

CRANFIELD UNIVERSITY

Silvia Arpano

Optimising polyacrylamide (PAM) spray application to mitigate the
agronomic effects of Soil Crust

School of Water, Energy and Environment

PhD

Academic Year: 2019 - 2022

Supervisors: Dr Robert Simmons and Dr Lynda Deeks
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ABSTRACT

The Leafy greens industry provides micronutrient-rich fresh produce at an affordable price. To meet the demand, multiple short crop cycles per year are seeded and harvested, for example, the summer spinach cycle can be as short as 21 days with 4 to 6 crop cycles in a season, in the UK. However, this high input/output agronomic system has a negative impact on other provisioning and regulating ecosystem services (ES). The primary soil-related ES that are affected are sequestration of soil carbon, crop production and water storage. The intensive soil management strategy promotes on-field loss of soil organic matter, which reduces soil resilience to erosive forces and contributes to the formation of capping and sealing. Soil capping and sealing inhibits seedling emergence, which reduces crop productivity. Within the rapid management cycle of leafy greens production there is limited time to incorporate soil amendments to offset the loss of SOM. This research explores the use of polyacrylamides (PAMs) as a soil surface amendment within this cropping system. Polyacrylamides are molecules with a long carbon backbone characterised by areas of different electric charge density. This trait allows them to bind to polar substance (e.g. water, soil colloids, soils organic matter). They are excellent flocculants and have been used for decades in furrow-irrigated crops to mitigate soil erosion and increase water infiltration. Besides flocculating particles in free-flowing water, PAMs have also been found to bind and protect soil aggregates by being adsorbed into aggregates and stabilising them. In combination, these two properties of PAMs have the potential to mitigate the agronomic effects of soil capping and sealing, including reducing emergence impedance, reducing splash contamination, and promoting water infiltration. However, PAMs are very hygroscopic and can be difficult to work with at concentrations above 500 ppm in water. This research investigated a new PAM broadcast system, using a Dual-Fluid nozzle which mixes PAM and water outside of the hydraulic system. The effect of PAMs on soil and crops were measured in a laboratory experiment and in five field trials on two crops, coriander and spinach. The metrics measured included soil crust, soil moisture, emergence and final yield quantity and quality.

The results of the research have shown the efficacy of PAM within commercial leafy greens crops. The application of PAM was associated with earlier emergence in coriander, that lead to higher biomass per plant and it also increased the emergence count in spinach, leading to an overall higher yield (47-39% for plots treated with 80 kg ha⁻¹ of PAM and 80kg ha⁻¹ PAM+Ca respectively). The amount of soil splash, and therefore potential for contamination of the product, was also reduced (24, 41 and 59% decrease in splash detached soil from plots treated with 40, 80 and 120 kg ha⁻¹ PAM respectively compared to the control). An economic appraisal based on the field data, also determined that PAM could be economically viable within the commercial cropping system and identified future improvements.

Keywords:

dual-fluid nozzle, synthetic soil conditioners, water use efficiency, splash erosion, infiltration, emergence homogeneity,

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LIST OF ABBREVIATIONS

AR	Application Rate
Ca+80	80 Kg Ha ⁻¹ Plus Calcium
CEC	Cationic Exchange Capacity
DAD	Day(s) After Drilling
FW	Fresh Weight
HC	Hydraulic Conductivity
KE	Kinetic Energy
LOI	Loss On Ignition
MW	Molecular Weight
PAM	Polyacrylamides
PR	Penetrative Resistance
SACI	Surface Area Corrugation Index
SOM	Soil Organic Matter
SR	Surface Roughness
WS	Water Scarcity
WUE	Water Use Efficiency

1 Application of Polyacrylamides in horticulture: surface application of an amendment to support sustainability

Abstract

Intensive field-based leafy green cultivation is a high input/high output industry, it supplies micronutrient-dense food at an affordable price, contributing to the transition to a nutrient-dense diet, essential for human wellbeing(Mirdehghan, 2010; Bailey, West and Black, 2015). The efficient provision of nutrient dense food, however, requires multiple crop cycles per year. Therefore, the provision of nutrient-dense leafy greens comes with a trade-off in term of other provisioning and regulating ecosystem services (ES). The intensive soil management impacts soil-related ES, including on-field loss of soil organic matter, which reduces soil resilience to erosive forces and contributes to the formation of capping and sealing. Soil capping and sealing inhibit emergence which reduces crop productivity. Within the rapid management of cycle of leafy green production there is limited time to incorporate soil amendments. This research explores the use of polyacrylamides (PAMs) as a soil surface amendment within this system. It explores the potential of PAMs to be applied effectively and efficiently within the commercial crop cycle and their potential to reduce the effects of soil capping and sealing on seedling emergence, improve water use efficiency and prevent contamination of the crop through soil splash.

1.1 Introduction

Intensive field-based leafy green cultivation is a high input/high output industry, it supplies micronutrient-dense food at an affordable price, contributing to the transition to a nutrient-dense diet, essential for human wellbeing(Mirdehghan, 2010; Bailey, West and Black, 2015). The efficient provision of nutrient dense food, however, requires multiple crop cycles per year. Therefore, the provision of nutrient-dense leafy greens comes with a trade-off in term of other provisioning and regulating ecosystem services (ES). The intensive soil management impacts soil-related ES, including on-field loss of soil organic matter, which reduces soil

resilience to erosive forces and contributes to the formation of capping and sealing.

Soil capping and sealing inhibit emergence which reduces crop productivity. Within the rapid management of cycle of leafy green production there is limited time to incorporate soil amendments. This research explores the use of polyacrylamides (PAMs) as a soil surface amendment within this system. It explores the potential of PAMs to be applied effectively and efficiently within the commercial crop cycle and their potential to reduce the effects of soil capping and sealing on seedling emergence, improve water use efficiency and prevent contamination of the crop through soil splash.

1.1.1 Crusting definition and Mechanism

The agronomic consequence of a deteriorating aggregate stability is the formation of a surface crust, a layer of reduced porosity and increased mechanical strength compared to the soil underneath. Soil crust formation is the result of the interaction between physical, chemical and biological processes (Le Bissonnais, 1996; Assouline, 2004). The primary drivers of soil crust formation occur simultaneously and are (i) the transfer of KE from the rain and/or irrigation drop to the soil, and (ii) soil moisture levels. Under rain and/or irrigation drop impacts, soil aggregates are compacted, their particles detached and splashed away. Simultaneously, the volume of water rapidly penetrating into the aggregates, contributes to their collapse via slaking, and decreases the aggregate resistance to the rain/irrigation drops in a process that involves physiochemical dispersion. This is due to the cohesive forces between soil colloids being weaker in water (Le Bissonnais, 1996). The disaggregated soil particles are then transported by the water medium, and are washed-in to the spaces between the aggregates below the impacted layer, and are compacted again by the rain/irrigation drops, in what could be classified as depositional crust (Assouline, 2004). When this hydrated soil seal is left to dry, the cohesive forces between colloids re-cement into a new, denser, configuration forming a de-hydrated soil crust. Some soil erodibility factors are independent from farm

management, e.g. texture and mineralogy (Wakindiki and Ben-Hur, 2002), or rain-drought patterns (FAO, 1993; Le Bissonnais, 1996), while others, like aggregate size distribution and stability (Tisdall and Oades, 1982; Mamedov *et al.*, 2017), or the exposure time of soil to rainfall/irrigation events are affected by agricultural practices.

1.1.2 Agronomic Consequences of Capping and Sealing

The major on-site effects of soil crusting for baby leaf and field grown herb production, are connected with reduced infiltration rates, splash contamination of stems and leaves, and with the mechanical impedance of crop emergence (WattsFarm; personal communication, 2019). Traditional strategies aimed towards the natural restoration of soil structure, do not fit in the business model for intensive baby leaf horticulture, that involves up to six 21-28 day crop growing cycles and repeated soil disturbance necessary to build fine seedbeds does not allow natural soil structure and aggregate stability to be generated as in less-disturbed soils (Sumner, 2000; Pagliai, Vignozzi and Pellegrini, 2004; Bronick and Lal, 2005).

1.1.3 Emergence/stand establishment/loss in yield

Soil crusts have a detrimental effect on seed germination even when other factors, such as soil moisture, aeration and temperature are not found to be limiting (Awashwal and Thierstein, 1985). The mechanical resistance imposed by a dry crust is enough to reduce the emergence rate of small seeded crops like sorghum (from 67 to 31% emergence at 3.0 kg cm⁻²), cotton (reduced to 0 at 0.29 kg cm⁻²), millet (0.23 kg cm⁻²) and guar (0.72 kg cm⁻²) (Awashwal and Thierstein, 1985). In arid and semiarid environments emergence of arable crops such as wheat (Braunack and Dexter, 1988; Anzooman *et al.*, 2018) and even maize (Borselli *et al.*, 1996) has also been studied and found to be restricted by the formation of a soil crust.

The correlation between seedling emergence and soil quality was first explored by Hanks and Thorp (1956), who found that a combination of lower soil moisture

and surface impedance caused a reduced emergence rate in winter wheat (26% against 80 and 82, respectively at 28 KPa plus dry soil, 15 KPa plus dry soil and 28 KPa plus soil at field capacity). Interest in this topic continued, with emergence trials on several arable crops such as wheat sorghum (Soman, Peacock and Bidinger, 1984; Daba, 1999), sugar beet (Lehrsch, Lentz and Kincaid, 2005), and barley (Abu-Awwad and Kharabsheh, 2000). Of note was the use of a synthetic soil conditioner, polyvinyl alcohol (PVA), which was applied to a treatment and successfully prevented the formation of a soil crust (Braunack and Dexter, 1988). The effect only of the PVA was mentioned in the paper, and no explanation was given of whether its effectiveness was due to the prevention of soil seal formation or to a water retention effect that it might have had on the surface.

1.1.4 Soil splash contamination and small scale erosion

Soil splash consists of the detachment and subsequent transportation of a portion of soil as a result of the impact of a water drop. It can be considered the early stage of the erosion process (Morgan, 2005). Soil splash depends on the rain erosivity, that being the mass and the velocity of the raindrops hitting a unit area, and the soil erodibility. In addition, the soil's physio-chemical characteristics, such as texture and presence of colloids, also affect the aggregate stability and the porosity (Le Bissonnais, 1996; Fernández-Raga *et al.*, 2017).

A soil continuously tilled and seeded for multiple harvests per year, spends a significant portion of the year with less than 50% canopy cover. As a consequence, rainfall impacts directly on soil particles, displacing them. Vertical displacement of soil onto the crop stems might be a vector for soil borne diseases, it might also affect the height of the cut during the harvest or require a more aggressive crop washing process during the post processing phases. The raw consumption of unwashed green produce has been described as one of the top sources of human exposure to microbial contamination from non-animal food sources (efsa, 2014). While microbial contamination can occur at any step in the food chain (FAO and WHO, 2008; efsa, 2013), pre-harvest sources of contamination have been found to be important in the build-up of *E.coli*, *Listeria*

and *Salmonella* in soils where leafy greens are grown (Park *et al.*, 2014). The strong relation between cumulative rainfall duration and survival of these pathogens on the soil has been proven over several field trials in the US (Park *et al.*, 2014) and their transmission to lettuce through soil splash has been found to be significant in recent experiments (Castro-Ibáñez *et al.*, 2015; Lee *et al.*, 2019).

1.1.5 Soil capping and a reduced water use efficiency (WUE)

When the soil surface is capped, the crust acts as an impermeable layer, reducing infiltration rate by as much as 14 times compared to an uncapped soil (Hardie and Almajmaie, 2019). As a result, the irrigation event, designed to fulfil the needs of the plant (Kohli *et al.*, 2011), is not able to deliver the required mm ha⁻¹ of water to the rhizosphere. Also, excess water ponds on the surface and ultimately leads to runoff of excess water and to an efficacy decrease in rainfall and irrigation events (Awashwal and Thierstein, 1985; Souza *et al.*, 2014). The price for a cubic meter of water in the study area (Kent, UK) was £3.72 m⁻³, and a 10 mm irrigation costed £607 ha⁻¹ (ref Chapter 6), meaning that an infiltration rate lower than the irrigation rate results in a financial loss for the farmer (ref Chapter 4). Off-field effects, include leaching of fertilisers and pesticides are potentially more impactful on society, causing eutrophication of freshwaters, micro pollution, and potential damage to the aquatic ecosystem because of scouring (Stoate *et al.*, 2001).

1.1.6 Conventional Mitigation Strategies

Current practices in intensive horticulture consist mainly of increasing the inputs, including increasing seeding rate and number of irrigation events. Any benefits of the addition of the occasional amendment (e.g. compost) at the beginning of a growing season and when switching between two non-compatible species is not enough to prevent the soil from capping. Depending on the field susceptibility to capping and on the season, to achieve the optimum final soil coverage, spinach and parsley can be seeded at up to 130% of the recommended seeding rate, with consequential losses in input efficiency for the farm management. Another approach is to prevent the soil seal from cementing by applying 8 millimetres of sprinkler irrigation just before the cotyledons emerge through the soil surface

(BBCH phase 08, (Meier, 2001)). While this approach might be effective for crops like spinach and dill, characterised by a relatively high weight per 1000 seeds and a short pre-emergence stage, it is not the most effective solution for crops characterised by lighter seeds with longer and less predictable pre-emergence times, such as Parsley.

1.1.7 Synthetic Soil Conditioners

Conventional practices used to promote soil structural regeneration such as mixed cropping, no tillage, and cover crops aimed at establishing a complete Soil Organic Carbon Pool (Bronick and Lal, 2005; Lal, 2014) are not compatible with the fast-paced agronomy associated with intensive baby leaf spinach and coriander production systems. Such systems demand production at a price point that can only be economically viable if multiple crop cycles are achieved in a growing season (Stichele and Young, 2012).

In the nineties, small quantities (20-40 kg ha⁻¹) of polyacrylamide (PAMs) were found to be effective at reducing soil loss when mixed with running water in row crops (Lentz and Sojka 1994a; Levy et al. 1992a; Mitchell 1986), at the time it was revolutionary for such amendments to treat only the soil that comes into contact with water and not the whole profile (Orts, Sojka and Glenn, 2000) and led to the wide implementation of PAMs in row crop in the United States (Lentz *et al.*, 2000; Sojka *et al.*, 2007).

In more recent years, a growing body of research has considered a more renewable alternative to the petroleum-derived, yet highly effective polyacrylamide. The closest match are polysaccharides, such as guar gum or starch. The properties shared with polyacrylamides are comparable molar weight (up to 1 to 2 10⁶ kg mol⁻¹), hydrophilic properties, and the strong tendency to form hydrogen bonds (Lu, Xiao and Xu, 2009; Lentz, 2015a). Table 1.1 contains an overview of the relevant studies on biopolymers.

While some biopolymers, such as chitosan and cellulose did mitigate the agronomic effect of soil crust formation (Orts, Sojka and Glenn, 2000; Lu *et al.*,

2018), they were systematically outperformed by PAM, to the point that PAMs are used as a benchmark treatment to test the efficacy of other biopolymers (Lentz, 2015a).

However, to date, no biopolymer can outperform and outprice polyacrylamides, because polyacrylamides are already widely used and available as wastewater treatment flocculant, and therefore a pre-existing and mature supply chain already exists, reducing infrastructure costs (SNF, 2021)

Authors	Year	biopolymer	field / laboratory methodology	Delivery	Application rate (AR)
(Shaviv, Ravina, and Zaslavsky 1987)	1987	l	laboratory	mixed in	n-a
(Ben-Hur <i>et al.</i> , 1989b)	1989	g	laboratory	sprinkler	5 kg ha ⁻¹
(Ben-Hur and Letey, 1989)	1989	g	laboratory	sprinkler	0.1% w/w solution
(Gal <i>et al.</i> , 1992)	1992	s	laboratory	sprinkler	1%w/w solution
(Levy <i>et al.</i> , 1992a)	1992	g	laboratory	sprinkler	5 to 40 kg ha ⁻¹
(Orts and Sojka 1999)	1999	ps	laboratory	furrow	100 ppm
(Orts, Sojka and Glenn, 2000)	2000	c, ch, x	laboratory/field	furrow	10 to 100 ppm in furrow
(Maghchiche, 2010)	2010	c, e	laboratory	mixed in	n-a
(Patil et al 2011)	2010	a, al, g, b	laboratory	mixed in	1 to 23 g kg ⁻¹
(Sartore et al. 2013)	2013	p,l	laboratory/field	spray	350 g m ⁻²
(Lentz, 2015a)	2015	b	laboratory	soak	0.001 to 0.01% w/w
(Smitha and Sachan, 2016)	2016	a	laboratory	mixed in	0.75 g kg ⁻¹
(Fatehi <i>et al.</i> , 2018)	2018	p	laboratory	mixed in	10g kg ⁻¹
(Sartore <i>et al.</i> , 2018)	2018	p, l	field spray, small parcels	spray	0.000225 %w/w

Authors	Year	biopolymer	field / laboratory methodology	Delivery	Application rate (AR)
(Lu <i>et al.</i> , 2018)	2018	ch	laboratory	mixed in	1 to 5 %w/w
(El-din <i>et al.</i> , 2016)	2019	p	laboratory	mixed in	1 to 2,5 %w/w

Table 1.1 List of relevant publication about biopolymers and their use in agriculture

a=agar agar; al=alginate psillum; b=bacterial exopolysaccharide; ch=chitosan; ca=casein; ce=cellulose g=guar gum; l=lignosulphonate p=polyaniline ps=polysaccharides s=siloxane x= xanthate

1.1.8 Agricultural Polyacrylamides: Morphology and Structure

Polyacrylamides are a broad spectrum of organic polymers, characterised by a Carbon flexible backbone featuring an acrylamide subunit every second Carbon (Lancaster and O'Connor, 1982; Hecker, 1998a). A Polyacrylamide monomer is the functional derivative of an acrylic acid $R-C(=O)OH$ where the OH group is substituted by a primary Ammine NH_2 (Brown, Campbell and Farrell, 2013). The result is a molecule that features an R group that links the acrylamide to the carbon backbone, and an extremity with two branches of opposite charges:

–The $(=O)$ Oxygen of the Acrylic Acid has a high e^- density on the outer region of the atom, due to the two complete p orbitals that are not involved in the double bond with the Carbon.

–The N, is part of a primary ammine, bonded to the rest of the molecule and to two H atoms: since N is more electronegative than H, the area around the Hydrogens is less likely to be negatively charged.

Consequently, although Acrylamide is not a polar molecule *per se*, it features areas of different electronic density, and therefore is prone to form extra molecular bonds with other molecules, driven by the London Dispersion Forces and by Hydrogen bonds. Despite being classified as weak binding forces, with respectively 3 and 1-2 folds-weaker strength compared to an ionic bond, they allow hydrogen (Hecker, 1998a; Tang, 2011) and Van Der Waals bonds (Lentz 2015; Lentz et al. 2000; Orts et al. 1999; Sojka et al. 2007 and many others) these polar regions distributed along the polymer, means that it is soluble in water even at high Molecular Weight, considering that readily available compounds can reach MW of 18 million kg (Du Pont, 2010) whereas the ones used for soil stabilisation are usually around 12 million (Orts *et al.*, 2007).

1.1.9 Polyacrylamide charge polarity and density

When polymerised on its own, Acrylamides are amphoteric, and have a neutral charge. As a consequence, it is common practice to copolymerise it with positively charged molecules to form Cationic PAMs and negatively charged

molecules to form Anionic PAMs. The charges are located on either side of the carbon backbone and affect the interaction of the PAM with the substrate, and not the integrity of the Carbon covalent bonds.

Cationic PAMs are usually copolymerised with primary, secondary, tertiary, or quaternary ammonium salts as positive moieties (Rabiee, Ershad-Langroudi and Zeynali, 2015). Their C=O interacts directly with the Clay anions through ion-dipole interaction and hydrogen bonds without any intermediary, but their use as soil amendments is restricted due to their adsorption to gills of aquatic organisms (Biesinger and Stokes, 1986).

An anionic PAMs, however, is the product of the copolymerisation with anionic units, containing a sulphate or a phosphate group (Aly, 2018). Anionic PAM is preferred as a soil conditioner due to its non-toxicity and it is usually copolymerised with acrylic acid, a molecule with similar MW and stearic volume (Sojka *et al.*, 2007). The presence of negative moieties on PAMs repels the negatively-charged surfaces of clay particles under laboratory conditions (Green, Stott and Graveel, 2005). As a consequence, anionic PAM relies on the presence of divalent cations available in the soil to bind with colloids through bridging. Anionic PAM is therefore more sensitive to soil pH, or to the manual addition of divalent cations to the soil (Laird, 1997).

1.1.10 Polyacrylamides' Properties

The features and the behaviour of the Polyacrylamide are linked to the architectural properties of the molecule: the length of the chain, the presence, nature, density and distribution of the charges along the chain, and if the structure of the polymer is linear or cross-linked.

The mean molecular weight of commercially available PAMs ranges from a few thousands to 20 million g mol⁻¹ (Bavernick, 1994). Every acrylamide unit weighs 71 g mol⁻¹, meaning that a 12 million g mol⁻¹ PAM, commonly used as soil amendment, has a mean molecular size of ca. 170000 bases. "Low" MW PAM does not exceed 10⁵ g mol⁻¹, "Medium"-sized PAMs range from 10⁵ to 10⁶, "High"

MW PAMs range from 1×10^6 to 5×10^6 g mol⁻¹ and anything above 10^6 is labelled as “Very High” (Bavernick, 1994; Rabiee, Ershad-Langroudi and Zeynali, 2015). Viscosity is positively correlated with MW and used in analytical studies to derive MW (Bavernick, 1994; Hecker, 1998a; Shatat, Niazi and Ariffin, 2017). Although a wide range of MWs are commercially available, the ones used for agriculture traditionally range from 12 to 18 million g mol⁻¹ (Levy and Agassi, 1995; Orts *et al.*, 1999; Green, Stott and Graveel, 2005; Costine *et al.*, 2018). The length of the polymer plays an important role in the correlation between dosage and effectiveness in flocculating soil particles. Low MW chains rapidly form lighter floccules at lower (g L⁻¹) concentrations, whereas heavier MW PAMs have been shown to have higher rates of precipitation at higher dosages, due to the formation of fewer but heavier floccules (Costine *et al.*, 2018).

The Molecular Mass Distribution (MMD) is a measure of how homogenous the PAM's MW is and provides an estimate of the molecular size distribution. Molecular weight homogeneity is a useful indicator of the quality of the polymerisation (Hecker, 1998a), and is usually measured through X-ray Scattering (Orts *et al.*, 2007). Although more research has been done on the mixture of different types of polymers than on polyacrylamides only, the use of different MW PAMs has mostly been investigated in solid-liquid flocculation, where the MW affects the speed of sedimentation. Mixture with different polymer lengths help the reaction kinesis. The fraction with the smaller MW initiates the flocculation, while heavier molecules allows bigger and heavier floccules, resulting in a quicker reaction overall (Du *et al.*, 2012). The effect of the MMD of PAMs applied to agriculture might become important if the manager is targeting a specific soil particle size distribution, for example in coarse soils where the higher MW would allow bridging across wider distances (Levy and Agassi, 1995; Chang, Im and Cho, 2016).

The Charge Density is expressed as the ratio between molarity or weight of charged units over the weight or molarity of total units. Rather than labelling PAMs with their actual charge density, it is common practice to classify them in qualitative categories. Polyacrylamides with less than 10% charged units are

generally considered “low charged”, between 10 and 30% as “moderate” and above 30% are considered “high charged”. Due to the polymerisation process, pure acrylamide PAMs have a negligible fraction (2-3%) of anionic charges, caused by the presence of residual amide groups that did not take part in the polymerisation, pure acrylamide polymers are still classified as non-ionic (Bavernick, 1994). An anionic charge density of 20% has found to be effective in improving water infiltration into soil (Shainberg, Warrington and Rengasamy, 1990), but more recent evidence has shown how Charge Density is secondary to MW and soil CEC in terms of PAMs performance in preventing soil erosion (Green, Stott and Graveel, 2005).

Besides affecting the polarity, the nature of the charges also affects the intra molecular bonds and therefore the final shape of the molecule (Hecker, 1998a). For example, a high charged PAM has a significant number of repulsing forces that do not allow a tight recoil of the molecule. These characteristics produce a less viscous fluid at the same MW, and thus in a better ratio between efficacy and practicality, because the molecule is likely to stay in its unfolded configuration and interact more with the substrate.

1.1.11 Limits of Polyacrylamide application in horticultural context

Polyacrylamides have a high efficacy at low application rates compared to alternative soil conditions such as gypsum. The length of the polymeric chain and the charge density allow PAM used in an agricultural context to adsorb several times its weight in water and bind to charged molecules suspended in water. When dissolved in water at concentration higher than 3.5 ppm ($=3.5 \text{ g L}^{-1}$) the viscosity of PAM increases and changes with temperature, concentration and flow conditions (Bjorneberg, 1998a).

The main limitation of using PAM at the field-scale is the practicality of its application. Polyacrylamides have been successfully implemented (i) where their application was relatively easy, such as in Corn Belt furrows, and (ii) in one off treatments with a high return value, such as civil engineering projects that can tolerate the requirement of high amounts of water per hectare needed to enable

an effective application of the product. In intensive horticulture, the challenge is to deliver an effective amount of PAMs, typically between 10 and 40 kg ha⁻¹ (Sojka *et al.*, 2007), to improve infiltration in situ by protecting the soil surface from capping and sealing processes.

1.1.12 The successful case of furrow irrigation

The first study that reported the use of PAM in an agriculture context was undertaken in the seventies (Paganyas *et al.*, 1972). Paganyas *et al.* (1972) reported a decrease in runoff of irrigation erosion using what was described as a “K” polymer, but plausibly this could have been a polyacrylamide, or a similar polymer (Sojka *et al.*, 2007). A decade later, Mitchell (1986) replicates the same experiment on a silty clay loam soil, reporting quantitative data on infiltration. They observed a 57% increase in infiltration rate with an application of 32 kg of PAM per hectare and also reported qualitative observations of runoff decreasing when PAMs were applied to irrigation water, both as dry granules. A second wave of studies came in the nineties. Treating only the soil surface rather than the entire profile, determined an efficacy at lower application rates compared to their incorporation in the soil profile. Moreover, PAM’s handling in furrow was extremely simple (no PPE, no machinery) (Lentz *et al.*, 2000) and supported by a consistent record of improved infiltration readings across several field trials (Table 1.2). These studies focused on the efficacy of different furrow application methods (Mitchell, 1986) exploring the mechanisms of adsorption into the soil (Ben-Hur *et al.*, 1992), the effect of different MW (Levy and Agassi, 1995), the possibility to use less costly copolymers (Lentz *et al.*, 1992a), the magnitude of charge, molecular weight and molecule architecture (Rodrick D Lentz and Sojka, 1994) (Table 1.2). The best practices for optimal erosion control was published in 1997, and are the backbone upon which the USDA’s “PAMphlet” was based and updated (Sojka, Lentz and Ease, 2018). Tables 1.2, 1.3, and 1.4 present an overview of where PAMs have been applied in an agriculture context in either field or laboratory environments.

