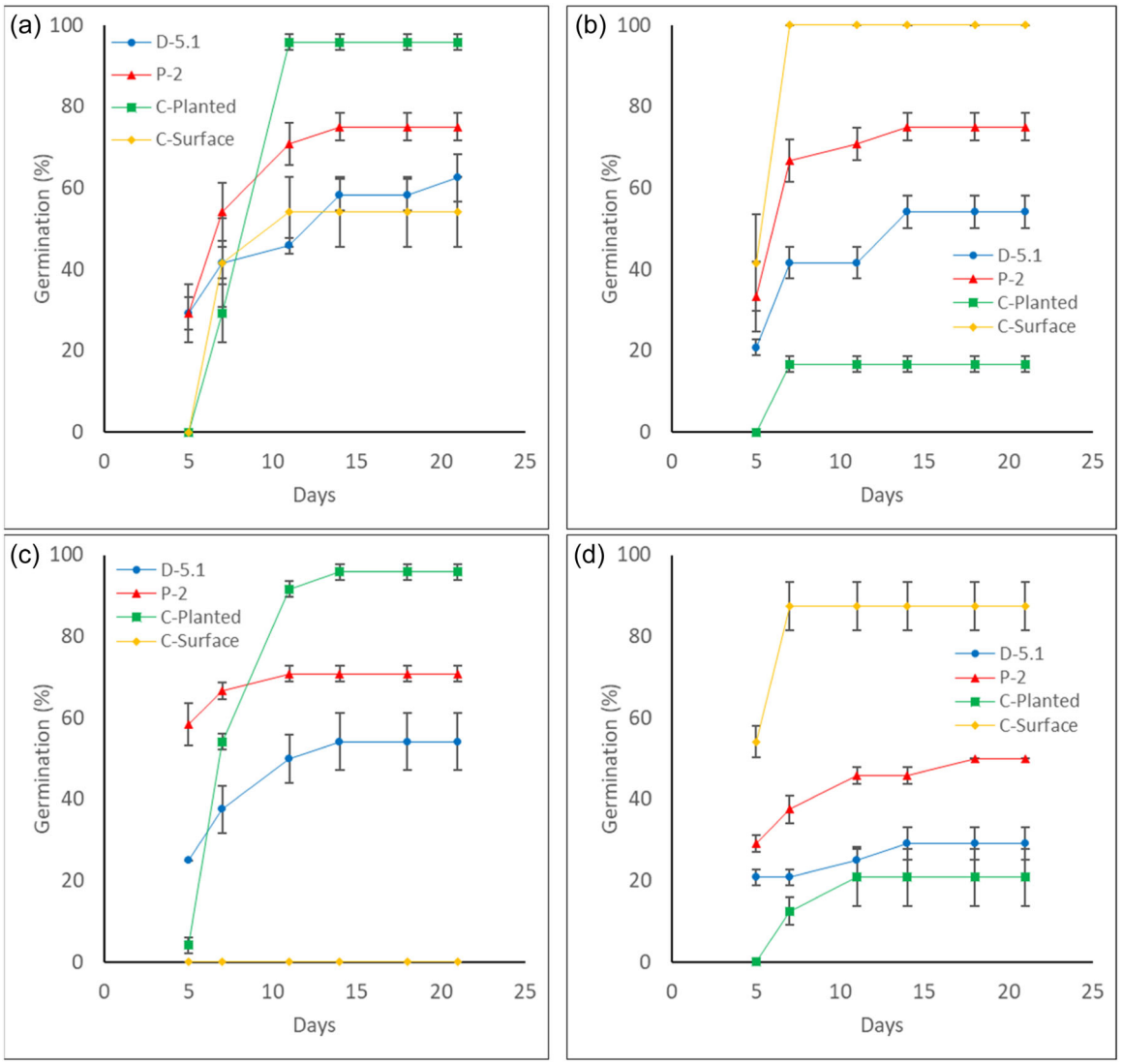



**FIGURE 4** Germination percentage of (a) beans 50% field capacity (FC), (b) beans 90% FC, (c) cucumber 50% FC, (d) cucumber 90% FC.