Authors	Year	Charge	Architecture	State	MW (g mol ⁻¹)	Co-amendment	Field/ Laboratory	Soil	Application Rate (AR)
(Weeks, E and Colter, William, 1952)	1952	-	-	-	-	-	lab		-
(Paganyas <i>et al.</i> , 1972)	1975	-	-	-	-	-	field		-
(Mitchell, 1986)	1986	-	-	-	-	-	field	silty clay loam	6.6 to 32.2
(Lentz <i>et al.</i> , 1992b)	1992	anionic 20%	linear	powder	1 x 10 ⁷	starch	field	Silt Loam ^a	5 to 20 g m ⁻³
(R. D. Lentz and Sojka, 1994c)	1994	anionic 18%	linear	granules	15 x 10 ⁶	-	field	silt loam	<0,7 kg ha ⁻¹
(Levy and Agassi, 1995)	1995	anionic 20%	linear	-	2*10 ⁷ , 2*10 ⁵	-	field	various	20kg ha ⁻¹
(Trout, Sojka and Lentz, 1995)	1995	anionic 18%	linear	-	15 x 10 ⁶	-	field	silt loam	<0,7 kg ha ⁻¹
(Sojka, Lentz and Westermann, 1998)	1998	anionic 18%	linear	-	~13.5 × 10 ⁶	-	field	Silt Loam ^a	1g m ⁻³
(Lentz, Sojka and Mackey, 2002)	2002	anionic 18%	-	dry	1.2 to 1.5 10 ⁶	-	field	Silt Loam ^a	10 kg m ⁻³
(Roshanizarmehri <i>et al.</i> , 2018a)	2018	-	-	-	-	magnetite	field	Silt loam ^a	12.5 to 25 kg ha ⁻¹
(Zheng <i>et al.</i> , 2020)	2020	undisclosed	undisclosed	undisclosed	undisclosed	magnetite	lab	sandy	3kg m ⁻³
(Lentz <i>et al.</i> , 2020)	2020	anionic 18%	linear	granular, liquid emulsion	15 to 20 Mg mol ⁻¹	sodium acrylate, acid ammonium copolymers	field		10 to 125 g m ⁻³

Table 1.2 Overview of Publications on Polyacrylamide application in Furrows

a The soil is Portneuf Silt Loam, the USDA's Trials Location

Generally, the studies in Table 1.2 converge to an 18% hydrolysed anionic linear PAM. The simplest application consists of a patch method, where the granular polymer is applied in the bottom of the furrow within the first meter, downstream, of the inflow of the furrow. When the water comes into contact with the PAM, it forms a slimy layer that dissolves slowly, to ca. 10 ppm, into the furrow water (Sojka *et al.*, 2007; Sojka, Lentz and Ease, 2018). Residual amounts of the patch are usually still effective in subsequent irrigations, nonetheless, the patch method is less effective on steep slopes. Using the patch method, the most effective point at which soil stabilisation takes place is in the early stages of the irrigation event, when the PAM is initially wetted. At this point the soil surface of the furrow is immediately stabilised, preventing the detachment and the off-site transportation of soil particles (Trout, Sojka and Lentz, 1995).

1.1.13 The unfulfilled potential of sprinkler application

The application of PAMs to systems irrigated with sprinklers emerged at the same time as the furrow application and received as much interest, despite never really being implemented at a field-scale, as shown in Table 1.3. From the beginning, the main mitigation was aligned to reduce stresses on the soil surface caused by high-intensity irrigation (Ben-Hur *et al.*, 1989a; Shainberg, Warrington and Rengasamy, 1990; Gal *et al.*, 1992).

Rather than erosion control, the homogeneity of infiltration rate and velocity were the primary concerns of sprinkler irrigations. A typical sprinkler irrigation event of 8 mm corresponds to a 5.4 year return storm in Kent, UK (FEH 2020; Nelson Irrigation n.d.), and is usually characterised by bigger raindrop sizes (undisclosed by industry) that have greater kinetic energy, which are likely to cause soil sealing and crusting (Valentine and Ruiz Figueroa, 1987; Aase, Bjorneberg and Sojka, 1998). Soil capping and sealing are of major concern in many countries including semi-arid environments, especially on light and free draining soils, when they occur at the pre-emergence stage, as they reduce the overall efficiency of water use in crop management.

In sprinkler irrigation systems, PAMs would need to protect the soil from the impact of drops, both from rainstorms (Bullard *et al.*, 2018) and sprinkler (Lado *et al.*, 2016a). The early studies focused primarily on the efficacy of PAMs applied to prevent raindrop erosion. These studies applied diluted solutions of PAM through a hand-held sprayer (Ben-Hur *et al.*, 1989a; Smith, Levy and Shainberg, 1990), a trend that sometimes appears in the methodology of more recent papers (Abu-Zreig, 2006; Abu-Zreig, Al-Sharif and Amayreh, 2007; Li and Wang, 2016). The first experiment reporting the application of PAM through a full-size sprinkler nozzle was in 1992 (Levy *et al.*), followed by Ben-Hur (1997), Aase (1998), Levy (1999) and many others. Linear PAMs with a lower MW than PAMs used in furrow irrigation settings (10^5 instead of 10^6 g mol⁻¹) are generally chosen because of their lower viscosity (Ben-Hur *et al.*, 1989a; Shainberg, Warrington and Rengasamy, 1990). Laboratory studies have shown PAM applications to be sensitive to the water that is being used for irrigation. Rainfall water does not contain enough electrolytes to be used as divalent cationic bridges between the polymer and clay (Levin *et al.*, 1991; Sojka *et al.*, 2007). While experiments using waste water to deliver PAM through sprinkler irrigation found that PAMs react with the particles in waste water, decreasing its efficiency to stabilise the soil (Sepaskhah and Shahabizad, 2010). Early studies converged on an application rate of 20 kg ha⁻¹ (Shainberg, Warrington and Rengasamy, 1990; Smith, Levy and Shainberg, 1990; Levin *et al.*, 1991), which was found to reduce runoff, but there are a number of papers that report much higher application rates, ca. 40 kg ha⁻¹ (Ben-Hur and R Keren, 1997; Ben-Hur, 2001; Yonter and Uysal, 2010; Ao *et al.*, 2016) and papers reporting PAM's efficacy at less than 10kg ha⁻¹ (Aase, Bjorneberg and Sojka, 1998; Bjorneberg and Aase, 2000). The difference in the amount of PAM needed, is a function of the way in which it is delivered to the soil. Polyacrylamides delivered to the soil through a sprinkler system can be applied at a lower rate than the PAMs applied to a dry soil surface (ben-hur 1989). Table 1.3 displays relevant publications testing PAM on sprinkler-irrigated crops.

	Year	Charge	State	MW _a (g mol ⁻¹)	Co-amendment	Field/ Lab	Soil	Delivery	Application rate
(Ben-Hur and Letey, 1989)	1989	anionic "low"	-	15 to 20 10 ⁶	-	laboratory	sandy loam	sprinkler	5 kg ha ⁻¹
(Shainberg, et al., 1990)	1990	-	-	-	Phospho-gypsum	laboratory	sandy, clay loam	hand spray 0.05 w/w solution	10 to 40 kg ha ⁻¹
(Levin <i>et al.</i> , 1991)	1991	anionic 20%	powder	1 10 ⁷	Phospho-gypsum	laboratory		sprinkler	20 kg ha ⁻¹
(Levy <i>et al.</i> , 1992b)	1992	anionic	-	1 10 ⁷	-	laboratory		sprinkler	2 to 40 kg ha ⁻¹
(Ben-Hur and R. Keren, 1997)	1997	non-ionic, anionic 20%	-	1 - 2 10 ⁶	-	laboratory	sandy loam	sprinkler	25, 50, 75 kg ha ⁻¹
(Aase, et al., 1998)	1998	anionic 18%	granular	1.5 10 ⁶	-		silt loam	sprinkler	1 to 5 kg ha ⁻¹
(Levy and Rapp, 1999)	1999	anionic 20%	-	5 10 ⁵	-	laboratory	loess	hand spray 0.1w/w solution	20 to 40 kg ha ⁻¹
(Bjorneberg and Aase, 2000)	2000	anionic 18%	granular	1.5 10 ⁷	-	laboratory	silt loam ^b	sprinkler	1 to 3 kg ha ⁻¹
(Ben-Hur, 2001)	2001	non-ionic	-	1 - 2 10 ⁵	-	laboratory +field	sandy loam	sprinkler	20 to 40 kg ha ⁻¹
(Bjorneberg <i>et al.</i> , 2003a)	2003	anionic 18%	granular	1.5 10 ⁷	-	field	silt loam ^b	sprinkler	2.1 to 3kg ha ⁻¹
(Lehrsche, et al., 2005)	2005	cationic 80-100%	liquid	5 to 25 10 ²	-	field	silt loam	sprayed	0 to 1100 kg ha ⁻¹

Table 1.3 Overview of Publications on Polyacrylamide implemented for sprinkler-irrigated crops

^aMW=Molecular Weight; ^b The soil is Portneuf Silt Loam, the USDA's Trials Location

Despite consistent laboratory-based evidence supporting the idea that PAM can protect the soil from the impacts of sprinkler irrigation (Table 1.3), its use has been applied at a field scale only twice. First in 2001, on a potato field in Israel, where it was applied using a Moving System Irrigation Sprinkler (MSIS) (Ben-Hur, 2001), the freshly sown crop was treated with a PAM hand sprayer and then subjected to the usual cultivation operations. An application of 40 kg ha⁻¹ decreased the Total Runoff by 75%, at the end of the cropping cycle, but did not have significant effect on the yield. Second, in a two-year field trial in Idaho, on fine beans watered by a Solid-set Sprinkler System (Bjorneberg *et al.*, 2003a). The application rates were 2.1 and 3.0 kg PAM ha⁻¹ per annum, divided in four irrigation events every year. PAM treatments were associated with lower erosion rates and had no significant effect on runoff and final yield.

1.1.14 The return of granular form and the new wave of studies

Although PAM efficacy in preventing soil seal and reducing runoff has been demonstrated multiple times, achieving consistent distribution through spray solutions can be difficult due to the bulkiness and viscosity of the compound.

A new generation of studies are experimenting with granular PAM applied to the soil surface using topsoil as a vector (Table 1.4). This method has been shown to mitigate erosion when applied to the surface at 10-12 kg ha⁻¹ rates (Abrol *et al.*, 2013), and was adopted in subsequent studies with consistent results (Chang *et al.*, 2019) both in the study of nutrient loss due to runoff (Ao *et al.*, 2016; Li, Xu and Ao, 2019a) and in combination with fly ashes (Yang, Tang and Feng, 2020)

Authors	Year	Charge	Architecture	State	MW ^a g mol ⁻¹	Co-amendment	Field/ Laboratory	Soil	Delivery	AR ^b (kg ha ⁻¹)
(Känkänen <i>et al.</i> , 2011)	2011	-	cross-linked	granular	-	-	field		sowed with seeds	1,2 to 4
(Abrol <i>et al.</i> , 2013)	2013	anionic 18%	linear	granular	12 10 ⁶	gypsum	laboratory	silty loam	dry mixed in	5 to 20
(Atichat, 2015)	2015	anionic	linear	liquid	1.0 10 ⁷	-	laboratory	sandy loam	atomised	4 to 8
(Lado <i>et al.</i> , 2016a)Ó	2016	anionic 15%	-	granular	1.0 10 ⁷	burned calci cregosoil	laboratory		dry mixed in	25 to 100
(Ao <i>et al.</i> , 2016)	2016	anionic	linear	granular	2 10 ⁶	-	laboratory	loess	dry mixed in	5 to 40
(Li and Wang, 2016)	2016	anionic 30%	linear	granular	1.5 10 ⁷	-	laboratory		dry mixed in	0.5 to 8
(Li and Wang, 2016)	2018	-	-	granular	-	alone, mulch, grass strip	field		dry mixed in	20
(Lei <i>et al.</i> , 2019)○	2019	-	linear	granular	-	-	laboratory		dry mixed in	0.5 to 8
(Chang <i>et al.</i> , 2019)	2019	anionic	linear	granular	1.2 10 ⁶	-	laboratory		dry mix in	10 to 20
(Yang, Tang and Feng, 2020)	2020	anionic 30%	linear	granular	-	fly ash	laboratory		dry mixed in	0.01 to 0.02% w/w soil

Table 1.4 Overview of Publications on Polyacrylamide implemented as non-furrow

^aMW=Molecular Weight; ^b AR= Application Rate

1.1.15 How the current technology is unfit for the task

As shown in Table 1.5, the ratio of laboratory to field studies of furrow experiments is inverse to the ratio of publications investigating PAM applied to any alternatively irrigated crop system. Out of the 12 papers on furrow irrigated crops, 2 were lab-based and the rest were field-based. While, despite having a similar number of total publications (n=11), there were a higher proportion of papers relating to sprinkler-irrigated crop based on laboratory experiments (n=9) than on field trials (n=2), suggesting that efficacy of on-field sprinkler delivery technology is yet to be fully realised.

Application Type	Total	Laboratory	Field
Furrow	12	2	10
Sprinkler	11	9	2
Hand Spray	7	7	0
Dry Mixed In	9	8	1
Sprayed	1	0	1
Hydroseeder	4	2	2
Sowed	1	0	1
PVC Sleeve	1	0	1

Table 1.5 Polyacrylamide-related publications divided by application method, laboratory or field application. Data derived from Tables 1.2, 1.3 and 1.4. A more detailed version of this table is available in the introduction section of Chapter 3.

The main advantage of PAMs is their efficacy in protecting soil surface at a lower application rate, and when combined with an easy application method, like in furrow, has been proven to be a successful, widely adopted technology (Sojka *et al.*, 2007). The abundance of laboratory trials throughout the decades has proven its efficacy (Table 1.3 and 1.5) but the actual application of PAM as a spray or by impregnating the soil surface with a hand poured 3 ppm solution, is not

compatible with field operations, due to the quantity of water needed on the field to achieve the desired application rates with conventional sprayers.

In 2015 a laboratory trial on soil microcosm evaluated the effect of PAM applied with a rotary spray atomiser. The application of 8kg ha⁻¹ of a anionic PAM was found to be effective against a 15 min rainfall event of 20mm (Atichat, 2015). The PAM, presented as an emulsion, was atomised over the soil without being pre-mixed with water, allowing a reduction of 100% of the water volume required with a traditional sprayer. However, the fine droplets of the atomised Polyacrylamide, were prone to wind drift, and therefore extremely hard to clean once they deposited on the machinery (Rob Simmons and Ceri Dawson, personal communication).

1.1.16 Dual-fluid technology: a constraint-born knowledge gap

The implementation of PAM's on field systems outside furrows has not advanced so rapidly because of the technical constraints of PAMs' delivery process. There is no current evidence in literature of a system able to deliver 20 to 80 kg ha⁻¹ of PAMs without the need of tens of cubic meters of water per hectare and without compromising on molecular weight and charge density (Lehrsch, Lentz and Kincaid, 2005). The "hydroseeder" approach (low concentrated PAMs delivered using a firehose and up to 70 m³ ha⁻¹ (McLaughlin and Brown, 2006)) was not considered viable for a crop that is irrigated two to three times within the first two weeks, and it is not viable considering that commercial crop production needs to be cost and resource-effective (Stoate *et al.*, 2001; Pretty, 2018).

The limitation of using PAM mixed at any concentration higher than 2% is that it clogs up irrigation pipes and nozzles. To overcome this, the alternative is to mix the PAM with water outside the tubing/nozzle system. In its liquid form, PAM is coiled in mycellaes, and although viscous, it still has Newtonian rheological properties (Bjorneberg, 1998a), it is therefore possible to pump it in a hydraulic system by itself. A dual fluid nozzle, would allow PAM and Water to mix outside of the tubing. Outside tubing, PAM can be mixed at higher concentrations with water. Therefore, because of the reduction in the quantity of water needed in the

overall delivery of PAM to the soil surface, making the technology more portable and practical. The scope of this project is to implement this new technology from laboratory to a commercial field trial, to evaluate its performance within commercial management practice, and to assess its commercial feasibility.

1.2 Research Aims and Objectives

Polyacrylamides can potentially help to relieve the effects of soil stress found in intensive horticulture without sacrificing productivity. The aim of this project was to investigate if PAMs applied to the soil surface before germination can protect the soil from aggregate breakdown and (i) avoid soil sealing and capping, resulting in a homogenous emergence and a reduction of the seedling used per square meter, (ii) increase water infiltration, optimising water management, and (iii) mitigate soil splash contamination effect on the crop stems. The following objectives were undertaken to meet this:

- **Objective 1:** Determine the optimum product formulation and application rate to prevent capping and mitigate soil splash
- **Objective 2:** Evaluate the efficacy of the optimum PAM formulations/rates obtained from Objective 1 to facilitate seedling emergence and splash contamination for a range of target crops
- **Objective 3:** In collaboration with SNF, design a PAM sprayer that can be readily retro-fitted to the back of a seed drill
- **Objective 4:** Assess the practical applicability of applying best option formulations and applications using the PAM sprayer through a series of field trials
- **Objective 5:** Carry out a cost-benefit analysis of the application of best option PAM formulations/applications rates in the context of target crops investigated

1.3 Thesis Outline

This thesis has been written in a paper format. Therefore, contributions to scientific knowledge were written as individual academic journal articles (Chapters 2 to 5). Please note that due to the thesis format, introduction, methodology, results and discussion are presented within each chapter. Repetition of the experimental design description and methodology occurs between chapters. This research is structured to reflect the framework of the Technology Readiness Level (TRL) (European Commission, 2017), a framework designed to describe the stages of the implementation of a new technology, from the observation of a phenomenon, to the full commercial implementation. (Figure 1.1).

Chapter 1 provides background information about the agronomy of the leafy green industry, outlining the crop-specific consequences of intensification. It also reviews synthetic soil conditioners, specifically polyacrylamides including the history of its use in agriculture, changes in methods of application and chemical and molecular properties of consequence. An overview of the research topic and the wider context of the research is also presented. Contributed to Objective 1.

Chapter 2 provides an assessment of soil crusting. The primary aim of this research was to identify three similarly textured soils that had received comparable management but that had been observed to have different soil structural responses to irrigation, in order to determine which soil was the most susceptible to crusting. The secondary aim was to identify the most appropriate metrics to measure soil sealing and crusting that could be used in laboratory as well as on the field. The nozzle characterisation advised the upscaling process and contributed to Objective 3.

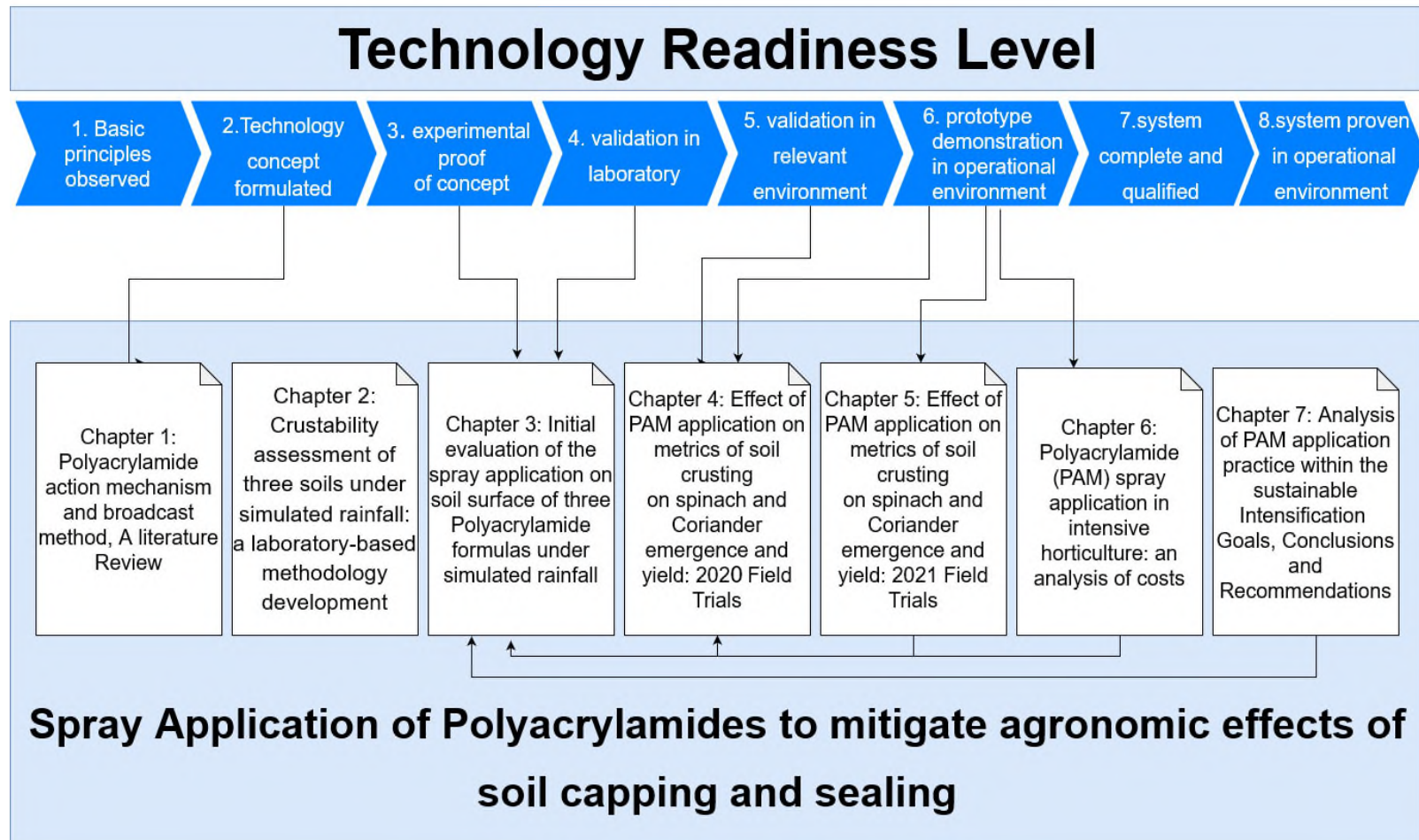


Figure 1.1 Thesis structure in relation to the Technology Readiness Level (European Commission, 2017)

Chapter 3: Presents the results of the Twin-Fluid nozzle tests. The primary aim was to investigate the use of a Twin-Fluid nozzle prototype in delivering three different PAM formulations to the surface of a crust-susceptible soil (identified in Chapter 2). The Twin-Fluid nozzle allowed the PAM and water to mix outside the sprayer hydraulic system, allowing the PAM micelle to activate in mid-air, avoiding the wind drift associated with a previous application method, the rotary spray atomiser. The secondary aim of this experiment was to identify the PAM that could be both applied effectively and also achieved the best agronomic results e.g. reduced soil capping. This work delivers experimental evidence at TRL 3 and 4 (Figure 1.1) and contributed to Objectives 1,3 and 4,

Chapter 4 Investigates the efficacy of the Dual-Fluid delivery method for PAM in a commercial crop of coriander (*Coriandrum sativum*) and Spinach (*Spinacea olearia*). The primary research objective was to measure the efficacy of a single PAM formulation (selected in Chapter 3) at three application rates (20, 40 and 80 kg ha⁻¹) sprayed 24 hrs after seeding. The efficacy of the PAM was assessed using the metrics tested in Chapter 2 and 3, specifically splash detachment as a measure of aggregate stability and soil moisture retention using volumetric soil water content. The trial also investigated the impact of PAM application rate on the homogeneity of crop emergence and final yield compared to the current commercial protocol. This work delivers experimental evidence at TRL 5 and 6 (Figure 1.1) and contributed to Objectives 2, 3, 4 and 5.

Chapter 5 also investigates the efficacy of the Dual-Fluid delivery method of PAM building on the trials presented in Chapter 4. It presents an investigation of whether higher application rates trigger a mulching effect by effectively creating a polymer barrier between the soil and rain or irrigation drop impacts. Results are also presented on the effect of adding Calcium Nitrate to the water prior to mixing with the PAM, to determine if this affects selected metrics of soil crusting, spinach emergence metrics and yield. Finally, results are presented that evaluate the efficacy of PAMs on water use efficiency by eliminating one of the two pre-emergence irrigations as compared to current management practices. This work

delivers experimental evidence at TRL 6 (Figure 1.1) and contributed to Objectives 3, 4 and 5.

Chapter 6 critically evaluates whether the spray application of PAMs using a Dual-Fluid nozzle is economically viable in the context of intensive leafy green production. The aim was to evaluate the incorporation of a single PAM application post-drilling in the crop management, quantify its costs and compare costs with conventional practice. Crop performance data from Chapter 5 was used to evaluate the economic performance benefits of the treatments investigated. This work delivers experimental evidence at TRL 6 (Figure 1.1) and contributed to Objective 5.

Chapter 7 presents the conclusions from the main outcomes of the study, identifies the research output and potential impact, and relates the research to wider Sustainable Development Goals.

1.4 References

- Aase, J. K., Bjorneberg, D. L. and Sojka, R. E. (1998) 'Sprinkler Irrigation Runoff and Erosion Control with Polyacrylamide — Laboratory Tests', *Soil Science Society of America Journal*, 62(6), p. 1681. doi: 10.2136/sssaj1998.03615995006200060028x.
- Abrol, V. *et al.* (2013) 'Efficacy of dry granular anionic polyacrylamide (PAM) on infiltration, runoff and erosion', *European Journal of Soil Science*, 64(5), pp. 699–705. doi: 10.1111/ejss.12076.
- Abu-Awwad, A. M. and Kharabsheh, A. A. (2000) 'Influence of supplemental irrigation and soil surface furrowing on barley yield in arid areas affected by surface crust', *Journal of Arid Environments*, 46(3), pp. 227–237. doi: 10.1006/jare.2000.0673.
- Abu-Zreig, M. (2006) 'Control of rainfall-induced soil erosion with various types of polyacrylamide', *Journal of Soils and Sediments*, 6(3), pp. 137–144. doi: 10.1065/jss2006.04.152.
- Abu-Zreig, M., Al-Sharif, M. and Amayreh, J. (2007) 'Erosion control of arid land in Jordan with two anionic polyacrylamides', *Arid Land Research and Management*, 21(4), pp. 315–328. doi: 10.1080/15324980701603557.
- Aly, A. (2018) 'Preparation and Evaluation of Some Anionic Starch Derivatives as Flocculants Preparation and Evaluation of Some Anionic Starch Derivatives as Flocculants Research Paper', (April 2002). doi: 10.1002/1521-379X(200204)54.
- Anzooman, M. *et al.* (2018) 'Selection for rapid germination and emergence may improve wheat seedling establishment in the presence of soil surface crusts', *Plant and Soil*. Plant and Soil, 426(1–2), pp. 227–239. doi: 10.1007/s11104-018-3609-6.
- Ao, C. *et al.* (2016) 'Efficacy of granular polyacrylamide on runoff, erosion and nitrogen loss at loess slope under rainfall simulation', *Environmental Earth Sciences*, 75(6). doi: 10.1007/s12665-015-5110-3.
- Assouline, S. (2004) 'Rainfall-Induced Soil Surface Sealing: A Critical Review of Observations, Conceptual Models, and Solutions', *Vadose Zone Journal*, pp. 1–60.
- Atichat, C. (2015) *CRITICAL EVALUATION OF ANIONIC POLYACRYLAMIDE BASED SOIL CONDITIONERS TO REDUCE SOIL SURFACE CRUSTING*. Cranfield University. Available at: <https://mta-cranfield-ac->

uk.eu1.proxy.openathens.net/handle/1826.1/11127.

Awashwal, N. . and Thierstein, G. . (1985) 'Characteristics , Impedance To Seedling Emergence , Methods of Crust Manage- Ment As Well As Measures of Encouraging Emergence Through the Crust Have Been Gathered and Discussed , in Order To Provide an Insight Into the Problem of Soil Crusting and Its Im', *Soil & Tillage Research*, 5(1985), pp. 289–302.

Bailey, R. L., West, K. P. and Black, R. E. (2015) 'The epidemiology of global micronutrient deficiencies', *Annals of Nutrition and Metabolism*, 66(suppl 2), pp. 22–33. doi: 10.1159/000371618.

Bavernick, F. W. (1994) 'Polyacrylamide Characteristics Related to Soil Applications', *Soil Science*.

Ben-Hur, M. *et al.* (1989a) 'Polymers as soil conditioners under consecutive irrigations and rainfall', *Soil Science Society of America Journal*, 53(4), pp. 1173–1177. doi: 10.2136/sssaj1989.03615995005300040030x.

Ben-Hur, M. *et al.* (1989b) 'Polymers as Soil Conditioners Under Consecutive Irrigations and Rainfall', *Soil Science Society of America Journal*, 53(4), pp. 1173–1177. doi: 10.2136/sssaj1989.03615995005300040030x.

Ben-Hur, M. *et al.* (1992) 'ADSORPTION OF POLYMERS ON CLAYS AS AFFECTED BY CLAY CHARGE AND STRUCTURE, POLYMER PROPERTIES, AND WATER QUALITY', *Soil Science*.

Ben-Hur, M. (2001) 'Soil conditioner effects on runoff and potato yield under sprinkler irrigation', *Agronomy Journal*, 93(5), pp. 1156–1163. doi: 10.2134/agronj2001.9351156x.

2 Crustability assessment of three soils under simulated rainfall: a laboratory-based methodology development

Abstract

A soil crust is a de-hydrated layer of variable thickness characterised by low porosity and high penetrative resistance. The negative agronomic impacts associated with surface crusts are reduced infiltration, increased runoff and erosion risk, and impeded seedling emergence. However, methodology to assess crust are diverse and fragmented across literature. The aim of this research was to select an array of metrics that capture the changes on the soil surface and that are appropriate to be used throughout the research project. This research critically evaluated the comparative 'crustability' of three crust susceptible soils subjected to a simulated rainfall event of increasing duration and Kinetic Energy. Soil 2, a clay loam, was the most susceptible to crusting under the simulated rainfall events studied, presenting various degrees of aggregate breakdown (11 an 38% of surface roughness lost after respectively 4 and 10 minutes of rainfall), , crust strength (5.29 and 7.02 MPa of 40and 10 minutes rainfalls compared to Control's 0.01 MPa) and unsaturated hydraulic conductivity (2.82 and 3.26 mm hr⁻¹ associated with 4 and 10 minutes rainfall versus Control's 21.2 mm hr⁻¹)) varying according to increasing crust durations. Penetrative resistance and 3D scanning showed the highest efficacy as crust development metrics, showing significant differences between all treatments within each soil.

2.1 Introduction

High intensity farming practices are known to degrade soil. This has both economic as well as environmental impacts (Pagliai, Vignozzi and Pellegrini, 2004; Bronick and Lal, 2005). Of particular concern to the horticultural industry is soil degradation leading to the formation of a rainfall or overhead irrigation induced soil structural crust. A soil crust is a de-hydrated layer at the immediate soil surface of variable thickness characterised by low porosity and hydraulic conductivity and high penetrative resistance. The physiochemical action of

rainfall breaks aggregates downs and compacts them, forming a structural seal. The finer soil particles are dissolved in the liquid matrix on the structural seal surface and set down to form a depositional seal. Upon desiccation, the seal formed by cementation into a crust (C. Valentin and Bresson, 1992). The agronomic effect associated with surface crusts are reduced infiltration (Valentin and Bresson, 1997; Bronick and Lal, 2005) increased risk of runoff and erosion (Armenise *et al.*, 2018), and impeded seedling emergence (McIntyre, 1958; Awadhwal and Thierstein, 1985). Mechanical impedance to seedling emergence caused by structural crusts is a limiting factor in stand establishment and has been shown for a wide variety of commercial crops to delay stand establishment and reduce plant populations (Awadhwal and Thierstein, 1985; Lehrsch, Lentz and Kincaid, 2005). In some cases, final plant densities can be reduced to the point that replanting is necessary (WattsFarm, spoken communication 2019). Uniform emergence of seedlings, has a direct influence on final yields as well as the proportion of yield in high value size grades at harvest (Lamichhane *et al.*, 2020). Consequently, structural crusts can have a profound effect on the commercial viability of crop production systems.

Frequent soil tillage operations (consisting of a pre-season subsoiling plus a GPS-guided double pass of a seedbed former, repeated prior to every crop cycle) required to generate fine seedbeds for e.g. baby leaf salads, spinach and herb cultivation, expediate the oxidation of the natural-occurring soil organic matter (SOM). Baby leaf salads and field grown herbs are also typically associated with high kinetic energy (KE) short duration (8 ± 1 min) high intensity (75 ± 30 mm hr⁻¹) pre-emergence irrigations to facilitate seed germination and emergence. However, this energy input can promote the formation of a soil seal and upon dehydration, crusting which impedes emergence, stand establishment and final yields. The combination of intensively cultivated fine seed beds and frequent high intensity irrigations results in these high value horticultural production systems being more prone to soil crusting than broad acre arable production (Pagliai, Vignozzi and Pellegrini, 2004; Bronick and Lal, 2005).

There is little standardisation (Assouline, 2004; Pulido Moncada *et al.*, 2014) in the methodologies used to measure the magnitude of a soil crust, but all methodologies can be grouped according to direct observation of the soil morphology or indirect measurements, that quantify the crust's main agronomic effects: reduced hydraulic conductivity and increased penetrative resistance. Along with these two methodological groups, a third approach aims to evaluate a soil's 'crustability' index, aiming to prevent crust formation. Several indexes of crustability have been developed over the last forty years (Boiffin J., 1982; C. Valentin and Bresson, 1992; FAO, 1993; Le Bissonnais, 2016). This final approach is applied in crust prevention studies and will not be considered in this research.

Morphological approaches consider 2D or 3D observations of the immediate soil surface. The principle guiding the earliest crusting index, D_{min} , was that the smallest aggregates are the first to breakdown, hence the size of the smallest visible aggregate on the surface was used as an index of crust formation (Boiffin 1984). Direct observation of the crust have been used to explore its formation process since 1939 (Duley, 1939), with increasing interest until the early two-thousands as reviewed by Pagliai and Stoops (2010). The use of micro and macro CT scans have been shown to be useful to study the development of soil crusts in order to understand crusting dynamics (Pagliai and Stoops, 2010). A variation of a crust morphology metric is Soil Surface Roughness (SSR), a metric used in erodibility assessments (Zobeck and Onstad, 1987; Hudson, 1995). The traditional methodology consists of a mono-dimensional reading recorded with pins or a roller chain with 3D SSR assessments can be considered an evolution in accuracy and precision. Three-dimensional readings can be achieved using Photogrammetry or laser scanning surface scanning). The former is used to generate a digital elevation model (DEM), and the later, to produce a 3D surface profile (Jester and Klik, 2005; Thomsen *et al.*, 2014). Two characteristics considered essential when choosing the most suitable tool are accuracy of the measurement and practicality. With photogrammetry, instantaneous data capture is useful in assessing dynamic processes (Lu *et al.*, 2018), but has limitations

caused by the fixed angles and distance from the sensor, because the DEM is only able to record the maximum height at any even point, leaving out of the area measurement any surface that has an inclination higher than 90°. A comparative study found photogrammetry- generated DEMs to be less accurate than laser scanners in capturing the smaller soil aggregates (Jester and Klik, 2005). Conversely, laser scanner measurements have been found to be time consuming, (34 minutes compared to 5 minutes per scan), but required overall less time in post processing (Jester and Klik, 2005). In this study, the small dimension of the experimental unit (100mm Ø microcosm) and aggregates (< 2mm), outweighed the use of traditional SRR instruments and photogrammetry, leaving laser scanning as the most suitable strategy to measure SRR and therefore crustability.

Despite the number of publications featuring CT scanning derived morphological measurements and their relevance to understanding a crust's intrinsic properties (Valentin and Bresson, 1992; Horton, Ankeny and Allmaras, 1994; Pagliai and Stoops, 2010), most of the studies where a soil crust is framed within an agronomic context have since the early days, been dominated by indirect measures, for example hydraulic conductivity (HC) (Duley, 1939; McIntyre, 1958) and penetrative resistance, (PR) (Richards, 1953a). These approaches are still relevant today (Armenise *et al.*, 2018; Bullard *et al.*, 2018; Hardie and Almajmaie, 2019). Hydraulic Conductivity is the most common index of soil crustability (Duley, 1939; Valentin & Bresson, 1992a and many others), and measures the effect of the crust on the water infiltration rate (IR). The presence of a relatively thin layer of reduced porosity at the soil surface also affects the water intake of underlying unaltered soil matrix (Hardie and Almajmaie, 2019). As a consequence measuring the IR using saturated conductivity methods is problematic because of the brittle layer of crust that is easily disrupted (Pulido Moncada *et al.*, 2014; Souza *et al.*, 2014; Nciizah and Wakindiki, 2015). Unsaturated hydraulic conductivity, in particular using a Decagon Mini Disk Infiltrometer, has grown in popularity because it does not disrupt the surface crust like a traditional infiltration ring which requires insertion. In addition, it is more

portable than a full-sized infiltrometer and it can be used for both laboratory and field trials (Pulido Moncada *et al.*, 2014; Armenise *et al.*, 2018; Hardie and Almajmaie, 2019).

The second indirect metric, penetrative resistance (PR), measures the mechanical impedance of the crust. Emergence of seedlings has been shown to drop from 100 to 0% when the crust strength increased from 0.10 to 0.27 kg cm⁻² (0.009 to 0.026 MPa) (Richards, 1953b). There is no precise formula to determine the relationship between seedling emergence and crust PR due to differences in seedling physiology, in the energy reservoirs of the seed and in their phenology (Awadhwai and Thierstein, 1985), in addition to other factors including crust moisture content and the presence of conditioners in the crust (Rubio *et al.*, 1989; Borselli *et al.*, 1996). Crust strength can be measured by the falling cone method (Al-Durrah and Bradford, 1982b), the Geotester (Lehrsch, Lentz and Kincaid, 2005; Pulido Moncada *et al.*, 2014; Bullard *et al.*, 2018) or with devices that in addition to the one-point values produced by the penetrometer or the Geotester, also describe the variation of PR within the soil profile. Callebaut (1985) explored the effect of volumetric water content on PR using a needle penetrometer similar to the Instron (T-5001 manufactured by J.J. Lloyd Instruments Ltd). Callebaut (1985) showed that low moisture content soils are associated with higher PR in respect to more hydrated soils (1.5 MPa at 11 %vol versus 0.25 at 31%) 15mm depth on a loamy sand soil, texturally similar to the ones used in this research. These PR values were just below the ones reported by Richards (1953). More recently, a Instron Tensiometer, originally designed to evaluate the tensile strength of materials was employed to survey a wide array of Scottish soils (Griffiths *et al.*, 2015).

Another approach, that assesses soil crustability before the rainfall event, uses aggregate stability as the primary experimental index to establish whether a soil is prone to crusting. As soil particles that fill soil pores come from disaggregated aggregates, the assumption is that soils with less stable aggregates will be more prone to crusting. The most recent iteration of this approach was published by Le Bissonnais (2016), which also discusses different processes causing aggregate

breakdown and crust formation. However, soil tillage operations typical of intensive baby leaf and herb cultivation pulverises existing aggregates in primary particles. For this reason, aggregate stability measurements reviewed by Le Bissonnais (2016) are not going to be considered as suitable metrics in this study.

The primary objective of this research was to critically evaluate the comparative 'crustability' of three crust susceptible soils from Watts Farms, Kent in order to identify a suitable test soil for subsequent laboratory and field-based PAM performance trials. In addition, three metrics were evaluated in terms of their ability to quantify changes in the degree of crusting and applicability for adaptation for field trials.

2.2 Materials and Methods

2.2.1 Soils

The light loamy soils on Watts Farm meet most of the risk factors connected with soil crustability. Their relatively high proportion of silts and sands fractions compared with clays (Table 2.1a) suggests unstable aggregates (Le Bissonnais, 2016), mineralogy test reveals that even the finer particle class belong to tectosylicates, with a phyllosilicates fraction around 7.6 to 13.9% of mineral portion (Table 2.1b). Three different fields managed by Watts Farms, Southfleet, Kent, UK were sampled on the 10th of July 2019. The three field locations were known to have comparable soil textures but different agronomic behaviour in terms of crustability (Watts Farm, personal communication, 2019).

Soil 1 is an association between a Calcaric Leptosol and a Calcalir Endoleptic Cambisol, a shallow, well drained calcareous silty soil (LandIS, 2022). Soil 1 is considered to be the least crust-susceptible of the three, with the highest crop emergence and water use efficiency. Soil 2 is a Chromic Endoleptic Luvisol, a quartzite-rich clay loam (LandIS, 2022), and is empirically considered the most crust susceptible of the three soils (Watts Farm, personal communication, 2019). Soil 3 is an association between a Calcaric Cambisol and a Calcaric Endoleptic Cambisol, a well-drained, calcareous, fine silty, and often very stony (LandIS,

2021). For each field, a 3-point randomly selected bulk (circa 30 kg) composite sample was collected from 0.0 - 0.3m depth at least 20 m from the field boundary. The soils were subsequently air-dried at 24 ± 2 °C, de-stoned and sieved to <2.0 mm before use. Physical-chemical characteristics of the test soils are shown in Table 2.1.a. The relatively high 600 °C Loss On Ignition (LOI) values do not reflect the real SOM, because of the underlying chalky parent material. Soil analyses were made following the corresponding ISO Standard or methodology (pH, BS ISO 10390:2005; Soil Moisture at 110 and LOI 600 °C, (Klute, 1986); Particle Size Distribution, ISO 11277:2009; Cation Exchange Capacity, BS 7755-3.12:1996).

Mineralogy Tests done by the James Hutton Institute shows that all the samples are dominated by quartz, with small to trace amounts of K-feldspar and Plagioclase (another feldspar) the clay minerals (Table 2.1b).

Soil ID	Field Name	pH	Soil moisture (110 °C)	LOI (600°C)	Clay (%)	Silt (%)	Sand (%)	Texture ¹	LandIS soil association ²	CEC (cmol kg ⁻¹)
1	Lineside	6.5	0.95%	2.52 %	16.2	11.2	72.3	sandy loam	0343h ANDOVER 1	0.06
2	Beslee 34	5.7	1.62%	3.76 %	31.2	23.2	44.94	clay loam	0571g FYFIELD 4	0.04
3	Worleys 14	6.0	1.99%	3.24 %	28.6	19.7	55.59	sandy clay loam	0511f COOMBE 1	0.04

Table 2.1a Physical-chemical characteristics of the test soils.

¹ (Marshall and Holmes, 1979); ²(LandIS, 2021)

	Tectosilicates				Ca Carbonate ³	Iron Oxides		Phyllosilicates	
ID	Quartz	K-feldspar	Plagioclase	Muscovite	Calcite	Goethite	Hematite	Chlorite	I+I/S-ML ⁴
1	77.9	6.4	5.1	0.2	0.3	2.1	0.3	0.1	7.6
2	67.4	6.9	6.4	0	0.3	3.9	0.3	0.9	13.9
3	72.3	6.6	3.4	0	0.2	3.6	0.2	0.3	13.4

Table 2.1b Mineralogy Results (%weight) (X-Ray Powder Diffraction (XRPD)) (Kames Hutton Institute, 2020)

³ Calcium Carbonate Residues after 1000 °C LOI, ⁴ Illite + Smectite Clay fractions, full mineralogy is available in Appendix E

2.2.2 Experiment Design and Treatments

The test soils were packed into PVC microcosms of 100mm Ø and 60mm depth. Two, 2.0 mm wide, 80 mm long slots were cut 5.0 mm below the microcosms' top to allow drainage from the soil surface. A 0.5 mm thick fabric mesh was attached to the base of the microcosm to retain the soil and to ensure free drainage of water. Above this a Wattman 100 mm disc filter paper was placed inside at the base of the microcosm to prevent soil particles passing through the fabric mesh and to slow down water drainage enough to facilitate surface ponding and allow the formation of a depositional soil crust on top of the structural crust. The microcosms were packed to a depth of 40 mm with <2.0 mm diameter of Garside Sand (Garside 80EW, Leighton Buzzard, UK) following the methodology also used by (Agassi, Shainberg and Morin, 1981; Armenise *et al.*, 2018) above which a 20 mm layer of air-dried soil at a bulk density (BD) of 1.2 g cm⁻³ was added. The soil BD was decided based on the results of field and air-dried BD samples collected the previous growing season, sampling the soil matrix just below a soil crust. Surface roughness on soil microcosms was homogenised. A consistent number of aggregates, 4.0 g (from the total sample weight) of aggregates between 0.1 and 0.2 mm were isolated and layered on top of each microcosm. Antecedent soil moisture content has been found to affect the aggregate breakdown (Loch, 1994; Le Bissonnais, 2016). In the field, the upper mm of soil in freshly tilled soils during a dry summer are close to air-dried. Therefore, to simulate field conditions air-dried soil (at 20 °C) was used.

Each of the three soils in the microcosms were exposed to a single intensity storm event of three durations as compared with a zero-rainfall control (Table 2). The return period (Table 2) of these rainfall events was based on the location of Watts Farm (553505, 168123) and generated using the UK centre for Ecology and Flood Estimation Handbook Web Service (FEH, 2019). Every treatment was replicated four times (n = 48). Destructive measurements, such as Penetrative resistance and hydraulic conductivity were recorded on separated microcosms, increasing the physical number of units to 96 per soil type.

Rainfall Duration (min)	Rainfall Depth (mm)	Rainfall Return Period (years)*
0	0	N-A
2	4	<1
4	7	4
10	17	19

Table 2.2 Rainfall return period based on the location of Watts Farms

The time duration of the rainfall was designed to capture different stages of the crusting described in (C Valentin and Bresson, 1992): partial and complete aggregate slacking (2 and 4 minutes) and complete structural and depositional crust formation (10 minutes).

Simulated rainfall was generated using the Tower Rainfall Simulator at Cranfield University Soil Management Facility. The rainfall simulator consisted of a water reservoir with a 0.5 m² bed of hypodermic needles (BD Microlance 3.21g 0.8 × 40 mm), set 8.8 m above the plane of rainfall impact. A 21 mm-high weir on the edge of the reservoir allowed a constant water pressure over the needles, while a 4.0 mm wide metal mesh 1.0 m below the needle bed increased the drop-size randomisation. The needle pattern (presence, spacing and position) and the weir height were calibrated until a homogenous rainfall intensity, drop size distribution and KE were achieved on the plane of impact. The calibration of the Rainfall's attributes was achieved using collection cups and a Laser Optical Disdrometer (LOD, model OTT-Parsivel 2, OTT Messtechnik, Kempten, Germany) positioned at five locations within a 1.0m² target area and measured five times over a 10 min duration. The target Intensity is 100 mm ha⁻¹, with a tolerance of ± 10 mm h⁻¹. Rainfall characteristics are given in Table 2.3.

Following the rainfall simulation, development of a surface crust was initiated through surface dehydration. There were no walls on the sides of the drying bench, this allowed free airflow and facilitated the exchange of humidity with the surrounding environment. Drying time before hydraulic conductivity was 5.0

± 0.25 days after the rainfall event, for Penetrative resistance it was 6.0 ± 0.25 days.

Rainfall intensity designed mm h^{-1}	100
D50 (mm^3)	1.69
$\text{J m}^{-2} \text{h}^{-1}$	1792
$\text{J m}^{-2} \text{mm}^{-1}$	21.9

Table 2.3 Characterisation of the simulated rainfall

2.2.3 Soil Physical Measurements

2.2.3.1 3D Surface Roughness

3D scans of surface roughness were captured using a Creaform EXAScan 3D hand-held laser scanner with a resolution of 0.40 mm. A disk with the same internal diameter as the PVC microcosm (100mm Ø) and a 1600 mm^2 square opening in the centre was carefully placed on top of the soil in the microcosm at a precise orientation defined by a location marker on the microcosm's rim. The use of the precisely-oriented quadrat allowed the scans to be taken at precisely the same position before and after the simulated rainfall, (Figure 2.1). The 3D scanning process consisted of a rough 2.0 mm resolution pre-scan of the entire disk, followed by a precise scan of the target square at a resolution of 0.40mm. The result, a mesh file, was imported into Geomagic studio version 14.2.2. The scanned image for each microcosm was then clipped to the 1600 mm^2 area of the quadrat.

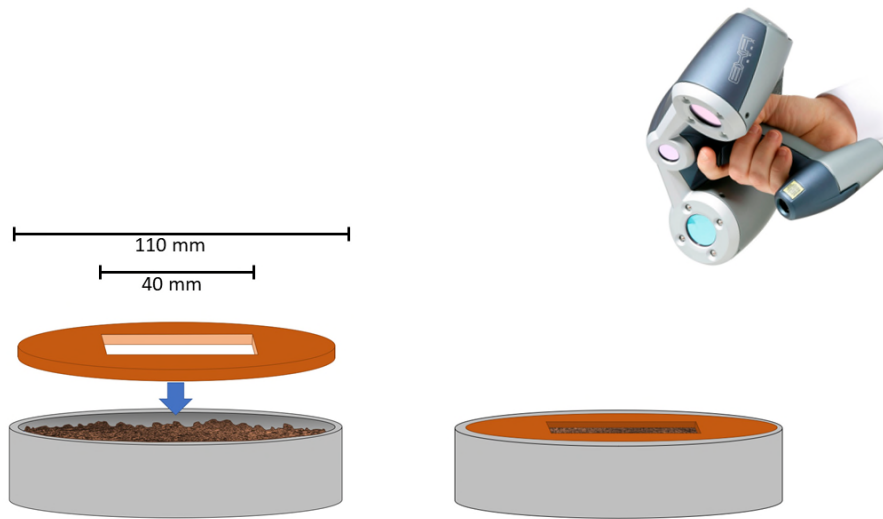


Figure 2.1 Diagram of scanning procedure using Creaform EXAScan 3D hand-held laser scanner (for simplicity, drainage slots are not showed)

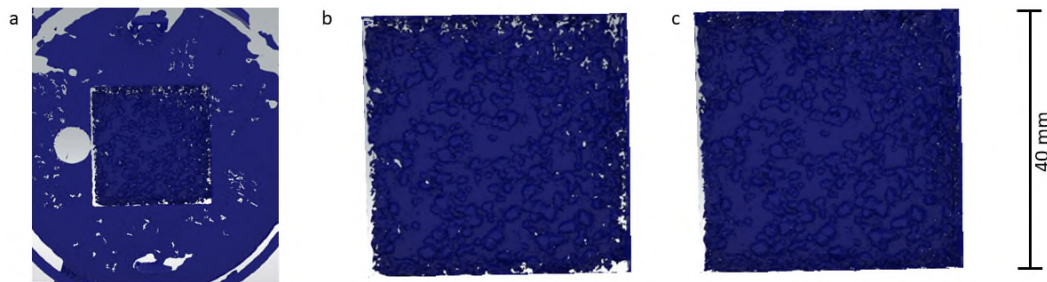


Figure 2.2 Laser scanning post-scanning image processing procedure.

Three stages of scan post-processing were undertaken: a scan is captured as a high resolution (0.4 mm resolution) mesh file. b. the scan is clipped to 1600 mm² area of the quadrat, c. Non-complex gaps in the scan are auto-filled using the hole autofill function in Geomagic studio version 14.2.2.

When a stable or partially disaggregated aggregate sits on the crust surface it may feature some surfaces with multiple angles that cannot be captured by the hand-held scanner. Gaps in the mesh can appear and are classified by the software in two categories. Non-complex gaps in the surface mesh, are gaps with a boundary defined within a single plane (it is possible to trace their perimeter with a virtual rope). In contrast complex gaps are formed when interference in the

scan creates a mesh with multiple planes (their perimeter is not linear, it might feature bifurcations). Only the non-complex gaps are filled using the hole autofill function in Geomagic studio version 14.2.2. Complex multiplane gaps were left as the surface area would have been overestimated. On average, the autofill function increased the final surface area by <2%. The index of surface roughness (SR) was computed by dividing the 3D surface area by the known scanned area, 1600 mm², producing a non-dimensional value similar to the output of the chain method.

Differences in the surface characteristics between Control and different rainfall duration treatments were assessed using a non-dimensional index of surface roughness (mm⁻² pre-rainfall:mm⁻² post rainfall duration treatment) following the approach of Bullard et al. (2018b). Consistency of soil packing was determined by measuring the SR of all soils before applying rainfall. The pre-rainfall SR of Soil 1, 10 minute treatment, was found to be significantly higher than the SR of Soils 2 and 3, meaning that the soil sieving and packing alone produced significantly different baseline SR values. As a consequence, the effect of each treatment was assessed using the relative change between pre- and post-treatment measurements and not using an absolute SR measurement captured after the rainfall.

2.2.3.2 Unsaturated hydraulic Conductivity (HC)

A Minidisc Infiltrometer (Decagon Devices) was used to determine differences in HC between treatments under ambient conditions 5.0 ±0.25 days after the rainfall event. Absolute HC values were less important than relative values for this comparison. Soil moisture homogeneity was assumed because the filter paper used in the microcosms regulated drainage and HC measurements taken within a short (0.25 day) window, 5.0 days after the rainfall event. Quadruplicates of HC, one per microcosm, were obtained for each treatment using a suction set at 20 mm, the most appropriate value for light soils according to the manufacturer's guidance (Decagon Devices, 2012). The HC measurement represented three layers or contrasting porosity namely a contact surface of Garside Sand, a

crusted layer of variable thickness, and a non-aggregated loose subjacent soil matrix. This experiment follows the conceptual model proposed by Hardie and Almajmaie (2019) where HC of a crusted soil is limited by the crust because of its reduced porosity. The HC was then computed using the method illustrated by Zhang (1997).