cucumber FW and DW using ANOVA determined no significant differences at 50% FC. However, significant differences in MC were observed, with P-2 producing cucumber seedlings with significantly higher MC than that of C-Planted (Figure 5d). At 90% FC both FW and MC concluded that encapsulants significantly improved the FW and MC of cucumber seedlings compared to both controls (Table S2 and Figure 5d). D-5.1 also produced a significant increase in DW compared to C-Surface. Analysis of cucumber root length was not significant for any condition at both 50% and 90% FC (Figure 5e). Shoot length analysis revealed more conclusive results. At 50% FC, there was a significant reduction in shoot length compared to C-Planted. At 90% FC encapsulants significantly reduced shoot length compared to C-Surface, but not C-Planted (Figure 5f). No significant results were obtained for total length of cucumber plants. At 50% FC, there was no significant effect for leaf development properties of cucumbers. In contrast at 90% FC, encapsulants successfully improved both leaf measurements as well as improved leaf count compared to both control conditions (Table S4).

## 3.4 | Nonagricultural, native seeds

Considering the evaluation of agricultural seeds and the superior germination performance of P-2 over D-5.1 in all conditions, as well as slightly more favourable growth results, P-2 was selected as the hydrogel for testing nonagricultural seeds. Assessing native seeds involved three Australian plant species: *A. stenophylla*, *C. refractus* and *E. coolabah*. This range covered grass species (*C. refractus*) and both fast and longer-establishing tree species (*A. stenophylla* and *E. Coolabah*). UAV seeding is far more likely to be utilised in a nonagricultural setting where large areas of complex terrain need to be seeded effectively. Although agricultural seeds may not directly translate to successful growth of long-term species it is likely that the poorer germination performance of D-5.1, particularly given the increase in presence of the white fungus compared to P-2 will result in a similar performance for the nonagricultural seeds. The use of P-2 also provides better insight into how PHM affects these arid species, so that other additives may be considered in the future if further