2.2.3.3 Penetrative Resistance (PR).

Penetrative resistance is a well-recognised metric of structural crust formation (Al-Durrah and Bradford, 1982a; Callebaut *et al.*, 1985; Pulido Moncada *et al.*, 2014; Bullard *et al.*, 2018) and is used as an indicator of potential resistance to emerging seedlings (Richards, 1953b; Awadhwai and Thierstein, 1985; Callebaut *et al.*, 1985; Lehrs and Kincaid, 2006). An Instron 5542 Universal testing system was used with data processed with the Instron Bluehill software ver2.35. This generated a dataset similar to Callebaut *et al.* (1985) because it provides the PR value at a resolution of 0.1 mm. The soil microcosms were tested 6 $\pm$ 0.1 days after the simulated rainfall event. Penetrative resistance was determined using a 3.0 mm diameter (= 7.05 mm²) probe with a vertical motion rate of 1 mm s⁻¹ to a maximum depth of 10 mm, half of the initial 20 mm layer of soil. The Instron gives a continuous readout of PR at 0.1 mm resolution. Where a soil crust is present, a higher PR is recorded by the probe, and when the crust breaks, the sensor records a drop in PR. The maximum value obtained is called Yield. The load at Yield is the maximum force recorded on the dataset, which normally happens just before the crust breaks (Instron Bluehill manual ver. 2.35). For the Control treatment, the peak load was below the threshold limit automatically set by the software. However, a peak was observable in the pressure as the probe displaced surface aggregates. In these cases the yield point was determined by investigating the Instron raw data. More detail about the PR dataset is available in Appendix E. To compare the PR with the turgor pressure exerted by the coleoptile during emergence, the raw data was then converted into MPa by dividing the force (Newton) by the probe area (7.05 mm²).

2.2.4 Statistical analysis

Normality of data was visually confirmed using plots of residuals versus fitted values. One Way and Repeated Measures ANOVA for PR and HC and 3D Surface Roughness, respectively were computed using Statistica version 13 (<http://statistica.io>.) Homogenous groups were computed using *post-hoc* Fisher LSD analysis with $\alpha=0.05$.

2.3 Results and Discussion

The output of the 3D Surface Roughness, Penetrative Resistance and Unsaturated Hydraulic Conductivity for all three soils are summarised in Table 2.4. The 3D surface roughness dataset shows significant differences associated with increasing rainfall duration associated with all soils. Penetrative resistance shows a similar pattern, despite soil 1 not showing significant difference between Control and 2-min simulated rainfall duration.

Rainfall duration (min)	3D Surface Roughness index ($\text{mm}^2 \text{mm}^{-2}$) ¹	Penetrative resistance (MPa)	Hydraulic Conductivity (mm h^{-1})
Soil 1 (Lineside Field)			
0	1.0	0.01 ^a	16.80 ^a
2	1.06 ^a	0.61 ^a	13.40 ^a
4	0.79 ^b	2.16 ^{ab}	16.9 ^a
10	0.62 ^c	3.64 ^c	11.59 ^a
Soil 2 (Beslee 34 Field)			
0	1.0	0.01 ^a	21.19 ^c
2	1.13 ^a	1.75 ^b	7.98 ^b
4	0.89 ^b	5.29 ^c	2.82 ^a
10	0.68 ^c	7.02 ^d	3.26 ^{ab}
Soil 3 (Worley Field)			
0	1.0	0.01 ^a	19.39 ^c
2	1.26 ^a	0.64 ^b	10.03 ^b

Rainfall duration (min)	3D Surface Roughness index (mm ² mm ⁻²) ¹	Penetrative resistance (MPa)	Hydraulic Conductivity (mm h ⁻¹)
4	0.92 ^b	2.09 ^c	4.56a ^b
10	0.76 ^c	3.76 ^d	0.66 ^a

Table 2.4 Differences in mean (n=4) surface roughness (SR) index (mm² mm⁻²) Penetrative Resistance (PR) and Hydraulic Conductivity (HC) for the test soils as a function of rainfall duration.

Within each column, values followed by the same letter are not significantly different ($p < 0.05$) following One Way or Repeated Measures ANOVA and post-hoc Fischer LSD analysis within every soil type. ¹ 3D surface roughness is displayed as a ratio of post-rainfall:pre-rainfall. Values >1.0 indicate an increase in SR and values <1.0 indicate a decrease in SR as compared with the pre-rainfall surface.

2.3.1 Surface Roughness (SR)

Variation in surface roughness before and after the rainfall event are shown in Table 2.4. The undisturbed pre-rainfall soil surface has an SR of 1.0. Values >1.0 indicate an increase in SR and values <1.0 indicate a decrease in SR as compared with the pre-rainfall surface. The Control treatment received no rainfall, resulting in an undisturbed soil surface. Within the same soil, all three soils showed significant differences in the SR index across all rainfall duration treatments. However, there was no significant difference in SR between soils within 2.0 and 4.0 minutes of rainfall (Figure 2.3), meaning that 3D scanning is a valid metric that homogenously detects the different stages of seal formation. For the 2.0 min rainfall duration treatment, the SR index increased by 6, 13 and 26% as compared with the pre-rainfall surface for Soil 1, 2 and 3 respectively (Table 2.4). This was caused by the simultaneous presence of partially disaggregation of aggregates and craters formed by raindrop impact, combining to create two orders of surface roughness namely <2.0 mm partially disaggregation aggregates and shallow, *circa* 1.0 mm raindrop impact craters. Between 2.0 and 4.0 min rainfall duration, the impacting raindrops compacted the microcosm's soil surface to 5.0 ± 2 mm below the drainage slots, and structural crust formation was initiated

(Valentin and Bresson, 1992). In addition, water started to pond in the microcosm, up to the level of the drainage slots. Consequently, the ponded water absorbed the KE of impacting raindrops. As rainfall duration increased to 10 min, the aggregates on the surface were further disaggregated into primary soil particles, suspended in the ponded water and recirculated by raindrop impacts. As a result, the SR index decreased to 0.79, 0.89 and 0.92 mm² mm⁻² for Soils 1, 2 and 3, respectively. After 10 mins, the rainfall simulation was stopped and the ponded water on the microcosms' surface was left to infiltrate. Suspended fine soil particles deposited and formed an homogenous depositional crust (Valentin and Bresson, 1992). By the end of the rainfall, the microcosm SR index had reduced by 38, 32 and 26%, with a final SR of 0.62, 0.68 and 0.76 mm² mm⁻² for Soils 1, 2 and 3, respectively.

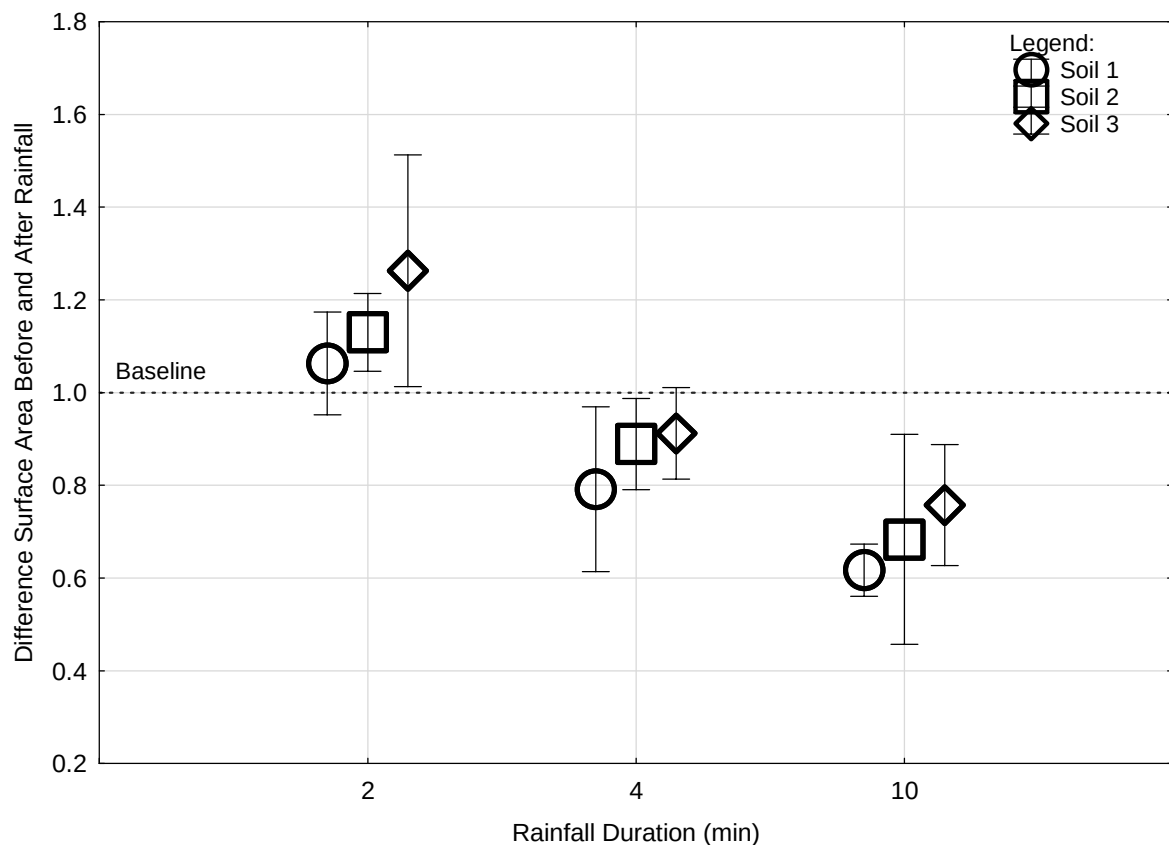


Figure 2.3 Differences in mean (n=4) surface roughness (SR) index (mm² mm⁻²) for the test soils as a function of rainfall duration. Vertical bars denote 95% confidence intervals. Values >1.0 indicate an increase in SR and values <1.0 indicate a decrease in SR as compared with the pre-rainfall surface. Surface Area is the ratio between surface areas (mm²) before and after 2.0, 4.0 and 10.0 min simulated rainfall treatments.

2.3.2 Penetrative resistance (PR)

The maximum force, or Yield, at crust break, typically occurred between 0.5mm and 8.0 mm depth, unlike the results observed by Callebaut *et al.* (1985) where the crust break generally happened between 1 and 1.5 mm. Where the microcosm exhibited a single circular crack around the internal rim, the continuous crusted area has a consistent, contiguous spatial extent across the replicates. Despite the consistent drying conditions, within the same treatment some of the microcosms featured surface cracks which led to consistently lower Yield points (Appendix D) and therefore increasing within treatment variability.

This was observed for Soil 2 in the 10 min rainfall treatment, and Soil 3 after 4.0 mins of rainfall (Figure 2.4). The PR recorded for the 2.0 min rainfall treatment exceeded the emergence threshold of 0.27 kg cm^{-2} ($=0.026 \text{ MPa}$) advised by Richards (1953) for large bean seedlings. The overall values obtained in this experiment were significantly higher than the ones obtained with the needle penetrometer used by Callebaut *et al.* (1985). This may be largely due to the fact that in this research, in contrast to Callebaut *et al.* (1985), soils were thoroughly air dried before the test. Due to the positive relationship between soil moisture and PR (Awadhwai and Thierstein, 1985; Borselli *et al.*, 1996; Bullard *et al.*, 2018), the PR values measured in this research were consequently higher than the ones measured in the field or with sand tables by the aforementioned authors. For this reason, the PR exerted by the test soils in this study are likely to be independent of variations in soil moisture and a function of intrinsic shear strength of the crust.

Figure 2.4 shows the variability in PR (MPa) at crust break for the test soils across the different rainfall duration treatments. For all soils, increasing rainfall duration resulted in significantly higher PR, suggesting that this could be an effective method in quantifying the degree of crust formation and potential impacts on seedling emergence. Soil 1 and 3 displayed statistically similar behaviour, with PR values for the 2.0 min rainfall duration treatments of 0.61 and 0.73 MPa. At 4.0 and 10 mins, PR values for Soil 1 and 3 were 2.16 and 2.09 and 3.64 and 3.75 MPa respectively (Figure 2.4). Similarly, for Soil 2 increasing the duration of rainfall resulted in significant increases in PR. However, the magnitude of the effect was significantly higher than for Soil 2 as compared with Soil 1 and 3 with PR values for the 4.0 and 10.0 min rainfall duration treatments of 5.29 and 7.58 MPa (Figure 4). Generally, PR of the Soil 2 crust was two to three times higher than the equivalent rainfall duration treatment on Soils 1 and 2. The particle size distribution, reveals that Soil 2 was richer (+10%) in silt, but texturally very similar to Soil 3, which may explain differences in PR responses. The mineralogy tests (Table 2.1b, Appendix E) confirm the results from the PSD, Soil 2 and 3 were more alike than Soils 1 and 3 in 600°C Loss on Ignition (LOI), and in mineral

fractions. The higher silt fraction in Soil 2 could have accelerated aggregate slacking (C Valentin and Bresson, 1992) and therefore should have been better detected in 3D scans, while the smaller surface volume compared to clayey soils, should have resulted in a weaker PR, due to the lower amount of colloidal surface charges (Versailles, 2013).

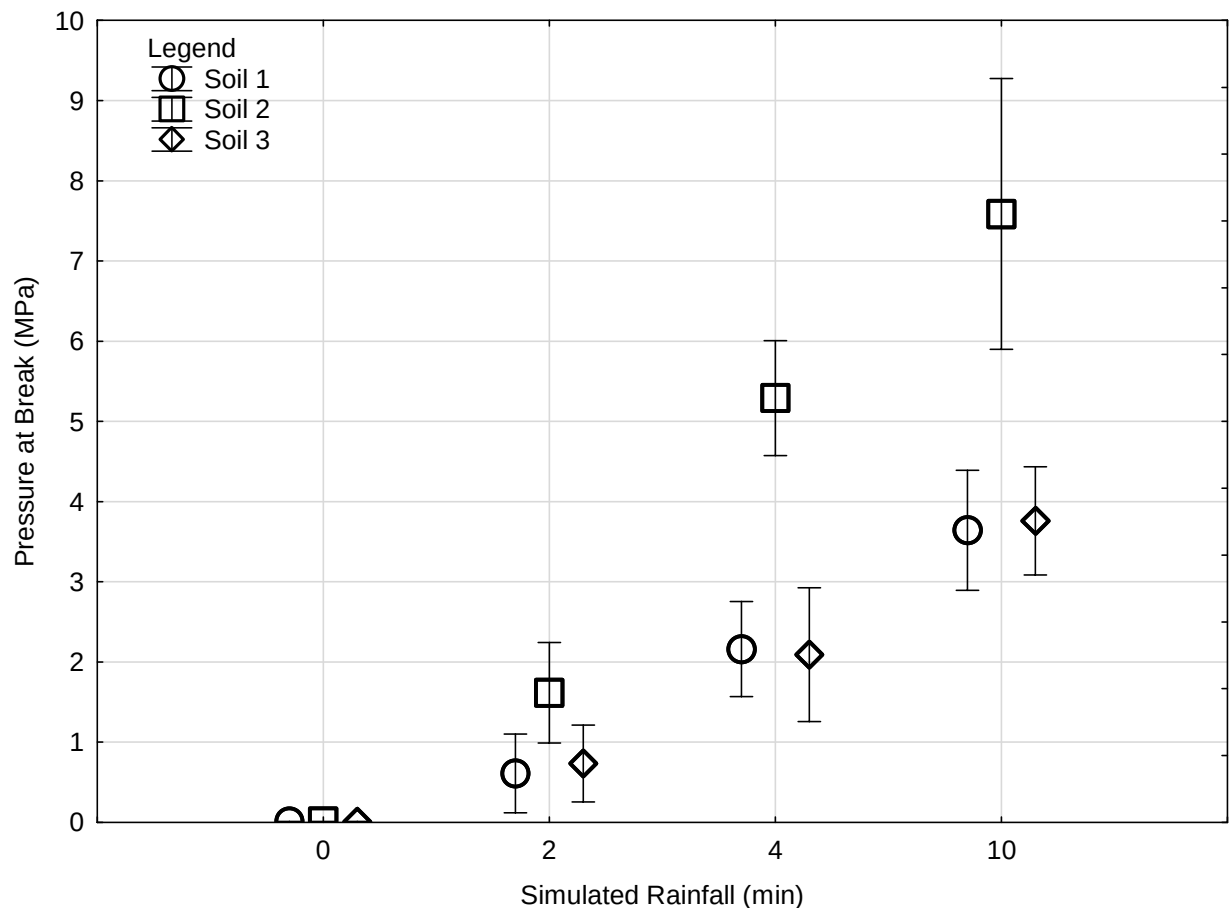


Figure 2.4 Differences in mean (n=4) penetrative resistance (MPa) for the test soils as a function of rainfall duration. Vertical bars denote 95% confidence intervals.

2.3.3 Unsaturated Hydraulic Conductivity (HC)

Mean (n=4) unsaturated hydraulic conductivity (HC) values are shown in Table 2.4 and Figure 2.5. The overall HC results are in line with the averages measured by Armenise *et al.* (2018) for similar soils obtained on microcosms placed on sand tables, ranging from 2.5 to 10 mm h⁻¹. However, they were two to three times lower than the values recorded by Bullard *et al.* (2018b) on soil trays, averaging

circa 75 mm h⁻¹. Soil 2 had the highest initial HC, 21.2 mm h⁻¹, that dropped to significantly to 7.98 mm hr⁻¹ (-62%) after 2.0 mins of rainfall. A further significant reduction in HC to 2.82 (-86%) occurred after 4.0 mins of rainfall (Figure 2.5 and Table 2.2). However, after 10 mins of rainfall the HC had stabilised at 3.2 mm hr⁻¹ which was statistically similar to the 4.0 min rainfall duration treatment. This suggests that in terms of HC an optimum crust was formed at 4.0 mins.

Soil 3 behaved in a similar way to Soil 2, which may in large part be due to the similarity in PSD and mineralogy (Table 2.1a and 2.1b). For the pre-rainfall control, the soil had a HC of 19.39 mm hr⁻¹, which decreased to 10.05 and 4.56 mm hr⁻¹ after 2.0 and 4.0 min of rainfall respectively although no significant difference in HC was observed between the 2.0 and 4.0 min rainfall events (Table 2). However, increasing rainfall duration to 10 mins resulted in significant reduction in HC to 0.66 mm hr⁻¹. Whilst Soil 2 HC was statistically similar between

the 4 and 10 min rainfall treatments, Soil 3 saw a continued drop in HC at 10 mins of rainfall suggesting further crust development.

For Soil 1 no significant different in HC was observed between the pre-rainfall control and rainfall duration treatments (Figure 2.5 Table 2.2) with mean values ranging between 11.6 and 16.8 mm hr⁻¹. A critical evaluation of the within rainfall duration treatment variability associated to Soil 1 suggests that HC is unaffected by rainfall including the 4yr return storm. The raw data confirmed a high variability in HC within the rainfall duration treatments which necessitated the removal of two outlier data points. A closer inspection of the metadata associated with the Soil 1 HC showed that the outliers were all recorded using the same infiltrometer, suggesting that the anomalous readings might have been caused by a fault in the equipment. Outliers aside, the HC values for Soil 1 after 4.0 and 10.0 mins of rainfall were significantly higher than the equivalent HC values recorded for Soils 2 and 3 (Figure 2.5 and Table 2.4). The lack of significant difference in HC over time, coupled with lower PR values observed for Soil 1, suggests that Soil 1's lower crustability is related to inherently higher porosity which is in part explained by the higher sand fraction associated with Soil 1 (72%) compared to 45% and 55% for Soil 2 and 3 respectively. This result is in contrast with a similar study conducted on microcosm that considered a diverse range of soil textures, where a sandy loam of similar soil textural class as Soil 1, was associated with the lowest Infiltration rates readings compared to silty clay loams and sandy silt loams (Armenise *et al.*, 2018).

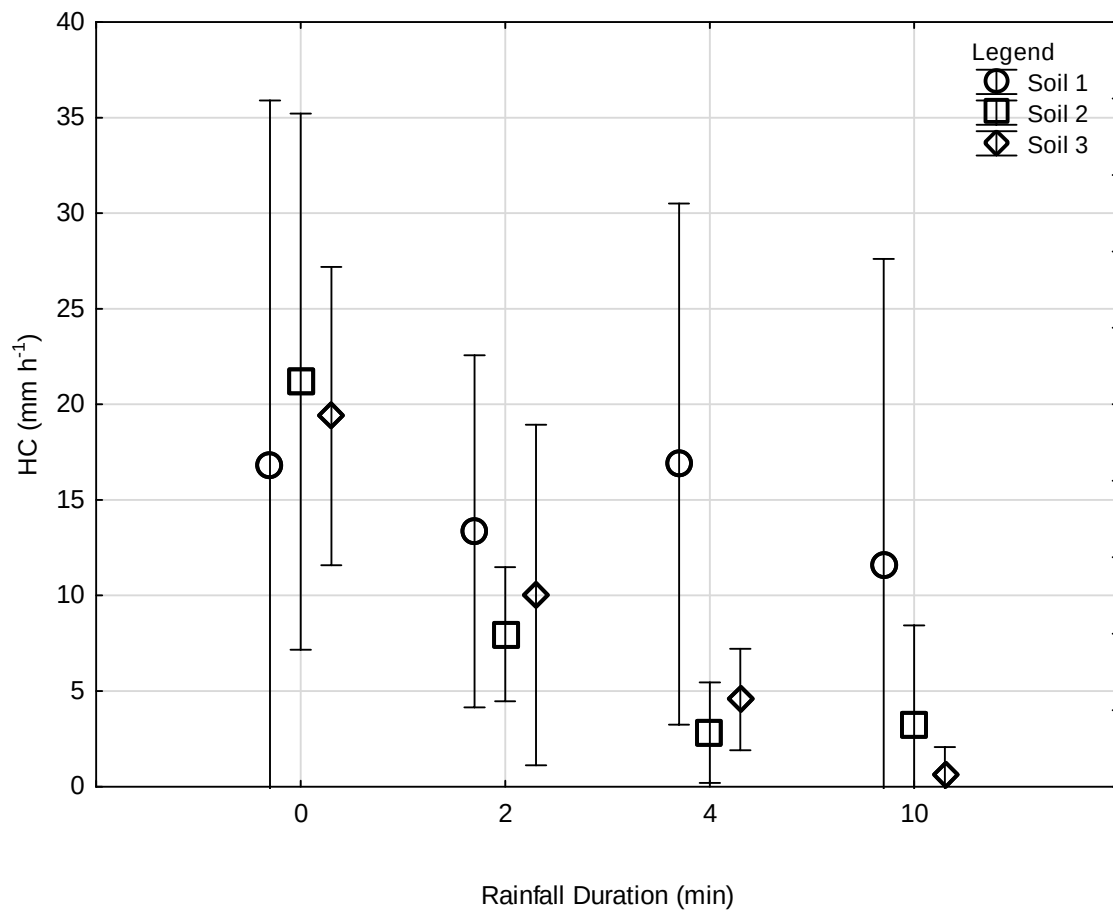


Figure 2.5 Differences in mean (n=4) Unsaturated Hydraulic Conductivity (mm hr⁻¹) between three tested soils as a function of rainfall duration. Vertical bars denote 95% confidence intervals.

2.3.4 Critical evaluation of metrics used to determine the comparative crustability of the test soils

The metric that produced the most consistent values in terms of data quality and resolution (0.1 mm) was PR. The PR measurement was both quick to undertake and generated accurate replicable results. The measurement of PR (MPa) is also a useful estimate of potential limitations to seedling emergence. While the use of the Instron 5542 Universal testing system is widely encouraged by the author for laboratory-based PR tests, its key limitation is that it cannot be used in the field. The outdoor alternative is the Pocket Geotester, a hand-held device that has an

accuracy of 1N. However, the Pocket Geotester does not record the load variation with the depth.

The advantage of measuring surface roughness (SR) using a Creaform EXAScan 3D hand-held laser scanner was that it was a non-destructive measure that enabled repeat observations of the same target area. This facilitated temporal changes in soil surface roughness to be quantified with a high degree of resolution (0.4 mm). Its primary limitation is the scanning and post-scanning image processing time required and limited portability of the equipment. Average post-scanning image processing time was 30 mins per soil scan. The 30GB of RAM available to the software during the scanning process limits the accuracy of the scan and slows the computing process during post-processing. The quality of the obtained dataset, however, presents multiple potential evolutions in terms of size of aggregates, and the study of in-situ aggregate breakdown processes.

Minidisc infiltrometer did not produce the same performance in detecting the response to the soil microcosms to the experimental rainfall events, confirming the results of Armenise (2018) characterised by relatively wide range and evident trends (2.5 to 20 h⁻¹ (Armenise *et al.*, 2018)) but not by significant differences featuring the same distinct significant different groups observed with PR and SR. In this study, the Control treatments exhibit a high variability in HC for those soils that are more prone to cratering in the 2.0 min duration treatment, such as Soil 1 and to a lesser extent Soil 2, while still exhibiting a general trend for decreasing HC with increasing rainfall duration. This along with PR, was a key factor in determining that Soil 2 is more susceptible to soil crusting. However, in contrast to the Instron 5542 Universal testing system mini disc infiltrometer Creaform EXAScan 3D hand-held laser scanner the minidisc infiltrometer is designed to be used on-field, making it the only instrument truly transferable for use in a field trial setting.

2.4 Conclusions

The aim of the experiment was to identify a soil type, and hence field, at Watts Farms susceptible to soil crusting. The secondary aim was to evaluate the suitability of three widely adopted metrics of 'crustability' for transfer to a field trial.

In terms of soil crust susceptibility, all three soils showed development of a soil crust. However, Soil 2 developed a crust with the greatest PR and hence potential restriction to seedling emergence. Soil 2 also demonstrated significant differences in HC between rainfall durations. The significant drop in infiltration rate after 2.0 mins of rainfall was also indicative of the soils susceptibility to crusting. Therefore, Soil 2 and Beslee 34 Field will be used to test the polyacrylamides (PAMs) in the field trial phases of the project. Penetrative resistance and Surface Roughness (SR) were the most accurate and precise metrics. However, the importance of HC in the soil crusting coupled with the portability of the Decagon Minidisc infiltrometer for future in-field experiments, cannot be ignored. Consequently, all three metrics will be continued in the next phases of this project.

2.5 References

- .Agassi, M., Shainberg, I. and Morin, J. (1981) 'Effect of Electrolyte Concentration and Soil Sodicity on Infiltration Rate and Crust Formation¹', *Soil Science Society of America Journal*, 45(5), p. 848. doi: 10.2136/sssaj1981.03615995004500050004x.
- Al-Durrah, M. M. and Bradford, J. M. (1982a) 'Parameters for Describing Soil Detachment Due to Single Waterdrop Impact¹', *Soil Science Society of America Journal*, 46(4), p. 836. doi: 10.2136/sssaj1982.03615995004600040034x.
- Al-Durrah, M. M. and Bradford, J. M. (1982b) 'The Mechanism of Raindrop Splash on Soil Surfaces', *Soil Science Society of America Journal*, 46(5), p. 1086. doi: 10.2136/sssaj1982.03615995004600050040x.
- Armenise, E. *et al.* (2018) 'Soil seal development under simulated rainfall:

Structural, physical and hydrological dynamics', *Journal of Hydrology*. The Authors, 556, pp. 211–219. doi: 10.1016/j.jhydrol.2017.10.073.

Assouline, S. (2004) 'Rainfall-Induced Soil Surface Sealing: A Critical Review of Observations, Conceptual Models, and Solutions', *Vadose Zone Journal*, pp. 1–60.