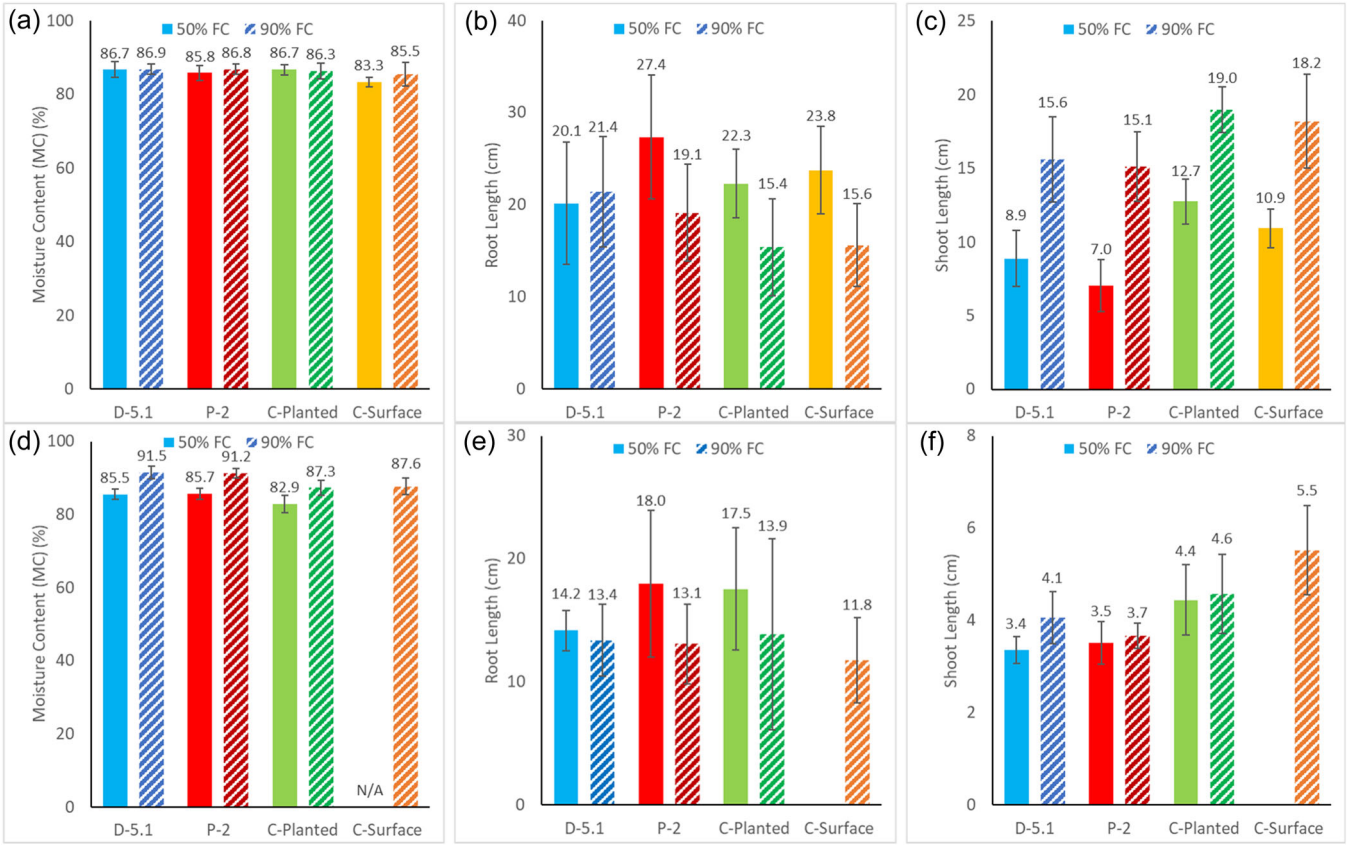



**FIGURE 5** Growth of beans; (a) moisture content (MC), (b) root Length, (c) shoot Length, and cucumbers; (d) MC, (e) root Length, (f) shoot Length.

investigation is warranted. As such the encapsulant should ideally be tailored to nonagricultural seeds, but ideally would be successful in improving both the germination and growth for agricultural crops as well.

*A. stenophylla* displayed highly positive germination results, with P-2 showing effective growth across both moisture conditions (Figure 6a,b). In contrast to beans and cucumbers, C-Surface seeds performed significantly worse than both P-2 and C-Planted seeds at 50% and 90% FC. P-2 was the most effective condition for *A. stenophylla* germination in both tests, slightly outperforming C-Planted seeds. This represents the most supportive use of PHM in germination compared to other tested plants, likely due to creating conditions like its natural habitat in semi-arid areas with sticky and moist soils. *A. stenophylla*'s ability to withstand waterlogged conditions explains its resilience to constant psyllium hydration.

At 50% FC, no successful germination of any encapsulated *C. refractus* seeds occurred (Figure 6c). At 90% FC (Figure 6d), while one seed germinated, the extended growth testing time (12 weeks) led to eventual rotting of the PHM, resulting in the death of the seedling. Future attempts to prevent such rotting would be unnecessary, as germination results were worse than those of C-Surface seeds in both conditions, underscoring the unsuitability of PHM as an encapsulant for *C. refractus* seeds. The lower germination rate is likely due to the conditions favoured by *C. refractus*, which involve surface sowing with a light soil covering in full sun to partial shade. The gel provides an overly moist environment, acting as a thick encapsulant that hinders germination. Consequently, these results suggest that PHM is not suitable for distributing grass seeds in semi-arid/arid ecosystem.

Unlike *C. refractus* seeds, PHM encapsulated *E. coolabah* seeds showed some germination at 50% FC (Figure 6e). At 90% FC (Figure 6f), encapsulated seeds outperformed C-Planted seeds but had no effect on germination compared to C-Surface, indicating no inhibition at 90%. However, after 9 and 10 weeks respectively, both 50% and 90% FC tests experienced significant gel deterioration and drying, leading to seedling death. While there may be potential benefits in higher moisture conditions, such as riverbanks or flood-prone areas, where P-2 at 90% FC resulted in more germinated seed pellets, the results weren't superior to C-Surface seeds. Investigating gel lifespan might not be worthwhile, as C-Surface seeding proves more effective, considering *E. coolabah*'s native environment in semi-arid and arid regions. Light and temperature, crucial for eucalyptus seed germination, were controlled, indicating the hydrogel did not inhibit these factors. Therefore, like *C. refractus*, encapsulating *E. coolabah* seeds in PHM may not be beneficial due to encapsulation and potential waterlogging.