Awadhwal, N. K. and Thierstein, G. E. (1985) 'Soil crust and its impact on crop establishment: A review', *Soil and Tillage Research*, 5(3), pp. 289–302. doi: 10.1016/0167-1987(85)90021-2.

Le Bissonnais, Y. (2016) 'Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology', *European Journal of Soil Science*, 67(1), pp. 11–21. doi: 10.1111/ejss.4_12311.

Boiffin J. (1982) 'La dégradation structurale des couches superficielles des sols sous l'action des pluies.'

Borselli, L. *et al.* (1996) 'Effect of gypsum on seedling emergence in a kaolinitic crusting soil', *Soil Technology*, 9(1–2), pp. 71–81. doi: 10.1016/0933-3630(95)00036-4.

Bronick, C. J. and Lal, R. (2005) 'Soil structure and management: A review', *Geoderma*, 124(1–2), pp. 3–22. doi: 10.1016/j.geoderma.2004.03.005.

Bullard, J. E. *et al.* (2018) 'Impact of multi-day rainfall events on surface roughness and physical crusting of very fine soils', *Geoderma*. Elsevier, 313(October 2017), pp. 181–192. doi: 10.1016/j.geoderma.2017.10.038.

Callebaut, F. *et al.* (1985) 'Determination of soil surface strength with a needle-type penetrometer', *Soil and Tillage Research*, 5(3), pp. 227–245.

Decagon Devices (2012) 'Mini Disk Infiltrometer', *Mini Disk Infiltrometer User's Manual Version 10*, p. 21. doi: 10.1007/s13398-014-0173-7.2.

Duley, F. L. (1939) 'Surface factors affecting the rate of intake of water by soils 1'.

FAO (1993) 'Soil tillage in Africa: needs and challenges', in *Soil tillage in Africa: needs and challenges*. 1st edn. Rome, p. Soil Crusting and Sealing. Available at: <http://www.fao.org/3/t1696e/t1696e06.htm#TopOfPage>.

FEH (2019) *Point data at 553505,168123: WattsFarm*. Available at: <https://fehweb.ceh.ac.uk/GB/map>.

Griffiths, B. S. *et al.* (2015) 'Probing soil physical and biological resilience data from a broad sampling of arable farms in Scotland', *Soil Use and Management*, 31(4), pp. 491–503. doi: 10.1111/sum.12214.

Hardie, M. and Almajmaie, A. (2019) 'Measuring and estimating the hydrological properties of a soil crust', *Journal of Hydrology*. Elsevier, 574(April), pp. 12–22. doi: 10.1016/j.jhydrol.2019.04.031.

Horton, R., Ankeny, M. D. and Allmaras, R. R. (1994) *Soil Compaction in crop Production*. Edited by B. D. Soane and C. van Ouwerkerk. Elsevier.

Hudson, N. (1995) *Soil Conservation*. 3rd edn. London: Batsford Limited.

Jester, W. and Klik, A. (2005) 'Soil surface roughness measurement - Methods, applicability, and surface representation', *Catena*, 64(2–3), pp. 174–192. doi: 10.1016/j.catena.2005.08.005.

Klute, A. (1986) *Methods of soil analysis*. 2nd edn. Madison: Soil Science Society of America.

Lamichhane, J. R. *et al.* (2020) 'Analysis of soybean germination, emergence, and prediction of a possible northward establishment of the crop under climate change', *European Journal of Agronomy*. Elsevier, 113(May 2019), p. 125972. doi: 10.1016/j.eja.2019.125972.

LandIS (2021) *The Soil Guide, Landis*. Available at: www.landis.org.uk (Accessed: 3 June 2021).

LandIS (2022) *The Soils Guide*. Available at: <https://www.landis.org.uk/soilsguide/mapunit.cfm?mu=57110> (Accessed: 18

May 2022).

Lehrsch, G. A. and Kincaid, D. C. (2006) 'Sprinkler droplet energy effects on soil penetration resistance and aggregate stability and size distribution', *Soil Science*, 171(6), pp. 435–447. doi: 10.1097/01.ss.0000227361.36922.ad.

Lehrsch, G. A., Lentz, R. D. and Kincaid, D. C. (2005) 'Polymer and sprinkler droplet energy effects on sugar beet emergence, soil penetration resistance, and aggregate stability', *Plant and Soil*, 273(1–2), pp. 1–13. doi: 10.1007/s11104-004-7614-6.

Loch, R. J. (1994) 'A method for measuring aggregate water stability of dryland soils with relevance to surface seal development', *Australian Journal of Soil Research*, 32(4), pp. 687–700. doi: 10.1071/SR9940687.

Lu, D. R. *et al.* (2018) 'Using Near-Surface Photogrammetry Assessment of Surface Roughness (NSPAS) to assess the effectiveness of erosion control treatments applied to slope forming materials from a mine site in West Africa', *Geomorphology*. Elsevier B.V., 64(1), pp. 188–195. doi: 10.1016/j.geomorph.2018.08.027.

Marshall, J. D. M. and J.W, H. (1979) *Soil Physics*. Cambridge: Cambridge University Press.

McIntyre, D. S. (1958) 'Permeability measurements of soil crusts formed by raindrop impact', *Soil Science*, 85(4), pp. 185–189. doi: 10.1097/00010694-195804000-00002.

Nciizah, A. D. and Wakindiki, I. I. C. (2015) 'Soil sealing and crusting effects on infiltration rate: a critical review of shortfalls in prediction models and solutions', *Archives of Agronomy and Soil Science*, 61(9), pp. 1211–1230. doi: 10.1080/03650340.2014.998203.

Pagliai, M. and Stoops, G. (2010) *Physical and Biological Surface Crusts and Seals, Interpretation of Micromorphological Features of Soils and Regoliths*. Elsevier B.V. doi: 10.1016/B978-0-444-53156-8.00019-2.

Pagliai, M., Vignozzi, N. and Pellegrini, S. (2004) 'Soil structure and the effect of management practices', in *Soil and Tillage Research*, pp. 131–143. doi: 10.1016/j.still.2004.07.002.

Pulido Moncada, M. *et al.* (2014) 'A comparison of methods to assess susceptibility to soil sealing', *Geoderma*. Elsevier B.V., 226–227(1), pp. 397–404. doi: 10.1016/j.geoderma.2014.03.014.

Richards, L. A. (1953a) 'Modulus of Rupture as an Index of Crusting of Soil 1', *soil Science Society of America*, 17(4), pp. 321–323. doi: 10.2136/sssaj1953.03615995001700040005x.

Richards, L. A. (1953b) 'Modulus of Rupture as an Index of Crusting of Soil 1', *soil Science Society of America*, 17(4), pp. 321–323. doi: 10.2136/sssaj1953.03615995001700040005x.

Rubio, H. O. *et al.* (1989) 'Effect of polyacrylamide on seedling emergence of three grass species', *Soil Science*, 148(5), pp. 356–360. doi: 10.1097/00010694-198911000-00006.

Souza, E. S. *et al.* (2014) 'Effect of crusting on the physical and hydraulic properties of a soil cropped with Castor beans (*Ricinus communis* L.) in the northeastern region of Brazil', *Soil and Tillage Research*. Elsevier B.V., 141, pp. 55–61. doi: 10.1016/j.still.2014.04.004.

Thomsen, L. M. *et al.* (2014) 'Soil surface roughness: comparing old and new measuring methods and application in a soil erosion model', *SOIL Discussions*, 1(1), pp. 981–1012. doi: 10.5194/soild-1-981-2014.

Valentin, C. and Bresson, L. M. (1992) 'Morphology, genesis and classification of surface crusts in loamy and sandy soils', *Geoderma*, 55(3–4), pp. 225–245. doi: 10.1016/0016-7061(92)90085-L.

Valentin, C and Bresson, L. M. (1992) 'Morphology , genesis and classification of surface crusts in loamy and sandy soils', 55.

Valentin, C. and Bresson, L. M. (1997) 'Soil Crusting', in *Methods for Assessment*

of Soil Degradation. Advances in Soil Science, pp. 89–101.

Versailles, S. H. (2013) 'Soil Colloids and Their Associations in Aggregates', 21(0), p. 598. Available at: <https://books.google.com/books?id=LgzyBwAAQBAJ&pgis=1>.

Zhang, R. (1997) 'Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer', *Soil Science Society of America Journal*, 61(4), pp. 1024–1030. doi: 10.2136/sssaj1997.03615995006100040005x.

Zobeck, T. M. and Onstad, C. A. (1987) 'Tillage and rainfall effects on random roughness: A review', *Soil and Tillage Research*, 9(1), pp. 1–20. doi: 10.1016/0167-1987(87)90047-X.

3 Initial evaluation of the spray application on soil surface of three Polyacrylamide formulas under simulated rainfall

Abstract

Polyacrylamide's (PAM) efficacy against the agronomic consequences of soil crusting and sealing namely reduced water infiltration and impedance to emergence are well-documented in literature. However, the limit to PAMs wide-scale application lies within the delivery method. This study evaluated a novel Twin-Fluid application method to apply three contrasting PAM formulations to a crust susceptible soil. Three PAMs with similar architecture and molecular weight (linear and 5 to 11 10^6 g mol⁻¹), different characteristics (anionic or cationic), and different synthesis processes (inverse emulsion or concentrated suspension) were tested. The PAM treated soil was subjected to two cycles of simulated rainfall (100 mm hr⁻¹) followed by a four days-long drying and the impact of PAM application on the degree of crusting assessed using direct and indirect measurements. SFA30 delivered significant improvements for Penetrative Resistance (7.73 versus 12.05 MPa associated with 40 kg ha⁻¹ and Control respectively, compared with 14.24 and 15.78 MPa associated with 40 kg ha⁻¹ of EM 240 and EM 533) and Surface Roughness (1.21 versus 1.17 mm² mm⁻² associated with 40 kg ha⁻¹ and Control respectively) EM 240 was associated with a significantly higher surface roughness (1.26 versus Control's 1.17 MPa) whereas hydraulic conductivity measurements did not result in any significant difference.

3.1 Introduction

Conventional outdoor leafy green soil and agronomic management practices require a 12 mm irrigation (delivered within 8 to 10 minutes) before plant emergence to activate seedlings (Personal Communication, Watts Farm 2020). This irrigation on bare recently tilled soil is equivalent of an 8.3 year return period storm (FEH, 2019). Irrigation on bare soil, together with the intense tillage undertaken during seedbed preparation are risk factors for aggregate breakdown

and the formation of structural seals (Neave and Rayburg, 2007; Pagliai and Stoops, 2010) that develop into structural crusts upon drying (C. Valentin and Bresson, 1992). The agronomic effect of structural crusts are reduced hydraulic conductivity and increased emergence impedance, resulting in poor water use efficiency, stand homogeneity and final yield. Current mitigation practices consist of an additional 10 mm irrigation to 'soften' the crust to facilitate emergence. However, this approach can result in a more severe crust that further decreases the soil's hydraulic conductivity and reduces water use efficiency of subsequent irrigations.

Traditional and emerging strategies aimed towards the natural restoration of the soil structure, such as implementation of a diversified and resilient soil organic matter (Pagliai, Vignozzi and Pellegrini, 2004; Lal, 2016) do not fit the business model for intensive baby leaf production systems, that involves 30-35 day crop growing cycles and is dictated by the market requirement (DEFRA, 2020b). Synthetic soil conditioners, due to their efficacy at low application rates could be a solution that fits with the leafy green agronomy (Bouranis, Theodoropoulos and Drossopoulos, 1995a; Ben-hur, 2014). Among the different soil conditioners Polyacrylamides (PAMs) are the most efficient at preventing aggregate breakdown and crust formation, at maintaining or improving hydraulic conductivity, and are often used as a performance benchmark for other synthetic and non-synthetic soil conditioners (Lentz, 2015a).

Polyacrylamides are available in a wide array of molecular weights, charge type, charge density and molecule architecture (Bavernick, 1994; Bouranis, Theodoropoulos and Drossopoulos, 1995b; Hecker, 1998a; Rabiee, Ershad-Langroudi and Zeynali, 2015), depending on their end-use. Polyacrylamide (Figure 3.1) is an amphoteric molecule with a neutral charge. Along its carbon backbone there are areas of different electrical density which promote the formation of extra-molecular bonds with polar molecules.

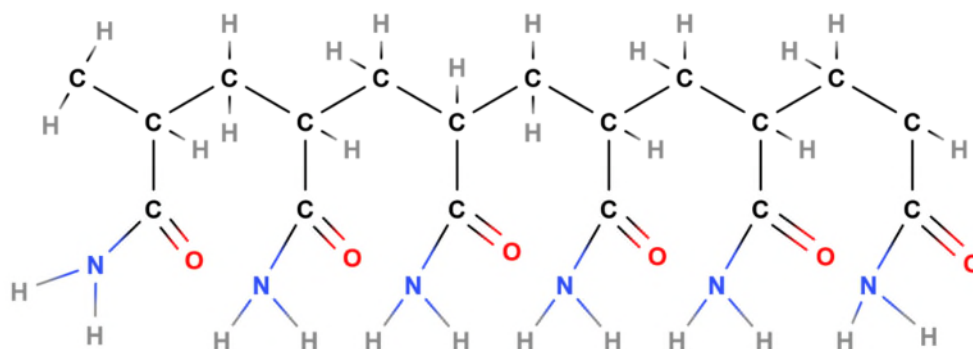


Figure 3.1 Chemical structure of the section of a non-ionic polyacrylamide (PAM) molecule displaying six acrylamide monomers

When preserved as a liquid, PAMs are commonly available in two forms depending on their polymerisation, as inverse emulsions or concentrated suspensions. In inverse emulsions polymerised acrylamide monomers are released into a continuous hydrophobic oil phase using a water-in-oil emulsifier. Polymerisation happens at the interface between the non-polar fluid and hydrophilic micelle, when it turns into the intermediate stage of a monomer-swollen polymer before the end of the polymerisation process (Vanderhoff et al. 1962). Two of the PAMs used in this study, FLOPAM EM533 and FLORET EM 240, are inverse emulsions. The third PAM, SFA30, is a concentrated suspension. Where the PAM polymers are mixed in a concentrated suspension, a “brine” of Ammonium Nitrate. The high concentration of ions in the polar medium (brine) keeps PAM molecules compacted into micelles (Brown, Campbell and Farrell, 2013), spherical particles of concentrated PAMs, and prevent the molecules from interacting with water and unfold, increasing viscosity.

When the folded PAM polymer comes into contact with any polar medium such as water, the molecule unfolds, and the viscosity increases (Hecker, 1998a). The higher the molecular weight (MW), the longer the carbon backbone of the molecule, the higher its efficacy to stabilise aggregates and prevent the agronomic effects of soil capping (Lentz, Sojka and Ross, 2000; Green, Stott and

Graveel, 2005; Abu-Zreig, 2006; Costine *et al.*, 2018). However, a high MW increases viscosity when mixed with water (Bjorneberg, 1998a) preventing spray application using conventional spray nozzles. Charge density affects the architecture of the PAM molecule. A higher number of active groups with the same polarity increases repulsive forces along the carbon backbone, preventing the molecule from recoiling and therefore potentially decreasing its viscosity (Hecker, 1998a).

The efficacy of PAMs to mitigate the agronomic consequences of soil crusting are well-documented (Chapter 1, Table 1.2, 1.3 and 1.4). However, the limit to PAMs wide-scale application to mitigate crusting lies in the delivery method. This is confirmed by the lack of investigation on the topic (Table 3.1).

Research on the application of PAMs in agriculture is dominated by the use of PAMs, to flocculate sediment in furrow irrigation systems, where the operator places either a brick of PAM polymer in the furrow, lines the furrow with powdered PAM, or uses a granular feeder to drop PAM into the water flow usually to reach a 1% solution of PAM in the irrigation water (Mitchell, 1986; Levy and Agassi, 1995; Levy and Rapp, 1999; Zin El-Abedin, Mattar and Alazba, 2015; Li and Wang, 2016). This accounts for twelve relevant publications, of which ten are field trials. This trend is inverted when application changes to overhead sprinkler systems, which is characterised by eleven laboratory-based experiments and two field trials with PAM application rates ranging from 5 to 40 kg ha⁻¹.

Surface application of 30 to 40 kg ha⁻¹ of PAM also extends to hand-held sprayers (seven laboratory-based publications), indicating that sprayed PAM is effective, but not yet efficient in terms of practicality. Nevertheless, the potentials of PAM spray application was intuited as early as 1989 (Ben-Hur *et al.*), only three years later than the first USDA publication on use of PAMs in furrow irrigation (Mitchell, 1986). One field trial in the early 2000s investigating the spray application of PAM demonstrated positive effects on water infiltration and the control of soil erosion.

Method of PAM Application	No. of papers	Laboratory based research	Field based research	References
Furrow Irrigation: PAM are applied to the furrow in powdered form, or are hung in the furrow in solid form	12	2	10	(Weeks, E and Colter, William, 1952; Paganyas <i>et al.</i> , 1972; Mitchell, 1986; Lentz <i>et al.</i> , 1992a, 2020; R. D. Lentz and Sojka, 1994a; Levy and Agassi, 1995; Trout, Sojka and Lentz, 1995; Lentz, Sojka and Robbins, 1998; Lentz, Sojka and Mackey, 2002; Roshanizarmehri <i>et al.</i> , 2018b; Zheng <i>et al.</i> , 2020)
Sprinkler Irrigation: A pre-mixed concentrated solution of PAM is diluted in water tanks that are either fed into an irrigation system or a rainfall simulator depending on whether trial is field or laboratory based.	11	9	1	(Ben-Hur <i>et al.</i> , 1989b; Levin <i>et al.</i> , 1991; Levy <i>et al.</i> , 1992b; Ben-Hur and R. Keren, 1997; Aase, Bjorneberg and Sojka, 1998; Ben-Hur, 2001; Bjorneberg <i>et al.</i> , 2003b; Sepaskhah and Mahdi-Hosseiniabadi, 2008; Sepaskhah and Shahabizad, 2010; Yonter and Uysal, 2010)
Hand Spraying: A pre-diluted layer of PAM is sprayed using a hand-held device.	8	7	1	(Shainberg, Warrington and Rengasamy, 1990; Levin <i>et al.</i> , 1991; Levy and Rapp, 1999; Abrol <i>et al.</i> , 2013; Zin El-Abedin, Mattar and Alazba, 2015; Lin, He and Chen, 2016)
Dry mixed into the soil surface: Granular PAM is broadcasted on soil surface or incorporated in the upper 0.10 m of the soil profile	11	9	2	(Abrol <i>et al.</i> , 2013; Ao <i>et al.</i> , 2016; Lado <i>et al.</i> , 2016b; Li and Wang, 2016; Wang, Chen and Lin, 2018; Li, Xu and Ao, 2019b; Yang, Tang and Feng, 2020)
Spraying of low MW PAM	1	0	1	(Lehrsch, Lentz and Kincaid, 2005)
Hydroseeding: PAM is broadcasted at low concentrations using hydroseeder	4	2	2	(Chaudhari and Flanagan, 1998; McLaughlin and Brown, 2006; Blankenship, Condon and Pyke, 2019; Zheng <i>et al.</i> , 2020)
Sown: Granular PAM are mixed with seeds and sown in the ground with the crop	1	0	1	(Känekänen <i>et al.</i> , 2011)
Sleeve: A flat polyethylene sleeve delivers a low-concentration PAM solution	1	0	1	(McNeal <i>et al.</i> , 2017)

Table 3.1 Published literature regarding the use of PAMs in an agricultural context.

However, this did not translate into higher crop yields (Bjorneberg *et al.*, 2003b). This resulted in spray-delivered PAM investigations being abandoned after one publication (Table 3.1).

Research on PAM application via sprinkler irrigation was abandoned after two papers, in favour to a return to granular application broadcast on the soil surface or incorporated in the upper 0.10 m of soil (Lado *et al.*, 2016; Yang, Tang and Feng, 2020), with one case of granular application using a beetroot seed drill, (Känkänen *et al.*, 2011)

Traditionally, in intensive horticultural production systems, the challenge is to deliver PAM to the immediate soil surface at an effective application rate typically between 10 and 40 kg ha⁻¹ (Sojka *et al.*, 2007) to improve the infiltration in situ by protecting the soil surface from crusting processes. Mixing high MW (107 kg mol⁻¹) PAM at any concentration higher than 3.5 mg l⁻¹ (3.5 g m⁻³) results in changes of viscosity in the solution (Levy *et al.*, 1992a; Bjorneberg, 1998a), that ultimately limit the amount of PAM that can be delivered to very low concentrations in order to avoid viscosity issues, especially if PAM is delivered using conventional spray nozzles.

In 2015 a laboratory trial on soil microcosms evaluated the effect of PAM applied with a rotary spray atomiser. The application of 8 kg ha⁻¹ of a anionic PAM was found to be effective against a 15 min duration rainfall event of 20 mm hr⁻¹ intensity (Atichat 2015). The PAM (inverse emulsion), was atomised over the soil without being previously mixed with water, allowing a 100% reduction in the water volume required with a traditional sprayer. However, fine drops of the atomised PAM, were prone to wind drift, and were extremely hard to clean once they were deposited on the machinery. Mixing PAM with water at higher concentration, could allow a smaller quantity of active ingredient to achieve optimum coverage on the soil surface without compromising the drop size distribution, and therefore maintaining a limited wind drift, with principles similar to the ones applied in other spray applications in agriculture (Kruger and Vieira, 2016). The aims of this research was to investigate the use of a Twin-Fluid nozzle prototype in delivering

three different PAM formulations to the surface of a crust-susceptible soil. Using the Twin-Fluid nozzle PAM and water mix outside the sprayer hydraulic system, allowing the PAM micelle to activate themselves in mid-air, avoiding the wind drift associated with the rotary spray atomiser. The efficacy of the PAMs tested to mitigate crusting was also investigated in order to select a PAM to take forwards to commercial field trials.

3.2 Materials and Methods

3.2.1 Agronomic Context

The experiment simulated an irrigation pattern indicative of that occurring in open-field horticulture at a commercial baby leaf and herb grower in Kent, UK (Watts Farm) namely two irrigations on bare soil within 2-4 days depending on the season and the crop. The first irrigation is on freshly tilled soil and serves to initiate germination. The second irrigation is given pre-emergence and re-hydrates the crust, allowing the young seedlings to emerge.

3.2.2 Polyacrylamides (PAMs)

In the protection of the soil surface, the objective is to permeate and stabilise the aggregates, rather than to retaining moisture in the soil. The preferred PAM architecture is therefore linear rather than cross-linked such as used in super absorbents employed for water retention in soil (Nascimento *et al.*, 2021). FLOPAM EM 533 is an anionic inverse emulsion PAM copolymer with sodium acrylate. Its comparatively “high” MW allows good flocculation capacity and its charge density of 30% places it into the “high density” category, according to Bavernick (1994). FLORET EM 240 is an inverse emulsion, “high” MW linear PAM, characterised by a 20% substitution of Adame® MeCl, that gives it a cationic charge (Table 3.2). The use of a cationic PAM is in order to elucidate differences in PAM:Soil sorption mechanisms between the PAMs tested. The cationic charges bind more effectively with the soil colloids (e.g., the negative surface charges of clays and SOM) and have higher efficacy at lower application rates (Ben-Hur and Letey, 1989). However, cationic PAMs are toxic at much

lower doses for aquatic life (Hamilton, Reinert and Freeman, 1994) and are therefore not used commercially. SFA 30 is a concentrated PAM suspension in ammonium nitrate, with *circa* 25% of acrylamide monomers substituted with sodium acrylate, giving it a “medium” anionic charge density (Table 3.2). The PAMs selected were manufactured in 2019 by SNF, France and stored appropriately until use.

Name	Commercial Form	Ionicity	Charge %	Copolymer	Architecture	Charge density	Average Molecular Weight
FLOPAM SFA 30	Concentrated Suspension	Anionic	30%	acrylamide + sodium acrylate	Linear	“Medium” $\approx 25\%$	High: $6 \cdot 10^6 \text{ g mol}^{-1}$
FLOPAM EM 533	Inverse Emulsion	Anionic	30%	acrylamide + sodium acrylate	Linear	“High” $\approx 30\%$	High: $20 \cdot 10^6 \text{ g mol}^{-1}$
FLORET EM 240	Inverse Emulsion	Cationic	30%	acrylamide + ADAME® MeCl	Linear	“Medium” $\approx 20\%$	Very High: 11 g mol^{-1}

Table 3.2 Characteristics of PAMs investigated in this study

All information was provided by SNF. The Molecular weight and charge density classifications are derived from (Bavernick, 1994). ADAME is a Trademark Dimethylaminoethyl acrylate, a cationic monomer.

3.2.3 Experimental Design and Treatment Procedures

The experiment investigated the efficacy of four PAM application rates, 0 (Control), 15, 25 and 40 kg ha^{-1} . Treatment efficacy in terms of spray application and ability to mitigate soil crusting was measured using three metrics namely 3D scanning, Penetrative Resistance (PR) and Unsaturated Hydraulic Conductivity (HC). Penetrative Resistance and HC, being destructive measurements were undertaken on separate samples.

3.1 Experiment Design

$$\text{Total } n = 3 \text{ PAMs} * 4 \text{ Application rates} * 4 \text{ replicates} = 48$$

The microcosms were subjected to a single PAM application followed by two cycles of a simulated rainfall event separated by a four-day drying period. Total treatment time was twelve days.

The two rainfall events (Table 3.3) consist of a 10 and 5 minutes rainfall events, designed following the outputs from Chapter two.

Rainfall Event	Duration (minutes)	Depth (mm)	Return Period (years)
First	10	16	17
Second	5	8	5.5

Table 3.3 Simulated rainfall characteristics and Return period

The rainfall return period was based on the location of Watts Farms and generated by the UK Centre for Ecology and Hydrology Flood Estimation Handbook Web Service <https://fehweb.ceh.ac.uk/GB/map>

3.2.4 Experimental Unit

The experimental unit consisted of a soil microcosm comprised of a 100mm Ø and 60mm high PVC pipe. The soil is a crust susceptible Clay Loam (31.2% clay, 23.16% silt and 45% sand) from Watts Farm, Kent, UK. It has a pH of 5.7, a SOM content of 1.62% and a CEC of 0.043 cmol kg⁻¹. In each unit, a 0.5 mm wide fabric mesh was fitted to the base to allow water percolation. Above this a Fisherbrand FB59 107 Wattman 100 mm disc filter was placed to prevent soil particles passing through the fabric mesh and to regulate water drainage. The microcosms were packed to a depth of 40 mm with <2.0 mm diameter Garside Sand (Garside 80EW, Leighton Buzzard, UK) (Agassi, Shainberg and Morin, 1981; Armenise et al., 2018) above which a 20 mm layer of air-dried soil at a bulk density (BD) of 1.2 g cm⁻³ was applied. The soil BD was replicated from on-site measurements collected the summer previous the experiment. To homogenise the immediate soil surface, 4.0 g of aggregates between 0.1 and 0.2 mm diameter were isolated from the designed weight and layered on top of each microcosm. The antecedent soil moisture content has been found to affect aggregate breakdown (Loch, 1994; Le Bissonnais, 2016), at the same time, the upper mm of soil in freshly tilled fields during a dry summer are close to air-dried, and

therefore air-dried soil at (20 °C) was considered to be an accurate representation of soil surface under summer field conditions in the UK.