Given that no PHM seedlings survived the full 12 weeks for *C. refractus* and *E. coolabah*, *A. stenophylla* had the only successfully

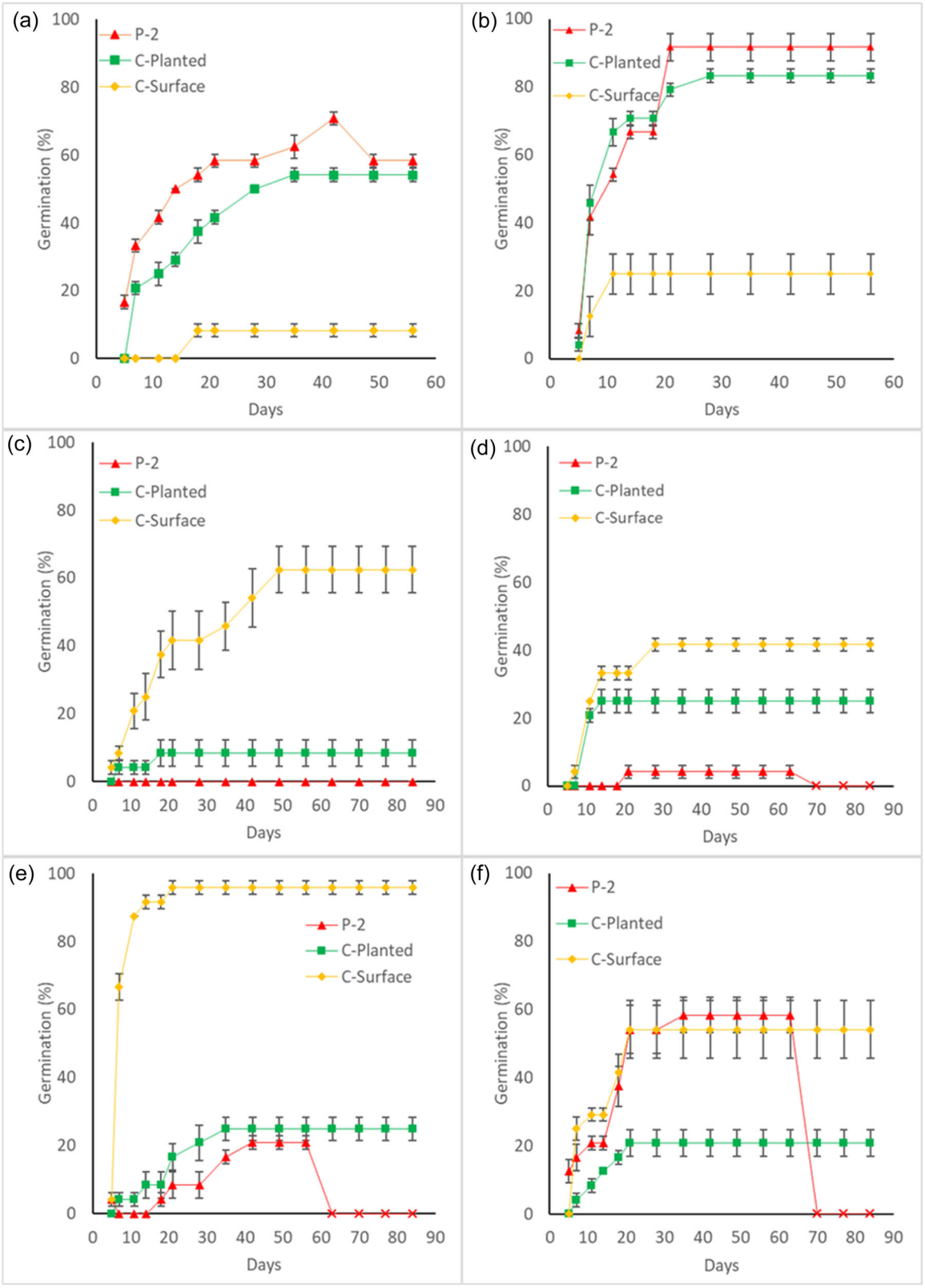



**FIGURE 6** Germination of *Acacia stenophylla* (a) 50% FC, (b) 90% field capacity (FC); *Cymbopogon refractus*, (c) 50% FC, (d) 90% FC; *Eucalyptus coolabah*, (e) 50% FC, (f) 90% FC.