3.2.5 PAM Application

A flat fan Dual-fluid nozzle was used to concurrently spray PAM and water to the soil surface (Figure 3.2). Issues of viscosity are avoided as PAM and water are mixed outside the nozzle and delivered to the ground with a flat-fan footprint. The nozzle, shown in Figure 3.2, features two separate inlets fed by water and PAM.

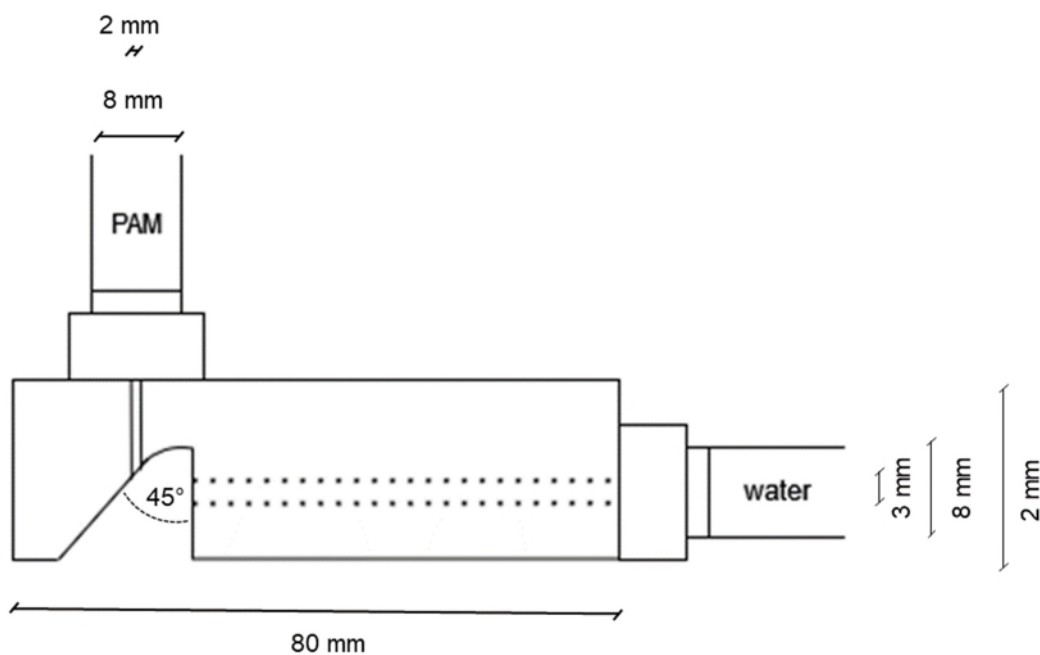


Figure 3.2 Diagram of the dual-fluid nozzle used in this experiment

Quantity and spraying parameters of PAM delivered (kg ha^{-1}) were determined by calibration and patternation of the sprayer and nozzle setup. The purpose of the calibration was to determine PAM flow at given pressures, while patternation investigated the nozzle's footprint, the characterisation of homogeneity and coverage of PAM on the ground.

3.2.6 Pedestrian PAM Sprayer Calibration

PAMs are viscous and hygroscopic liquids. These properties set a number of constraints to their characterisation, that can be summarised in the impossibility

of using conventional spraying test facilities (Personal Communication Clare Butler-Ellis – Silsoe Spray Applications Unit, 2020). The Calibration datasets are therefore highly dependent on the pedestrian PAM sprayer (Figure 3.4) and on the characteristics of its tubing layout. The patternation and calibration work had two main objectives a) to define the quantity and spatial uniformity of PAM applied b) to access spray homogeneity application for laboratory and field trials.

All three polymers tested were calibrated at 3 to 5 different pressure points ranging from 1 to 3 MPa. At each pressure point, set using the PAM pedestrian sprayer, water and PAM flow were captured using pre-weighted beakers and plastic bags respectively over a 20 sec time interval. The weight of PAM and water was divided by the spraying time to obtain PAM and water flow rates (g s^{-1}). Calibration at each pressure was replicated five times. The resultant calibration curves indicate for all PAMs tested, a linear relationship (Figure 3.3) between pressure and flow rate (g s^{-1}).

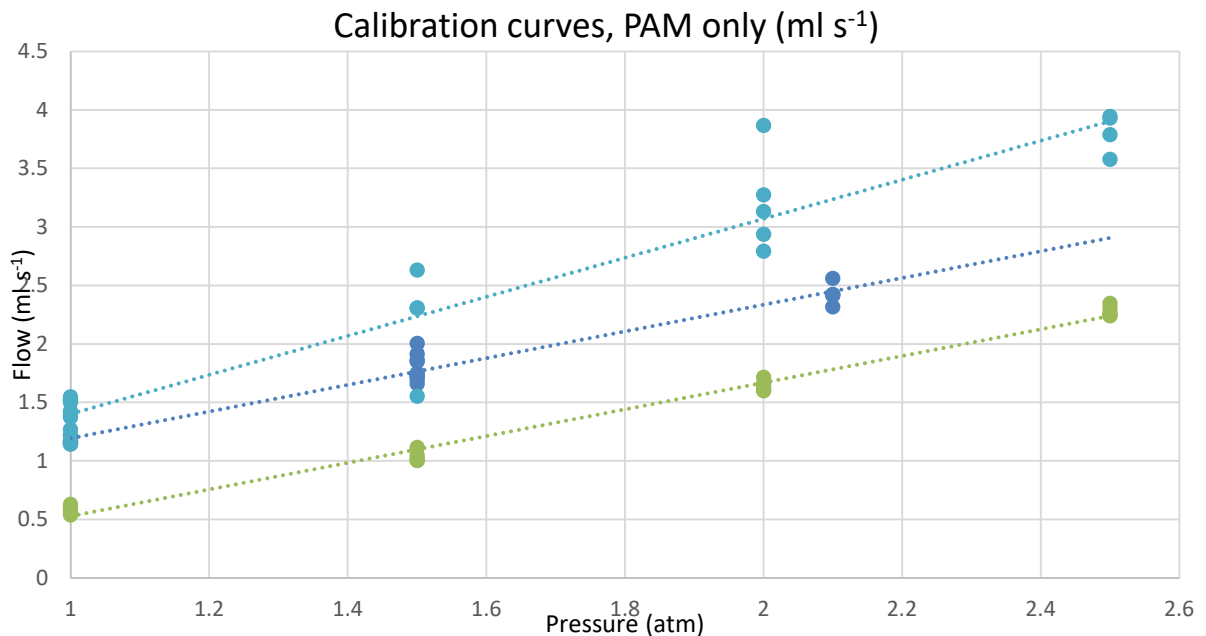


Figure 3.3 Calibration curves showing the relationship between operating pressure (atm) and flow rate (ml s^{-1}) for the PAMs investigated in this study.

Water calibration was carried on separately using seven datapoints ranging 0.5 to 3.5 atm and revealed a linear relationship between the sprayer's operating pressure and flow rate (l s^{-1}).

3.2.7 Dual-Fluid Spray nozzle patterning

Prior to nozzle patterning testing visual assessment of the spray pattern helped in isolating a narrower range of pressures. PAM and water were sprayed statically on to a dark surface. More homogenous PAM distribution was observed at lower water pressures of 1-3 atm. For each PAM, quantitative nozzle patterning was performed at 1 and 2 atm (Figure 3.5a) pressure. Water patterning was assessed at pressures of 1, 2 and 3 atm (Figure 3.5b). Patterning followed the methodology of Thornton and Kibble-White, (1974) to the simultaneous analysis of PAM and water. Patterning took place indoors, at a temperature range of 18-22 °C. A series of pre-labelled and weighted square boxes of 40 by 40 mm were secured on a wood support in a linear fashion and placed under the nozzle. The sprayer was then switched on for 20 seconds, the square boxes weighted for the first time. After 48h at 90°C the boxes were weighted a second time. The total net weight corresponded to Water+PAM, the net weight to the non-volatile solids of PAMs. The non-volatile PAM proportion were calculated by drying for 48h at 90°C a comparable quantity of the equivalent PAM.

The most homogenous PAM distribution occurred at low water pressures (1 and 2 atm) with 60.0% and 46.7% of PAM being delivered homogeneously ($0.45\text{g s}^{-1} \pm 0.1\text{g s}^{-1}$ when PAM pressure is set at 1 atm) within 240 mm from the nozzle's central axis. Water Pressure was raised at 2 atm after Patterning (Figure 3.5b). Following Patterning Results, the nozzles were placed at 0.40 m distance, to mitigate the lateral flow spikes (Figure 3.5a) with the overlapping footprints.

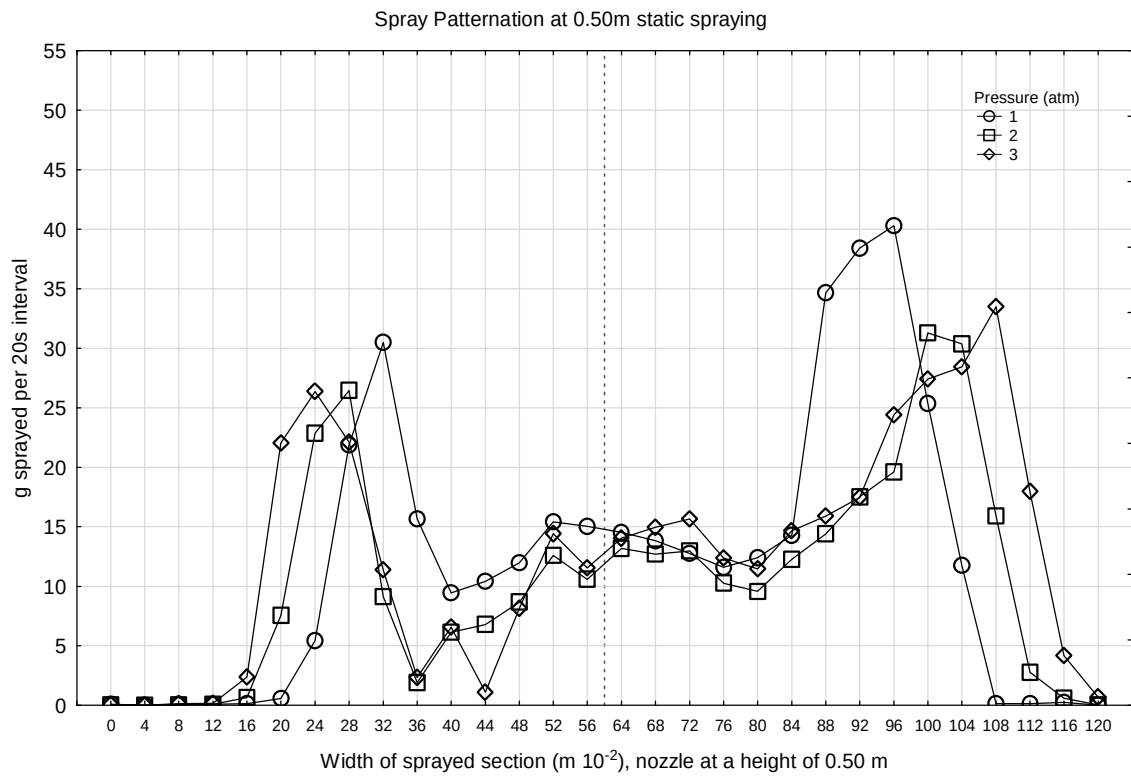


Figure 3.4 Water Patternation of Pedestrian Sprayer The graph shows the footprint of the dual fluid nozzle using only water. The vertical line denoted the axis where the nozzle sits

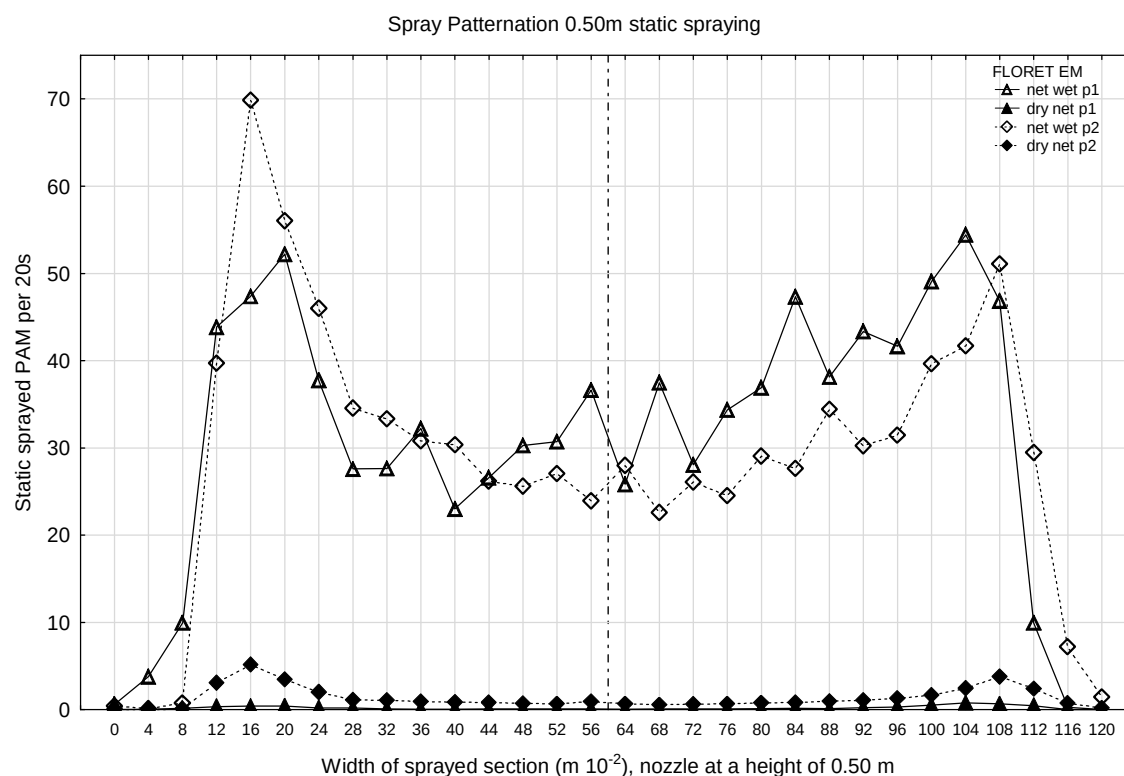


Figure 3.3b: Patternation of the Floret EM Polyacrylamide. The graph shows the footprint of PAM using two different praying pressures and shows the total weight sprayed (net wet) which contains water and polymer, and PAM only (net dry). The vertical line denoted the axis where the nozzle sits.

3.2.8 Polyacrylamide spray application

The nozzles were mounted on a bespoke pedestrian sprayer manufactured by Pulvexper, France (Figure 3.6). The sprayer has two analogue pressure gauge displays. Pressure values were taken as valid only in relation to the prototype in-use and to the tubing setup especially for the PAMs tested, which were characterized by high viscosity. Relationships between PAM and water application rates and pressure have a qualitative component and cannot be compared with other setups outside the frame of this experiment. Previous calibrations (Figure 3.) however, validated PAM and water flow, and therefore application rates. The Pedestrian PAM Sprayer can support up to six nozzles (Personal Communication Charles Lecoite, SNF). However, to ensure

consistency between calibration and experiment, three nozzles were connected on one side of the boom.

Application rate was varied according to the speed determined by the following formula:

3-2 Application rate as a function of flow and sprayer's speed

$$Speed[m\ s^{-1}] = \frac{Flow_{nozzles}[g\ s^{-1}]}{Width[m] * PAM\ [g\ m^{-2}]} \quad 3.2$$

3-3 Application rate as a function of flow and sprayer's speed

A water-permeable membrane was fitted on the floor. A one-metre wide area on the membrane was mapped into a grid using a tape and markers. Three batches of microcosms were randomly placed on the grid's spots, as shown in Figure 3.5. Spraying forward speed for $15\ kg\ ha^{-1}$ was $1.33\ m\ s^{-1}$, the speed associated with $25\ kg\ ha^{-1}$ was $0.8\ m\ s^{-1}$. $40\ kg\ ha^{-1}$ was achieved by two sprayer passes. The sprayer speed was calculated by marking the floor at 1 m intervals and placing an electronic metronome at the desired frequency (60 bpm and 100 bpm for 25 and $15\ m\ s^{-1}$ respectively). The sprayer's operator was moving at pace, covering 1m at every metronome's impulse.

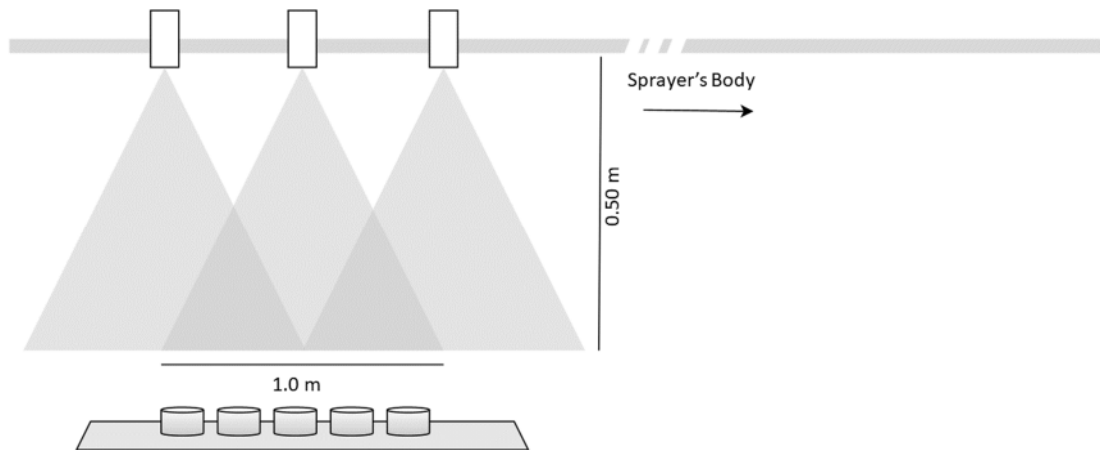


Figure 3.5 Diagram of Microcosm layout on the Boom during laboratory experiment



Figure 3.6 Pedestrian Sprayer The main body of the sprayer houses a pressure air chamber that feeds two separate hydraulic systems, for water and polymer. The two feeding systems are regulated independently by two pressure valves located just outside the main body of the sprayer. Detailed SOP available in Appendix B.

3.2.9 Rainfall Simulation

Simulated rainfall was generated using the Tower Rainfall Simulator at the Cranfield University Soil Management Facility. A 0.5 m² bed of hypodermic needles (BD Microlance 0.8 × 40 mm) is set 8.8 m above the plane of impact. Water was allowed to flow into the needle bed. A 21 mm high weir on the bed's edge allowed a constant water pressure over the needles. A 4 mm wide metal mesh 1.0 m below the needle bed facilitated drop-size randomisation. The needles' presence, spacing and position and the weir were calibrated until a homogenous rainfall intensity, drop size distribution and Kinetic Energy (KE) were achieved on the plane of impact. The calibration of the rainfall's attributes was achieved with splash cups placed on the plane of impact, and with a Laser Optical

Distrometer (LOD, model OTT-Parsivel 2, OTT Messtechnik, Kempten, Germany) positioned at five locations within a 1.0 m² area and measured 5 times × 1 min. Rainfall characteristics are summarised in Table 3.4. All the microcosms were labelled and randomly ranked, every randomly composed batch of 12 was then placed under the rainfall simulator on the areas characterised by the target rainfall density of 100 mm hr⁻¹, with a tolerance of ± 10 mm hr (Figure 3.7).

Rainfall intensity mm h ⁻¹	100
D50 (mm ³)	1.69
J m ⁻² h ⁻¹	1792
J m ⁻² mm ⁻¹	21.9

Table 3.4 Rainfall characterisation of the Simulated rainfall

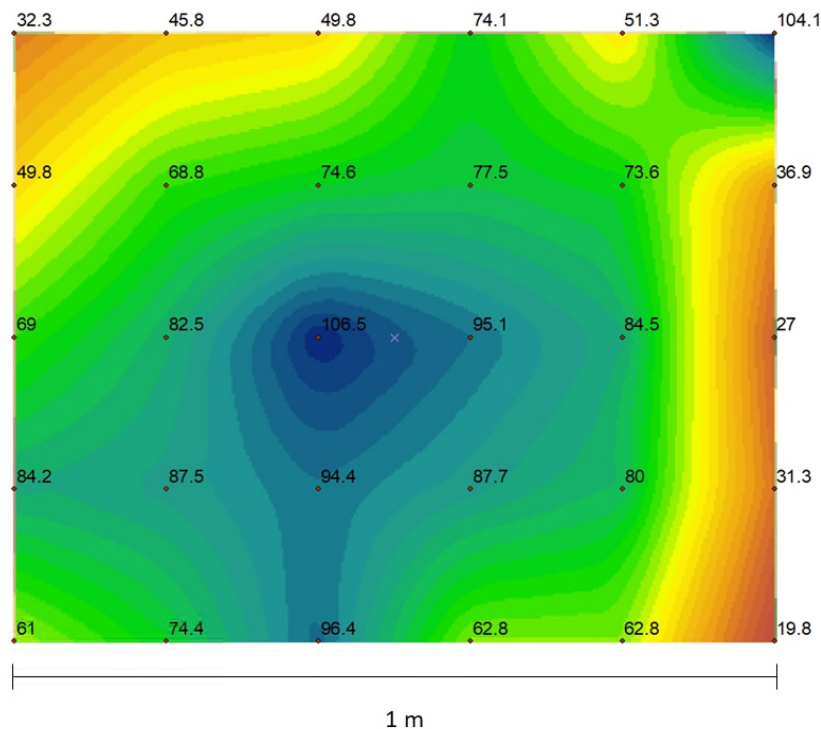


Figure 3.7 Heatmap of Rainfall Intensity (mm hr⁻¹) under the rainfall simulator

3.2.10 Dehydration of the surface seal post rainfall application

A set of eight downwards facing 250W lamps was evenly spread onto a 0.80 x 1.50 m metal shelf, with an average distance between the lamps of 0.27± 0.05

m. There are no reflective walls on the edges of the drying bench, in order to allow free airflow and facilitate the exchange of humidity with the surrounding environment. The variation of temperature was recorded at 40 min intervals with a thermal camera (FLIR E60) Visual assessment of the temperature variation on the quadrats was used to define areas that were drying homogeneously, and to map the areas where the microcosms were going to be placed (Appendix A). To comply with the facility's rules, the heat lamps were switched on only during laboratory's opening times, from 9:00 to 17:30.

3.2.11 Metrics to quantify degree of soil surface crusting

3.2.11.1 Surface Roughness as Surface Area Corrugation Index (SACI)

3D Surface Roughness was performed following Chapter's two method, the lead to the calculation the Surface Area Corrugation Index, that compare the relative loss of Soil Surface Roughness before and after the rainfall. Three dimensional (3D) scans of surface roughness were captured using a Creaform EXAScan 3D hand-held laser scanner with a resolution of 0.40 mm. A 100 mm Ø plastic with a 1600 mm² square (0.04 x 0.04 m) opening in the centre was carefully placed on top of the soil in the microcosm at a precise orientation marked with a marker on the microcosm's rim. The use of the precisely-oriented quadrat allowed the scans to be taken at the exact same position before and after the simulated rainfall events. The 3D scanning process consisted of a coarse 2.0 mm resolution pre-scan of the entire disk, followed by a precise scan of the target square at a resolution of 0.40 mm. The resultant mesh file was imported into Geomagic studio ver. 14.2.2. The mesh file was then clipped to the 1600 mm² area of the quadrat isolating only the known area of scanned soil. When necessary, minor gaps in the mesh were filled using the Geomagic studio (ver. 14.2.2) hole autofill function. On average, the autofill function increased the final scan surface area by <2%. SSR was computed by dividing the 3D surface area by the known scanned area, 1600 mm², factually producing a non-dimensional reading similar to the output of the chain method.

Differences in the SSR between the untreated Control and PAM rainfall duration treatments were assessed using a non-dimensional index of surface area adapted from Jester et al. (2005) of (mm^{-2} pre-rainfall: mm^{-2} post rainfall) following the approach of Bullard (Bullard *et al.*, 2018). A baseline One-way ANOVA assessment to confirm if all three soils were starting with statistically similar Surface roughness (as done in Chapter 2). The Soil Surface Roughness of one treatment Control of EM 533 showed a significant difference (data unshown) in the microcosm surface roughness before the rainfall, meaning that the starting soil surface roughness was not homogeneous across all treatments. As a result, the effect of each treatment is assessed using the relative decrease of the pre and post-treatment measurements called SACI.

3.2.11.2 Penetrative Resistance (PR).

Penetrative resistance is a well-recognised metric of structural sealing and crusting (Al-Durrah and Bradford, 1982; Callebaut et al., 1985; Pulido Moncada et al., 2014; Bullard et al., 2018) and is used as an indicator of potential resistance to emerging seedlings. An Instron 5542 Universal Testing System was used with data processed with the Instron Bluehill software ver 2.35, obtaining a dataset similar to the one of (Callebaut et al., 1985). The soil microcosms were tested 6 ± 1 days after the simulated rainfall event. Penetrative resistance was determined using a 3.0 mm diameter ($= 7.05 \text{ mm}^2$) probe with a vertical motion rate of 1 mm s^{-1} to a maximum depth of 11.0 mm. The Instron recorded the load on the probe at every 0.1 mm depth. When the crust broke under the probe's pressure, the software registered 'yield points', peaks of load followed by a sudden drop in pressure (Instron Bluehill manual ver. 2.35). For the Control treatments, no peak load was detected. However, a minor peak was observable as the probe displaced some of the surface aggregates. In these cases the yield point was very close to zero, and determined by investigating the Instron raw data points. To compare the PR with the turgor pressure exerted by the coleoptile during emergence, the raw data was then converted into MPa by dividing the load in Newtons by the probe surface area (7.05 mm^2).

3.2.11.3 Unsaturated hydraulic Conductivity (HC)

A Minidisc Infiltrometer (Decagon Devices) was used to capture the HC under laboratory conditions 5 days ± 6 h after the second rainfall event. Unlike other experiments with similar technology and equipment (Armenise *et al.*, 2018; Hardie and Almajmaie, 2019) it was decided not to use sand tables to equilibrate microcosm matric potential. Their use was preferable, but not compatible with the project's timetable due to their unavailability. Unlike other studies that were surveying HC measurements to be fed into universally used infiltration models, the scope of the experiment was to achieve a comparison between treatments within the working framework. Shifting the HC meaning from absolute to relative values, allowed to avoid use of the sand tables. Their absence was countered by lining the microcosms with filter paper and by performing the HC measurements within a short (6h) window after the rainfall event, to ensure soil moisture homogeneity. Quadruplicates of HC were obtained with a suction set at 20 mm, the most appropriate value for silty loam soils according to the manufacturer's guidance (Decagon Devices, 2012). The sample featured three different porosity layers: a contact surface made of Garside Sand, a crusted layer of variable thickness, and non-aggregated loose soil: this experiment follows the conceptual model proposed by Hardie et al. (2019), that considers the reduced porosity of the surface layer as the limiting factor for HC. The HC was then computed using the method adopted by Zhang (1997) from the minidisk infiltrometer data.