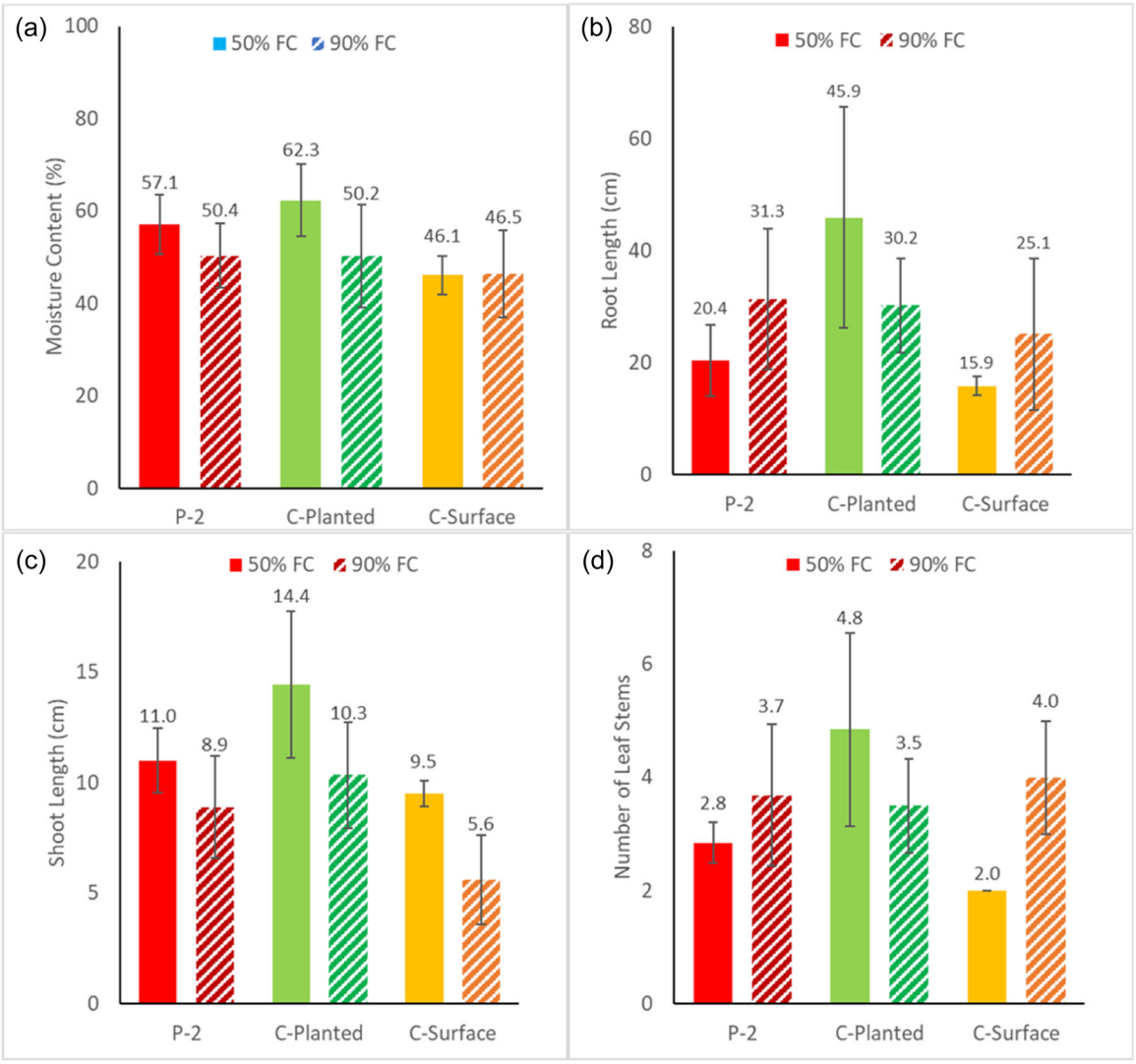



**FIGURE 7** *Acacia stenophylla* (a) Moisture content, (b) root length, (c) shoot length, (d) leaf stem count.

grown seedlings. As such the same growth assessments for the agricultural seedlings were repeated for the successfully grown *A. stenophylla* seedlings.

At 50% FC, P-2 exhibited a significant increase in FW and DW compared to C-Planted but did not produce a significant change in MC. At 90% FC, FW and DW as well as MC did not significantly differ from controls (Table S5 and Figure 7a). Root development showed a significant decrease with the application of the PHM encapsulant at 50% FC compared to C-Planted, but no change at 90% FC (Figure 7b). Shoot development and total length similarly was reduced compared to C-Planted at 50% FC, with no conclusive difference at 90% FC (Figure 7c). In terms of leaf development characteristics, no significant change was observed in leaf stem length at 50% FC, however both leaf width and leaf count were reduced compared to C-Planted (Figure 7d). Furthermore at 90% FC, there was no significant change in any assessed leaf development characteristic (Table S6).

## 4 | DISCUSSION

The results of the study showed that developed PHM encapsulants successfully met the stabilisation requirements allowing for their successful deployment from a UAV from a height of 3 m. Mucilages such as PHM naturally occur in smaller quantities and may facilitate seed establishment during natural seed dispersal cycles, by anchoring small seeds to surfaces (Zhao et al., 2021). Furthermore, mucilages may also facilitate in the natural repairing of DNA, which further improves seed survival (Yang et al., 2011). Previous studies have shown hydrogels have a diverse range of successful agricultural and reforestation applications particularly in challenging conditions (Dingley et al., 2024; Kaur et al., 2023; Patra et al., 2022). In agricultural applications PHM was shown to enhance FW compared to C-Surface, as well as DW for beans at 90% FC. Furthermore, bean root length and leaf development of both agricultural crops was also observed to have a significant increase at this condition. Previous

studies have shown that hydrated mucilages can improve the root development of chia seeds, facilitating water flow from soil to root system (Ahmed et al., 2014). Therefore, it is likely that in the moist soil condition the mucilage is able to facilitate this hydraulic activity better than in the drier condition. Mucilages can also facilitate the germination of seeds in low moisture conditions. Zhang et al. (2014). concluded that mucilages affect germination in two key ways, (i) extending the hydrated state of the embryo and (ii) it enables seed priming in drier conditions, preparing the seeds to germinate at the next rainfall. Given the nature of the agricultural seeds having little dormant behaviour these effects would be negligible, however, in the case of the nonagricultural seeds this priming would result in improved germination rates and efficiency at lower soil moisture conditions. Therefore, it is likely that the significant germination results for *A. stenophylla* at 50% FC is a result of this priming. Hence, under both soil conditions, P-2 was comparable to C-Planted and greatly outperformed C-Surface in terms of *A. stenophylla* germination. Germination was initiated by nutrients penetrating the hard seed coating, a common challenge with *A. stenophylla* seeds. However, in terms of growth C-Planted was the most supportive condition for *A. stenophylla* seeds at 50% FC, improving most measured criteria compared to P-2 (FW and DW, MC, root and shoot length, leaf width and count). However, at 90% FC the encapsulant greatly improved in performance, and whilst it consistently maintained a higher average performance across a range of criteria it was not sufficient to determine a significant improvement compared to C-Planted.

Given that beans did not require significant moisture to initiate germination, the excess water around the seed resulted in a fungus which negatively affected germination results. Moreover, in application this excess water content could influence plant development of which the effects are not fully reversible (Pociecha et al., 2008). Additionally, PHM encapsulants had minimal impact on overall seed growth in beans and cucumbers, with decreased shoot length observed for all encapsulants compared to C-Planted at 50% FC and negative shoot development compared to C-Surface at 90% FC, except for D-5.1 in the beans test. Therefore, it could be suggested that 50% FC may have sufficient water for beans to grow. However, the significant increase in plant mass for encapsulated seeds from 50% to 90% FC suggests plants prioritize MC instead of growth. Furthermore, the addition of 'Seasol Trilogy' could have resulted in improved root length by supplying peptides, organic nitrogen, and accessible carbon (Yusuf et al., 2011). In contrast, for cucumbers at 50% FC, it is likely that water requirements are not being met, resulting in lower plant MC. However, the encapsulants did have a noticeable higher average MC, wherein P-2 was significant to C-Planted. Whereas at 90% FC, PHM encapsulants were effective at improving the MC as well as all leaf development properties of cucumbers. It was also observed that root length decreased from 50% to 90% FC for P-2, suggesting that root development is not as critical when nutrients are readily available (van Noordwijk & Cadisch, 2002).

A key finding of the study was the death of *C. refractus* and *E. coolabah* seedlings, attributed to the lack of successful establishment before gel degradation occurred. Given, an uncontrolled environment, temperature, humidity, airflow, and light exposure can affect the drying time further resulting in reduced performance, particularly in more hostile environments where the research was focused.