3.2.12 Data collection and processing

Normality of data was visually explored using plots of residuals versus fitted values. One Way and Repeated Measures ANOVA for PR and HC and 3D Surface Roughness, respectively were computed using Statistica version 13 (<http://statistica.io>.) Post-Hoc analysis was Fischer LSD with $\alpha = 0.05$ within the same software.

3.3 Results and Discussion

The output of Surface Area Index, Penetrative Resistance and Unsaturated Hydraulic Conductivity is presented in Table 3.5.

PAM Application Rate (Kg ha⁻¹)	Surface Area Corrugation Index¹ (SACI) (mm² mm⁻²)	Penetrative Resistance (MPa) at break	Hydraulic Conductivity (mm h⁻¹)
EM 240			
0	1.17 ^{ab}	12.05 ^a	12.15 ^a
15	1.15 ^a	12.28 ^a	8.21 ^{ab}
25	1.16 ^a	6.33 ^b	8.83 ^{ab}
40	1.26 ^{cd}	14.24 ^{ac}	9.75 ^{ab}
EM 533			
0	1.17 ^{ab}	12.05 ^a	12.15 ^a
15	1.30 ^d	16.29 ^c	6.31 ^{ab}
25	1.23 ^{bcd}	12.05 ^a	8.62 ^{ab}
40	1.23 ^{bc}	15.78 ^c	9.29 ^{ab}
SFA30			
0	1.17 ^{ab}	12.05 ^a	12.15 ^a
15	1.16 ^a	7.25 ^b	11.69 ^a
25	1.24 ^{cd}	6.54 ^b	10.33 ^a
40	1.21 ^{abc}	7.73 ^b	11.55 ^a

Table 3.5 Effect of three different PAM formulation on soil microcosms subjected to simulated rainfall. within the same PAM, values followed by the same letter are not significantly different (p<0.05) following One Way or Repeated Measures ANOVA and post-hoc Fischer LSD

¹The 3D index of surface roughness is displayed as the Surface Area Corrugation Index (SACI), a ratio post-rainfall:before-rainfall Surface roughness already used in Chapter 2.

3.3.1 Index of Surface Area Corrugation Index (SACI)

Variation in the Area Corrugation Index (SACI) as expressed by the ratio between the surface area mm² mm⁻² measured before and after the first rainfall event, are shown in Figure 3.9. The higher the value, the more aggregates survived the rainfall event and were captured by the 3D scan. Generally, before the rainfall all microcosms average a 3D surface area of 3374 mm² (= 2.01 x the quadrat area

of 1600 mm²). After the 10 min rainfall event, most of the aggregates on the surface are destroyed, leaving a final mean SACI across all treatments of 1.2 mm² mm⁻² corresponding to an average drop of 57% of the surface roughness (Figure 3). Control treatments after rainfall averaged 1874 mm² (= 1.17 times the 1600 mm² quadrat area) corresponding to a drop of 56% of the surface roughness after 10 mins of rainfall.

Higher SACI values than the Control suggesting positive effects on aggregate stability. EM240 application (Figure 3.9) was found to be significantly different from the untreated Control at 40 kg ha⁻¹ only (1.26 mm² mm⁻²) with an increase in SACI of 7% as compared to the Control (1.17 mm² mm⁻²). EM 533 is associated with SACI values of 1.17 to 1.30, to 1.23 mm² mm⁻² for 15, 25 and 40 kg ha⁻¹ application rates, respectively. For EM533 only the SACI value at 15 kg ha⁻¹ is significantly different from the Control. For SFA30 the 25 kg ha⁻¹ treatment had a SACI value significantly higher than the Control and 15 kg ha⁻¹ application rate treatments (Figure 3.9) 40kg ha⁻¹ did not result in a significantly higher SACI than Control. SFA 30 was the only PAM formula not to show efficacy at 40 kg ha⁻¹. EM240 at 40 kg ha⁻¹ is the only treatment significantly higher than Control (1.26 versus Control's 1.17 mm² mm⁻²), and EM 533 showed significant difference on all treatments except 25 kg ha⁻¹ (1.17, 1.30, 1.23 and 1.23 mm² mm⁻² associated with Control, 15, 25 and 40 kg ha⁻¹) (Table 3.5)

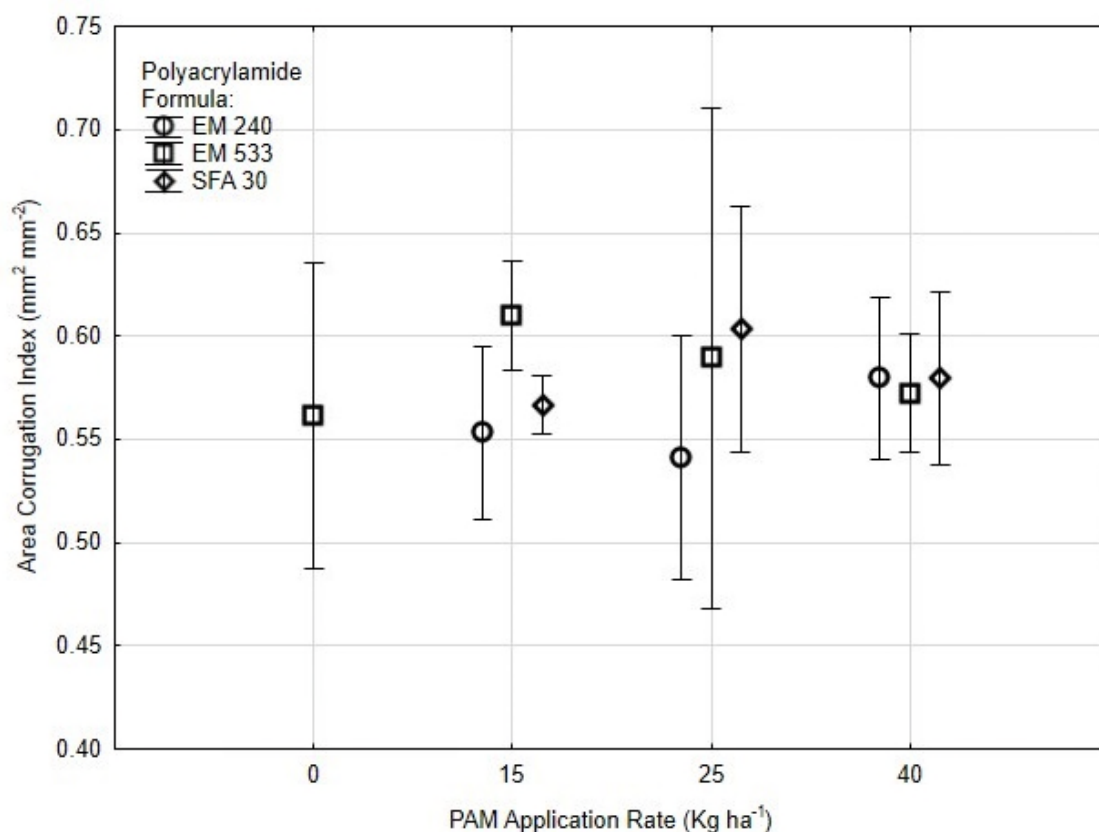


Figure 3.8 Effect of PAM application rate (kg ha⁻¹) and formulation on the Index of Surface Roughness. The mean (n=4) Surface Area Corrugation Index (SACI) is the ratio between the surface area (mm²: mm²) before and after both the 10 and 5 min rainfall events and two drying cycles. Vertical bars denote 95% confidence intervals.

3.3.2 Penetrative Resistance (PR)

The continuous dataset produced by the Intron 5542 Universal testing system cone penetrometer is analysed by the Instron Bluehill software ver 2.35 to isolate the 'yield point', the measurement associated with the greatest PR, usually recorded just before the crust breakage. All the values in this experiment exceed the germination threshold of 0.27 kg cm⁻² (=0.026 MPa) advised by Richards (1953) for bean seedlings. However, the drying conditions designed in this occasion might have been too harsh. In particular, the mitigation strategies to retain a controlled soil moisture in the microcosms did not compensate for the absence of sand tables. The result is a dataset that is not comparable with other

researchers obtained with in-field measurements (Griffiths *et al.*, 2015) or using sand tables (Callebaut *et al.*, 1985). However, the dataset does indicate the comparative efficacy of the PAM treatments tested. In Chapter 2, the PR of the experimental soil was evaluated against an increasing rainfall duration. The mean PR value after the longest rainfall treatment of 10 mins, was 7.0 MPa. This experiment measured PR after a cycle of two rainfall events of 10 and 5 minutes followed by longer drying periods, with a final mean PR value for the Control of 12.1 MPa (Figure 3.9).

SFA30 (anionic concentrated suspension) was associated with significantly lower PR values across all applications rates as compared with the Control and, with the exception of EM240 at 25 kg ha⁻¹, all other PAM treatments (Figure 3.9). Increasing SFA30 application rate from 15 – 40 kg ha⁻¹ did not result in reductions in PR with values of 7.25, 6.54 and 7.73 associated with 15, 25 and 40 kg ha⁻¹ respectively, compared to the Control, associated with 12.15 MPa (Figure 3.9).

For EM240, (cationic inverse emulsion) an application rate of 15 kg ha⁻¹, only increased the PR variability without any significant effect on PR (Figure 3.10). The EM240 15 kg ha⁻¹ PR result might have been affected by the inhomogeneity of PAM application with the fast single pass of the sprayer for the lowest application rate influenced by spatial variation in the nozzle's footprint to the ground. However, the mean 25 and 40 kg ha⁻¹ PR values are more precise, but less accurate (Figure 3.10). The 25 kg ha⁻¹ application significantly reducing PR compared with the Control whereas the 40 kg ha⁻¹ treatment is associated with a higher PR. This suggests for EM240, an association between higher application rate and crust PR. However, the results need to be considered in context. Empirical observations of EM240 PAM coverage indicated that EM240 at 40 kg ha⁻¹ covered < 20% of the microcosm surface. As shown by the 3D surface Roughness data, most of the aggregates were already slacked and disaggregated after the first rainfall event. A possible explanation is that PAM, remained on the soil surface, unfolding completely in the ponding water during and post the rainfall event stabilising the smooth surface post-rain. This

phenomenon might help explain the higher PR associated with 40 kg ha⁻¹ EM240 PAM treatment. A similar trend was observed for EM533 (Figure 3.9).

The anionic inverse emulsion, EM533, was associated with the worst performance in terms of PR with all EM533 treatments associated with equal or higher mean PR values as compared to the control (+35 and 31% higher for 15 and 40 kg ha⁻¹ respectively). EM533 has a similar performance pattern to cationic EM240 (high-low-high) but was generally associated with PR values 4.0 – 5.0 MPa higher at 15 and 25 kg ha⁻¹ than EM240 (Figure 3.10). No significant difference was observed between the EM533 and EM240 40 kg ha⁻¹ treatments with PR values of 14.2 and 15.8 MPa respectively. The relatively poor performance of the anionic inverted emulsion, EM 533, might in part be due to the negative charge polarity, which repels the negative exchange sites on clay particles which are (in the absence of bridging cations) like to be the majority of charged surfaces as the soil used in this experiment is characterised by low SOM (Chapter 2, Table 2.1a).

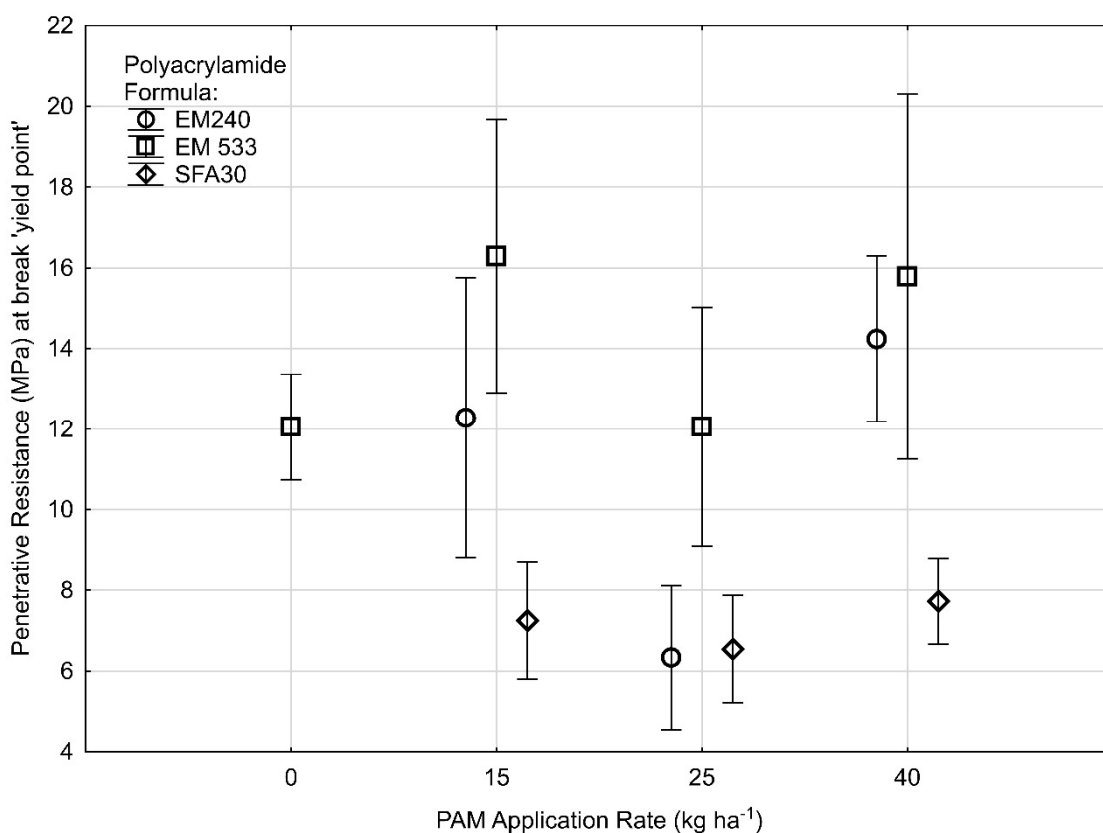


Figure 3.9 Effect of PAM application rate (kg ha^{-1}) and formulation on mean ($n=4$) crust Penetrative Resistance (MPa) at break following both the 10 and 5 min rainfall events and two drying cycles. The break point corresponds to the 'yield point' where probe breaks the crust and the Intron 5542 Universal testing system records a sudden drop of the load. Vertical bars denote 95% confidence intervals.

3.3.3 Unsaturated Hydraulic Conductivity (HC)

Compared with the results obtained in Chapter 2, where HC for the same soil decreased to 4 mm h^{-1} after ten minutes of rainfall, for the Control treatment, mean HC was 12 mm h^{-1} after two consecutive rainfall events (10 and 5 mins) and two drying periods (Figure 3.11). Rainfall intensity, soil and the Minidisk Infiltrometer settings did not vary between experiments. The only variable changed was the increased rainfall duration and hence KE of the two consecutive rainfall events, which exceeded the slacking threshold observed in Chapter 2, coupled with two wetting and drying cycles. Kebede et al., (2020) investigated six consecutive rainfall events on a 5.0 mm-sieved clay soil and observed that the HC of the Control dropped from 35 to 10 mm h^{-1} after the first rainfall event, to stabilise at 5 mm h^{-1} after the third (Figure 3.10). Adding PAM resulted in a decrease of HC, followed by an increase between the third and fourth events (Kebede et al., 2020). A similar trend could be isolated in the 15 kg ha^{-1} readings of the inverted emulsion PAMs (8.21 and 6.31 mm ha^{-1} for EM240 and EM 533 respectively versus 12 mm ha^{-1} of the Control), however, there is no significant difference between Control and any of the treatments. Its absence could be partially attributed to the high variability of the Control Treatment, as shown in Figure 3.11, but it is likely to be attributed by PAM's lack of effect on HC at the given application rates.

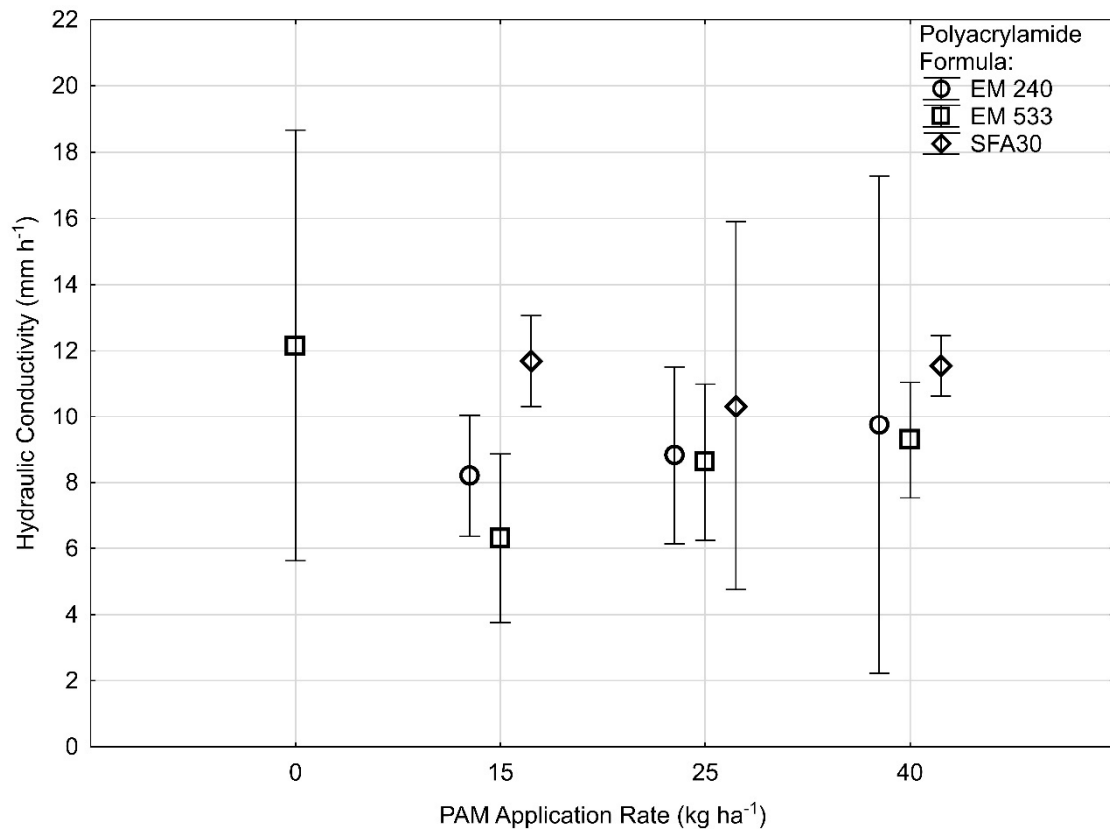


Figure 3.10 Effect of PAM application rate (kg ha⁻¹) and formulation on mean (n=4) Unsaturated Hydraulic Conductivity (n=48) expressed in mm h⁻¹ as a function of PAM formulations and their Application Rate. Vertical Bars denote 95% confidence Interval.

3.4 Conclusions

The primary aim of the experiment was to characterise and test the twin-fluid Nozzle in a controlled environment, the secondary was to investigate the effects of three PAMs formula on a crust-susceptible soil.

Spraying Polyacrylamides using the twin fluid nozzle, was successful in terms of practicality. The droplet drift in the environment was minimum, and no PAMs drifted towards the sprayer's body. As shown in the Patternation graphs, there is a slight accumulation of PAMs and Water on the sides of the nozzle's footprint, that increases at higher operative pressures. The easiest solution would be to

decrease pressure and distance between nozzles to take advantage of redundancy of sprayed footprints.

Cleaning and maintenance operations were time-consuming, in particular post-use care ranges from 1 hr for SFA 30 to 2 or 2.5 hrs for EM533 and EM 240. Most of the time increase however, was caused by the pedestrian sprayer and not by the nozzle themselves. The tubing system and arrangement was naturally convoluted and tight, increasing the time necessary to remove all PAMs from their tubing system (Appendix SOP). The practical difficulties of PAM handling and cleaning are notoriously considered the limiting factor to their full-scale application, and great care must be taken in reducing the impact that these two tasks have for the farmer. This research showed great improvement on the first, and at the same time identified critical areas, such as the tubing system, that need to be addressed before upscaling this technology to field-size.

At current application rates, EM533 and EM240, were in general ineffective at mitigating soil surface crusting. Results obtained from the 3D Index of Surface Roughness, PR and HC do not confirm the research hypothesis. Only SFA30 was effective at significantly reducing PR across all application rates and 3D surface roughness, at 25 and 40 kg ha⁻¹ application rates.

3.5 References

- Aase, J. K., Bjorneberg, D. L. and Sojka, R. E. (1998) 'Sprinkler Irrigation Runoff and Erosion Control with Polyacrylamide — Laboratory Tests', *Soil Science Society of America Journal*, 62(6), p. 1681. doi: 10.2136/sssaj1998.03615995006200060028x.
- Abrol, V. *et al.* (2013) 'Efficacy of dry granular anionic polyacrylamide (PAM) on infiltration, runoff and erosion', *European Journal of Soil Science*, 64(5), pp. 699–705. doi: 10.1111/ejss.12076.
- Abu-Zreig, M. (2006) 'Control of rainfall-induced soil erosion with various types of polyacrylamide', *Journal of Soils and Sediments*, 6(3), pp. 137–144. doi: 10.1065/jss2006.04.152.
- Ao, C. *et al.* (2016) 'Efficacy of granular polyacrylamide on runoff, erosion and nitrogen loss at loess slope under rainfall simulation', *Environmental Earth Sciences*, 75(6). doi: 10.1007/s12665-015-5110-3.
- Armenise, E. *et al.* (2018) 'Soil seal development under simulated rainfall: Structural, physical and hydrological dynamics', *Journal of Hydrology*. The Authors, 556, pp. 211–219. doi: 10.1016/j.jhydrol.2017.10.073.
- Atichat, C. (2015) *CRITICAL EVALUATION OF ANIONIC POLYACRYLAMIDE BASED SOIL CONDITIONERS TO REDUCE SOIL SURFACE CRUSTING*. Cranfield University. Available at: <https://mta-cranfield-ac-uk.eu1.proxy.openathens.net/handle/1826.1/11127>.
- Bavernick, F. W. (1994) 'Polyacrylamide Characteristics Related to Soil Applications', *Soil Science*.
- Ben-hur, M. (2014) 'Soil Research Using synthetic polymers as soil conditioners to control runoff and soil loss in arid and semi-arid regions — a review', p. 5175.
- Ben-Hur, M. *et al.* (1989a) 'Polymers as soil conditioners under consecutive irrigations and rainfall', *Soil Science Society of America Journal*, 53(4), pp. 1173–1177. doi: 10.2136/sssaj1989.03615995005300040030x.
- Ben-Hur, M. *et al.* (1989b) 'Polymers as Soil Conditioners Under Consecutive Irrigations and Rainfall', *Soil Science Society of America Journal*, 53(4), pp. 1173–1177. doi: 10.2136/sssaj1989.03615995005300040030x.
- Ben-Hur, M. (2001) 'Soil conditioner effects on runoff and potato yield under sprinkler irrigation', *Agronomy Journal*, 93(5), pp. 1156–1163. doi: 10.2134/agronj2001.9351156x.

- Ben-Hur, M. and Keren, R. (1997) 'Polymer Effects on Water Infiltration and Soil Aggregation', *Soil Science Society of America Journal*, 61(2), p. 565. doi: 10.2136/sssaj1997.03615995006100020028x.
- Ben-Hur, M. and Letey, J. (1989) 'Effect of Polysaccharides, Clay Dispersion, and Impact Energy on Water Infiltration', *Soil Science Society of America Journal*, 53(1), pp. 233–238. doi: 10.2136/sssaj1989.03615995005300010041x.
- Bjorneberg, D. L. (1998) 'Temperature, concentration, and pumping effects on PAM viscosity', *Transactions of the American Society of Agricultural Engineers*, 41(6), pp. 1651–1655. doi: 10.13031/2013.17340.
- Bjorneberg, D. L. *et al.* (2003) 'Using polyacrylamide with sprinkler irrigation to improve infiltration', *Journal of Soil and Water Conservation*, 58(5), pp. 283–289.
- Blankenship, W. D., Condon, L. A. and Pyke, D. A. (2019) 'Hydroseeding tackifiers and dryland moss restoration potential', *Restoration Ecology*, pp. 1–12. doi: 10.1111/rec.12997.
- Bouranis, D. L., Theodoropoulos, A. G. and Drossopoulos, J. B. (1995a) 'Designing synthetic polymers as soil conditioners', *Communications in Soil Science and Plant Analysis*, 26(9–10), pp. 1455–1480. doi: 10.1080/00103629509369384.
- Bouranis, D. L., Theodoropoulos, A. G. and Drossopoulos, J. B. (1995b) 'Designing synthetic polymers as soil conditioners', *Communications in Soil Science and Plant Analysis*, 26(9–10), pp. 1455–1480. doi: 10.1080/00103629509369384.
- Brown, W. H., Campbell, M. K. and Farrell, S. O. (2013) *elementi di Chimica Organica*. IX. Naples: Edi-SES.
- Bullard, J. E. *et al.* (2018) 'Impact of multi-day rainfall events on surface roughness and physical crusting of very fine soils', *Geoderma*. Elsevier, 313(October 2017), pp. 181–192. doi: 10.1016/j.geoderma.2017.10.038.
- Callebaut, F. *et al.* (1985) 'Determination of soil surface strength with a needle-type penetrometer', *Soil and Tillage Research*, 5(3), pp. 227–245.
- Chaudhari, K. and Flanagan, D. C. (1998) 'Polyacrylamide effect on sediment yield, runoff, and seedling emergence on a steep slope', in *ASAE Annual International Meeting*. Orlando, FL.
- Costine, A. *et al.* (2018) 'Variations in the molecular weight response of anionic polyacrylamides under different flocculation conditions', *Chemical Engineering Science*. Elsevier Ltd, 176, pp. 127–138. doi: 10.1016/j.ces.2017.10.031.

Decagon Devices (2012) 'Mini Disk Infiltrometer', *Mini Disk Infiltrometer User's Manual Version 10*, p. 21. doi: 10.1007/s13398-014-0173-7.2.

DEFRA (2020) *Food Statistics in your pocket: Food Chain - GOV.UK, Food Statistics in your pocket: Food Chain*. Available at: <https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-food-chain>.

FEH (2019) *Point data at 553505,168123: WattsFarm*. Available at: <https://fehweb.ceh.ac.uk/GB/map>.

Green, S. V., Stott, D. E. and Graveel, J. . (2005) 'Polyacrylamide Molecular Weight and Charge Effects on Infiltration under Simulated Rainfall', pp. 1786–1791.

Griffiths, B. S. *et al.* (2015) 'Probing soil physical and biological resilience data from a broad sampling of arable farms in Scotland', *Soil Use and Management*, 31(4), pp. 491–503. doi: 10.1111/sum.12214.