This suggests PHM seed encapsulants may have potential in high-moisture environments for fast-growing species unaffected by excess water, expanding beyond the original arid/semi-arid focus. Furthermore, this study noted that germination was significantly impacted depending on seed size, with many cucumbers, *C. refractus*, and *E. coolabah* seeds trapped within the PHM encapsulant, preventing germination. Skrzypczak et al. (2021) also noted that these barrier properties need optimization to allow seedling emergence for fully encapsulated seeds without significantly impacting deployment results, rendering the material unusable (Skrzypczak et al., 2021). Additionally, the unfavourable water content of the PHM encapsulant significantly impacted the germination of beans, *C. refractus*, and *E. coolabah*. Hence, an alternative encapsulant could be developed where water is stored within water retention granules, like those used in soil additive applications (Niazy, 2020). This would provide sufficient water to the seed over an extended period without oversaturating it, thus preventing fungus growth and lack of germination. Lastly, without extending the degradation time, PHM encapsulants cannot be used in nonagricultural applications, as many species are slow-growing and would suffer a similar fate to that of *C. refractus* and *E. coolabah* seeds.

Despite the varying performance of PHM seed encapsulants it is essential to consider external factors that were controlled during the investigation, namely, displacement due to environmental factors such as wind and rain, as well as seed predation. Water erosion is one key factor in seed displacement that can greatly influence seeding success, wherein smaller seed species (like *E. coolabah*) are more prone to displacement. A study by Cerdà and García-Fayos (2002) showed that under controlled conditions seed loss due to water erosion can be as high as 93% (Cerdà & García-Fayos 2002). Traditionally, predator satiation theory is utilised to theorise the number of seed required to ensure a desired level of establishment, however as studies have shown this theory is not always consistent (Xiao et al., 2005). Furthermore, given research estimates that seed predation levels often exceed 90% of available seed, ensuring seed protection could greatly improve establishment outcomes and project success (Dalling et al., 2010).

Future studies and applications should thoroughly investigate seed selection, as site requirements change and dictate the need for pioneering and successional species. Although outside the scope of this project, it is important to note that seeds should be collected from a variety of sites and ages to promote genetic diversity, thereby enhancing future seed quality and plant survival. Future investigations should maintain high seed quality, and prioritise stress-tolerant, fast-germinating, and site-adapted seeds, as these have the greatest chance of reforestation success. Future investigations may also consider alternative materials, such as the use of other mucilages such as mustard (*S. alba*) or linseed flax (*L. usitatissimum*), or processes to reduce processing time without compromising cost, transportation, and manufacturing considerations.

## 5 | CONCLUSION

The findings of this study showed that PHM encapsulants successfully met deployment criteria and improved germination for *A. stenophylla* seeds, as well as improving the performance of beans and cucumbers compared to C-surface seeds at 50% FC. PHM improved FW and DW of beans and cucumber FW at 90% FC and increased the MC of cucumbers under both soil conditions. Beans encapsulated in PHM encapsulant developed longer roots and more leaves at 90% FC than C-Surface seeds, while both PHM encapsulants improved cucumber leaf count and size at the same condition. However, PHM blends were less effective than C-Planted at 50% FC and C-Surface at 90% FC in total mass. Minimal impact was observed on shoot and root length for beans and cucumbers. An important observation of this study was the degradation of the PHM encapsulant, which given extended testing resulted in seedling death for both *C. refractus* and *E. coolabah* seedlings. Hence, the study suggests potential for PHM seed encapsulants in high-moisture environments, enhancing seed delivery and survival. Future research should focus on seed selection, genetic diversity, and consider alternative materials or processes. Beans and cucumbers were not accurate models for nonagricultural seed germination and growth, suggesting they could be avoided in future reforestation studies.

### AUTHOR CONTRIBUTIONS

**Cameron Dingley**: Investigation, data curation, formal analysis, methodology, visualization, writing original draft. **Peter Cass**: Conceptualisation, methodology, supervision, writing—review and editing. **Benu Adhikari**: Supervision, writing—review and editing. **Prajakta Bendre**: Methodology, data curation, review. **Nitin Mantri**: Supervision, methodology, resources. **Fugen Daver**: Conceptualization, project administration, supervision, validation, writing—review and editing.

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### CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### ETHICS STATEMENT

We, the authors of this article declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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