Hamilton, J. D., Reinert, K. H. and Freeman, M. B. (1994) 'Aquatic Assessment of Polymers', *Environmental Science Technology*, 28(4), pp. 186–192. doi: 10.1021/es00053a719.

Hardie, M. and Almajmaie, A. (2019) 'Measuring and estimating the hydrological properties of a soil crust', *Journal of Hydrology*. Elsevier, 574(April), pp. 12–22. doi: 10.1016/j.jhydrol.2019.04.031.

Hecker, R. (1998) *The Characterisation of Polyacrylamide Flocculants.pdf*. curtin University of Technology.

Jester, W. and Klik, A. (2005) 'Soil surface roughness measurement - Methods, applicability, and surface representation', *Catena*, 64(2–3), pp. 174–192. doi: 10.1016/j.catena.2005.08.005.

Känkänen, H. *et al.* (2011) 'Applying granulated and hydrated hydrophilic polymers at sowing to sustain seedling establishment of spring turnip rape', *Journal of Agricultural Science*, 149(5), pp. 567–577. doi: 10.1017/S0021859611000013.

Kebede, B. *et al.* (2020) 'Effectiveness of polyacrylamide in reducing runoff and soil loss under consecutive rainfall storms', *Sustainability (Switzerland)*, 12(4), pp. 1–18. doi: 10.3390/su12041597.

Kruger, G. and Vieira, B. C. (2016) *Herbicide Application Technology*. Second Edi, *Encyclopedia of Applied Plant Sciences*. Second Edi. Elsevier. doi: 10.1016/B978-0-12-394807-6.00232-X.

Lado, M. *et al.* (2016) 'Effectiveness of Granular Polyacrylamide to Reduce Soil Erosion During Consecutive Rainstorms in a Calcic Regosol Exposed to Different Fire Conditions', *Land Degradation and Development*, 27(5), pp. 1453–1462. doi: 10.1002/ldr.2448.

Lal, R. (2016) 'Soil health and carbon management', *Food and Energy Security*, 5(4), pp. 212–222. doi: 10.1002/fes3.96.

Lehrsch, G. A., Lentz, R. D. and Kincaid, D. C. (2005) 'Polymer and sprinkler droplet energy effects on sugar beet emergence, soil penetration resistance, and aggregate stability', *Plant and Soil*, 273(1–2), pp. 1–13. doi: 10.1007/s11104-004-7614-6.

Lentz, R. D. *et al.* (1992) 'Preventing irrigation furrow erosion with small applications of polymers', *Soil Science Society of America Journal*, 56(6), pp. 1926–1932. doi: 10.2136/sssaj1992.03615995005600060046x.

Lentz, R. D. (2015) 'Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam', *Geoderma*. Elsevier B.V., 241–242, pp. 289–294. doi: 10.1016/j.geoderma.2014.11.019.

Lentz, R. D. *et al.* (2020) 'SOIL WATER DISTRIBUTION IN IRRIGATION FURROWS TREATED WITH POLYACRYLAMIDE', 63(5), pp. 1451–1464.

Lentz, R. D. and Sojka, R. E. (1994) 'Field results using polyacrylamide to manage furrow erosion and infiltration', *Soil Science*, 158(4), pp. 274–282. doi: 10.1097/00010694-199410000-00007.

Lentz, R. D., Sojka, R. E. and Mackey, B. E. (2002) 'Fate and Efficacy of Polyacrylamide Applied in Furrow Irrigation', *Journal of Environmental Quality*, 31(2), pp. 661–670. doi: 10.2134/jeq2002.6610.

Lentz, R. D., Sojka, R. E. and Robbins, C. W. (1998) 'Reducing Phosphorus Losses from Surface-Irrigated Fields: Emerging Polyacrylamide Technology', *Journal of Environmental Quality*, 27(2), pp. 305–312. doi: 10.2134/jeq1998.00472425002700020009x.

Lentz, R. D., Sojka, R. E. and Ross, C. W. (2000) 'Polymer charge and molecular weight effects on treated irrigation furrow processes', *International journal of sediment research*, 15(1), pp. 17–30.

Levin, G. J. *et al.* (1991) 'Rain energy and soil amendments effects on infiltration and erosion of three different soil types.', *Australian Journal of Soil Research*, 29(3), pp. 455–465.

Levy, G. J. *et al.* (1992a) 'Polymers' effects on infiltration and soil erosion during

consecutive simulated sprinkler irrigations', *Soil Science Society of America Journal*, 56(3), pp. 902–907. doi: 10.2136/sssaj1992.03615995005600030037x.

Levy, G. J. *et al.* (1992b) 'Polymers' Effects on Infiltration and Soil Erosion during Consecutive Simulated Sprinkler Irrigations', *Soil Science Society of America Journal*, 56(3), pp. 902–907. doi: 10.2136/sssaj1992.03615995005600030037x.

Levy, G. J. and Agassi, M. (1995) 'Polymer molecular weight and degree of drying effects on infiltration and erosion of three different soils', *Australian Journal of Soil Research*, 33(6), pp. 1007–1018. doi: 10.1071/SR9951007.

Levy, G. J. and Rapp, I. (1999) 'Polymer effects on surface mechanical strength of a crusting loessial soil', *Australian Journal of Soil Research*, 37, pp. 227–239.

Li, F. H. and Wang, A. P. (2016) 'Interaction effects of polyacrylamide application and slope gradient on potassium and nitrogen losses under simulated rainfall', *Catena*, 136, pp. 162–174. doi: 10.1016/j.catena.2015.05.008.

Li, S., Xu, H. and Ao, C. (2019) 'Polyacrylamide and Rill Flow Rate Effects on Erosion and Ammonium Nitrogen Losses', *Water, Air, and Soil Pollution. Water, Air, & Soil Pollution*, 230(1). doi: 10.1007/s11270-018-4052-2.

Lin, L. R., He, Y. B. and Chen, J. Z. (2016) 'The influence of soil drying- and tillage-induced penetration resistance on maize root growth in a clayey soil', *Journal of Integrative Agriculture. Chinese Academy of Agricultural Sciences*, 15(5), pp. 1112–1120. doi: 10.1016/S2095-3119(15)61204-7.

McLaughlin, R. A. and Brown, T. T. (2006) 'Evaluation of erosion control products with and without added polyacrylamide', *Journal of the American Water Resources Association*, 42(3), pp. 675–684. doi: 10.1111/j.1752-1688.2006.tb04484.x.

McNeal, J. P. *et al.* (2017) 'Application of Polyacrylamide (PAM) through Lay-Flat Polyethylene Tubing: Effects on Infiltration, Erosion, N and P Transport, and Corn Yield', *Journal of Environmental Quality*, 46(4), pp. 855–861. doi: 10.2134/jeq2016.08.0299.

Mitchell, a. R. (1986) 'Polyacrylamide application in irrigation water to increase infiltration', *Soil Science*, pp. 353–358.

Nascimento, C. D. V. *et al.* (2021) 'Potential of superabsorbent hydrogels to improve agriculture under abiotic stresses', *Journal of Arid Environments. Elsevier Ltd*, 189(May 2020), p. 104496. doi: 10.1016/j.jaridenv.2021.104496.

Neave, M. and Rayburg, S. (2007) 'A field investigation into the effects of progressive rainfall-induced soil seal and crust development on runoff and

erosion rates: The impact of surface cover', *Geomorphology*, 87(4), pp. 378–390. doi: 10.1016/j.geomorph.2006.10.007.

Paganyas, K. P. *et al.* (1972) 'Experimental application of K-4 and K-9 in the control of the irrigational erosion of soils during cotton irrigation.', '*Teoreticheskiye Voprosy Obrabotki Pochv (Theoretical Problems in Soil Cultivation)*', 3.

Pagliai, M. and Stoops, G. (2010) *Physical and Biological Surface Crusts and Seals, Interpretation of Micromorphological Features of Soils and Regoliths*. Elsevier B.V. doi: 10.1016/B978-0-444-53156-8.00019-2.

Pagliai, M., Vignozzi, N. and Pellegrini, S. (2004) 'Soil structure and the effect of management practices', in *Soil and Tillage Research*, pp. 131–143. doi: 10.1016/j.still.2004.07.002.

Rabiee, A., Ershad-Langroudi, A. and Zeynali, M. E. (2015) 'A survey on cationic polyelectrolytes and their applications: Acrylamide derivatives', *Reviews in Chemical Engineering*, 31(3), pp. 239–261. doi: 10.1515/revce-2014-0056.

Roshanizarmehri, M. *et al.* (2018) 'Combined effects of polyacrylamide and nanomagnetite amendment on soil and water quality, Khorasan Razavi, Iran', *Journal of Environmental Management*. Elsevier, 223(June), pp. 703–712. doi: 10.1016/j.jenvman.2018.06.061.

Sepaskhah, A. R. and Mahdi-Hosseiniabadi, Z. (2008) 'Effect of polyacrylamide on the erodibility factor of a loam soil', *Biosystems Engineering*, 99(4), pp. 598–603. doi: 10.1016/j.biosystemseng.2007.12.009.

Sepaskhah, A. R. and Shahabizad, V. (2010) 'Effects of water quality and PAM application rate on the control of soil erosion, water infiltration and runoff for different soil textures measured in a rainfall simulator', *Biosystems Engineering*. IAgRE, 106(4), pp. 513–520. doi: 10.1016/j.biosystemseng.2010.05.019.

Shainberg, I., Warrington, D. N. and Rengasamy, P. (1990) 'Water Quality and PAM Interaction in Reducing Surface Sealing', *Soil Science*, 149(5), pp. 301–307. doi: 10.1097/00010694-199005000-00007.

Sojka, R. E. *et al.* (2007) 'Polyacrylamide in Agriculture and Environmental Land Management', *Advances in Agronomy*, 92(04), pp. 75–162. doi: 10.1016/S0065-2113(04)92002-0.

Thornton, M. E. and Kibble-White, R. (1974) 'Apparatus used for spray nozzle evaluation at the weed research organization', *PANS Pest Articles and News Summaries*, 20(4), pp. 465–475. doi: 10.1080/09670877409418229.

Trout, T. J., Sojka, R. E. and Lentz, R. D. (1995) 'Polyacrylamide effect on furrow

erosion and infiltration', *Transactions - American Society of Agricultural Engineers*, 38(3), pp. 761–766. doi: 10.13031/2013.27889.

Valentin, C. and Bresson, L. M. (1992) 'Morphology, genesis and classification of surface crusts in loamy and sandy soils', *Geoderma*, 55(3–4), pp. 225–245. doi: 10.1016/0016-7061(92)90085-L.

Vanderhoff, J. W. *et al.* (1962) 'Inverse Emulsion Polymerization', pp. 32–51. doi: 10.1021/ba-1962-0034.ch002.

Wang, F., Chen, J. and Lin, L. (2018) 'Effects of Rainfall-Induced Topsoil Structure Changes on Root-Zone Moisture Regime during the Dry Period', *Eurasian Soil Science*, 51(1), pp. 54–65. doi: 10.1134/S1064229318010155.

Weeks, E. L. and Colter, William, G. (1952) 'Effect of synthetic soil conditioners on erosion control', *Soil Science*, 73(6), pp. 473–484. doi: 10.1097/00010694-195206000-00006.

Yang, K., Tang, Z. and Feng, J. (2020) 'Effect of co-use of fly ash and granular polyacrylamide on infiltration, runoff, and sediment yield from sandy soil under simulated rainfall', *Agronomy*, 10(3). Available at: <https://www.scopus.com/record/display.uri?eid=2-s2.0-85081648956&origin=resultslist&sort=plf-f&cite=2-s2.0-84960953223&src=s&imp=t&sid=d60d454df4ad7bcfb9dc2fb2d925e67c&sot=cite&sdt=a&sl=0&relpos=4&citeCnt=0&searchTerm=>.

Yonter, G. and Uysal, H. (2010) 'Effects of polyacrylamide (PAM) applications on water erosion and crust formation for different types of soils in Menemen Plain, Turkey'.

Zhang, R. (1997) 'Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer', *Soil Science Society of America Journal*, 61(4), pp. 1024–1030. doi: 10.2136/sssaj1997.03615995006100040005x.

Zheng, M. *et al.* (2020) 'Simultaneous control of soil erosion and arsenic leaching at disturbed land using polyacrylamide modified magnetite nanoparticles', *Science of the Total Environment*. Elsevier B.V., 702, p. 134997. doi: 10.1016/j.scitotenv.2019.134997.

Zin El-Abedin, T. K., Mattar, M. A. and Alazba, A. A. (2015) 'Soil Wetting Pattern from Subsurface Drip Irrigation as Affected by Application of a Polyacrylamide Layer†', *Irrigation and Drainage*, 64(5), pp. 609–618. doi: 10.1002/ird.1937.

4 Effect of polyacrylamide (PAM) application on metrics of soil crusting on spinach (*Spinacea olearia*) and Coriander (*Coriandrum sativum*) emergence and yield: 2020 Field Trials

Abstract

The use of synthetic polymers as soil conditioners has been considered in an agricultural context since the 1970's. Polyacrylamides (PAM) are long-chained carbon polymers featuring an amide functional group that allows them to form bonds with soil colloids. The efficacy of PAMs to stabilise soil aggregates and prevent soil splash, capping and erosion has been well documented. However, its spray application has been limited by the high volume of water required to deliver an effective dose of PAM, due to its extreme viscosity when mixed with water. This study investigated the novel spray application of PAM using Dual-Fluid nozzles under commercial field conditions in high value intensive horticultural production. The impact of PAM application at mitigating the negative effects of soil crust formation on seedling emergence and stand establishment was quantified. Dual-fluid nozzles, mounted on the back of a seed drill, were used to apply PAM at rates of 20, 40 and 80 kg ha⁻¹ using 600-1300 litres of water ha⁻¹ as compared to a non-treated control. Two Trials of 20 plots (1.8 m by 20 m with 5 replicates per treatment) were established within commercial coriander *Coriandrum sativum* and Spinach (*Spinacea olearia*) blocks. Within each experimental plot replicate measurements of volumetric soil water content, hydraulic conductivity, splash detachment, emergence rate, final stand establishment and yield were recorded. Plots where PAM had been applied, were found to have a significantly higher soil moisture content under Coriander only and lower hydraulic conductivity in both crops as compared to the untreated control. For the PAM application rates evaluated in this study, no significant difference in soil splash detachment or emergence rate was observed between PAM treated and control plots. Experimental noise from unevenly distributed irrigation and treatment position on the field slope are believed to have masked treatment responses. The trial demonstrated that PAM can be successfully

applied to the soil surface using Dual-Fluid nozzles to reduce the quantity of irrigation water required to successfully grow commercial crops of Coriander and Spinach.

4.1 Introduction

The food supply chain in the UK concentrates 51% of the food supply in four major supermarket chains (DEFRA, 2020a) with a two-level supply chain consisting on bigger farms bidding to be listed as producers for supermarkets (Stichele and Young, 2012). Baby leaf and field grown herb producers supply the retailers with fresh produce throughout the growing season by implementing multiple growth cycles per year on the same field. This high-input practice has detrimental consequences on soil quality. The repeated high intensity seedbed preparation procedures prevent any organic matter build-up in the soil, (Bronick and Lal, 2005), and repeated high Kinetic Energy (KE) irrigations in early growth stages expose the soil to irrigation drops that cause compaction, swelling and aggregate collapse and particle rearrangement (Assouline, 2004).

Poor soil structure leads to soil crusting in the pre-emergence phase of the cycle. The soil crust consists of a layer of reduced porosity and increased mechanical strength compared to the soil underneath. Soil crust formation is the result of the interaction between physical, chemical and biological processes (Le Bissonnais, 1996; Assouline, 2004). The primary drivers of soil crust formation occur simultaneously and are (i) the transfer of KE from the rain and/or irrigation drop to the soil, and (ii) soil moisture levels. Under rain and/or irrigation drop impacts, soil aggregates are compacted, their particles detached and splashed away. Simultaneously, the volume of water rapidly penetrating into the aggregates, contributes to their collapse via slaking, and decreases the aggregate resistance to the rain/irrigation drops in a process that involves physiochemical dispersion. This is due to the cohesive forces between soil colloids being weaker in water (Le Bissonnais, 1996). The disaggregated soil particles are then transported by the water medium, and are washed-in to the spaces between the aggregates below the impacted layer, and are compacted again by the rain/irrigation drops, in what

could be classified as depositional crust (Assouline, 2004). When this hydrated soil seal is left to dry, the cohesive forces between colloids re-cement into a new, denser, configuration forming a de-hydrated soil crust. Some soil erodibility factors are independent from farm management, e.g. texture and mineralogy (Wakindiki and Ben-Hur, 2002), or rain-drought patterns (FAO, 1993; Le Bissonnais, 1996), while others, like aggregate size distribution and stability (Tisdall and Oades, 1982; Mamedov et al., 2017), or the exposure time of soil to rainfall/irrigation events are affected by agricultural practices.

The major on-site effects of soil crusting for baby leaf and field grown herb production, are connected with reduced infiltration rates, splash contamination of stems and leaves, and with the mechanical impedance of crop emergence. Traditional strategies aimed towards the natural restoration of soil structure, do not fit in the business model for intensive baby leaf horticulture, that involves 21-28 day crop growing cycles and repeated soil disturbance necessary to build fine seedbeds does not allow natural soil structure and aggregate stability to be generated as in less-disturbed soils (Sumner, 2000). Conventional practice exposes these erodible soils to the erosive forces of rainfall and irrigation. The current management practice to mitigate the mechanical impedance to seedling associated with soil crusts consists of wetting the soil surface with a 10 mm overhead boom irrigation just before emergence. This additional irrigation however, furtherly compacts the soil surface, does not increase soil porosity, and does not allow the water to efficiently reach the plant (Assouline, 2004). Polyacrylamides applied to the soil surface could (i) preserve soil structure on the surface, and maintain or improve soil infiltration rates in the period between seeding and stand establishment (ii) lessen water evaporation from the soil (iii) reduce splash contamination of soil onto stems and leaves.

Polyacrylamides have been known for decades as soil structure stabilisers (Orts et al., 2007) and their positive effects on soil has been recorded in numerous laboratory and a handful of field studies. Early research demonstrated how anionic, linear PAM can be effective in stabilising soil aggregates at low application rates (Helalia and J. Letey, 1989). Further investigation demonstrated

how PAM efficacy depends on the aggregate size distribution (Mamedov et al., 2017), the presence of smectitic clays (Mamedov et al., 2010), the co-application of di-valent cations via gypsum or tap water to bridge between the anionic charges of PAM and soil colloids (Smith, Levy and Shainberg, 1990). The positive effects of PAM application are not limited to runoff, but also extend to infiltration rate (Smith, Levy and Shainberg, 1990; Chang et al., 2019; Soltani-Gerdefaramarzi, Ghezelseflue and Boroughani, 2019), water retention and crop emergence (Rubio et al., 1989, 1992; Steinberger and West, 1991).

The aim of this study is to critically evaluate the efficacy of an innovative Dual-Fluid delivery method for PAM in commercial coriander (*Coriandrum sativum*) and Spinach (*Spinacea olearia*) production. The primary research objective is to measure the efficacy of a single PAM formulation at three application rates (20, 40 and 80 kg ha⁻¹) sprayed 24 hrs after seeding. Performance is assessed using splash detachment as a measure of aggregate stability, soil moisture retention using volumetric soil water content and crop emergence homogeneity to evaluate the effect of mechanical impedance.

4.2 Materials and Methods

4.2.1 Field Location and Soil

The two field trials took place at Watts Farm, Kent, UK (51°24'55.63"N, 0°18'41.42"E) from the 28th of July to the 9th of September. Watts Farm is a commercial grower specialising in intensive field grown baby leaf and herb production. The coriander (*Coriandrum sativum*) and Spinach (*Spinacea olearia*) trials took place on the same land plot and where both started within a 24 hr period. The soil is classified as a Chromic Endoleptic Luvisol, a quartzite-rich clay loam (LandIS, 2022). It is empirically considered the most crust susceptible of the three soils (Watts Farm, personal communication, 2019). In Chapter 2, this soil demonstrated the highest crust susceptibility to simulated rainfall in terms of Penetrative Resistance (5.29 and 7.02 MPa after 4 and 10 minutes of rainfall at 100 mm hr⁻¹) and in 3D Soil Surface Roughness (-11 and -32% of soil surface roughness lost after 4 and 10 minutes of rainfall at 100 mm hr⁻¹).

The soil at the trial site consists of 31.2% clay, 23.2% silt and 45.0 % sand. It has an organic matter content of 3.76 % by Loss on Ignition (Klute, 1986) and a pH of 5.72 (BS ISO 10390:2005). The soil cation exchange capacity (CEC) is low at 0.43 mmol l⁻¹ (BS 7755-3.12:1996). The field bulk density (BD) at the time of tillage was 1.24 g cm⁻³. Mineralogy analysis (Appendix E) indicates that 67% (w/w) consisted of quartz, with 7 % of K-feldspar and 6.4% plagioclase-feldspar, with a 13.9% of Illites+Smectites, the clay fractions most reactive to PAM (Mamedov et al., 2010). This explains the low CEC low values and why the soil is susceptible to crusting even though it is classified as a clay loam.

The weather conditions (Figure 4.1) during the experiment were monitored using a Delta-T weather station WSTN (GP1-27-51) located >200 m from the field trial that recorded humidity, wind speed and direction, solar radiation and rainfall (Figure 4.1).

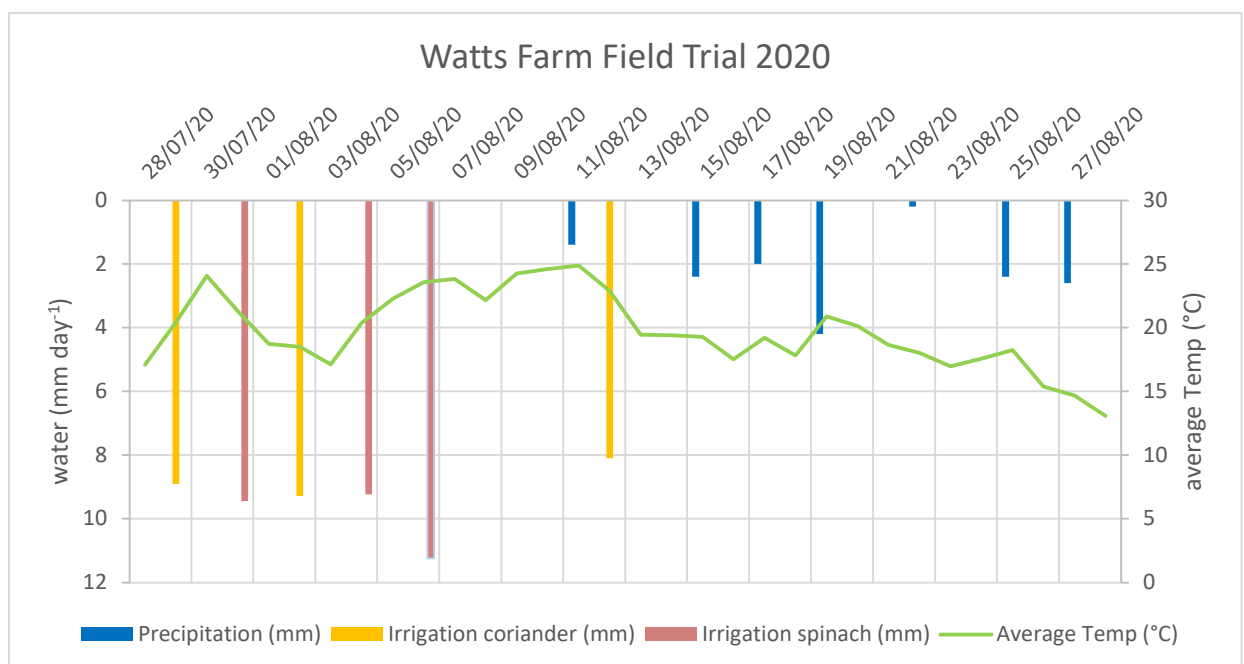


Figure 4.1 Irrigation (mm day⁻¹) and rainfall (mm day⁻¹) applied to the coriander and spinach trials and average daily temperature (°C) for the trial period (July-August 2020).

4.2.2 Experiment Design

For the spinach and coriander trials the experimental unit was a 20 m long, 1.8 m wide plot, that corresponds to a single seedbed separated by a 5 m buffer area. All performance metrics (replicated in quintuplicate) are taken in the central 10 m of each plot. The average slope is 2%. The experimental arrangement was completely randomised plots for coriander, and randomised block for spinach. Given the topography a homogenous slope, originally, both experiments were designed as completely randomised. However, spatial variation was caused inhomogeneity in irrigation, and therefore, the spinach trial, which started 24 hrs after the coriander trial was changed into randomised blocks.

4.2.3 Soil Preparation within Conventional Practices and Crop cycle

At the beginning of the growing season, the field was subsoiled perpendicularly to the future seedbed orientation to avoid any interference between subsoiler tramlines and future ridges. The formation of the seedbed consists in a GPS-guided double pass. While a power harrow breaks the aggregates on the seedbed surface, the sides are excavated and stabilised by the action of two-faced mouldboards and discs. Most fields require two passes, the second one usually within 24-48 hr of seed drilling. Seeds are drilled into the ground with a spider-precision drill that works one seedbed at the time. For the July-August 2020 cultivation period, coriander seeding rate was 996 seeds m⁻². This commercial practice is to allow optimal airflow between the canopy and reduce the incidence of pests and diseases. Spinach (*Spinacea olearia*) was planted at standard target density of 725 seeds m⁻².

4.2.4 Irrigation Regime

Baby leaf and herb irrigation management at Watts Farm is phenology-driven. All agronomic operations, (e.g. irrigation timing, pest control, harvest) are triggered by the plants' growth stage and by soil moisture. Typically, there are three irrigations applied in the first half of the crop cycle. The first applied after seeding, is to physiologically activate the seeds. The second pre-emergence is to hydrate and soften the soil crust to facilitate uniform emergence. The third is applied at

the two true-leaf stage (Watts Farm; Personal Communication, 2019). The time periods between irrigations as shown in Figure 4.1 are a good representation of a typical water regime in Watts Farm. A Briggs Chassis VR5 hose-reel operated at 56 MPa (5.0 atm) pressure at the farm pump with a programmed moving forward speed of $60 \pm 15 \text{ m h}^{-1}$ was used to apply the scheduled irrigation events. The irrigation boom was fitted with Nelson 3TN/3NV #38 Nozzles. Uneven irrigation could be categorised in two groups. The primary cause was due to changes in the speed of the hose reel. Speed of hose reel being a function of water pressure at the central pump of the farm and of the slope on the field. Changes in speed of the hose reel resulted in differences in mm rate of delivery at different blocks, whilst keeping homogeneity within the plots of the same block, as in Spinach (Figure 4.2). The secondary effect of irrigation inhomogeneity occurred at nozzle level, when pressure and water delivery was different between nozzles, resulting in different quantities of delivery as can be seen in bands of colours within adjacent plots and buffer areas (e.g. buffer areas in Coriander, in Figure 4.2).

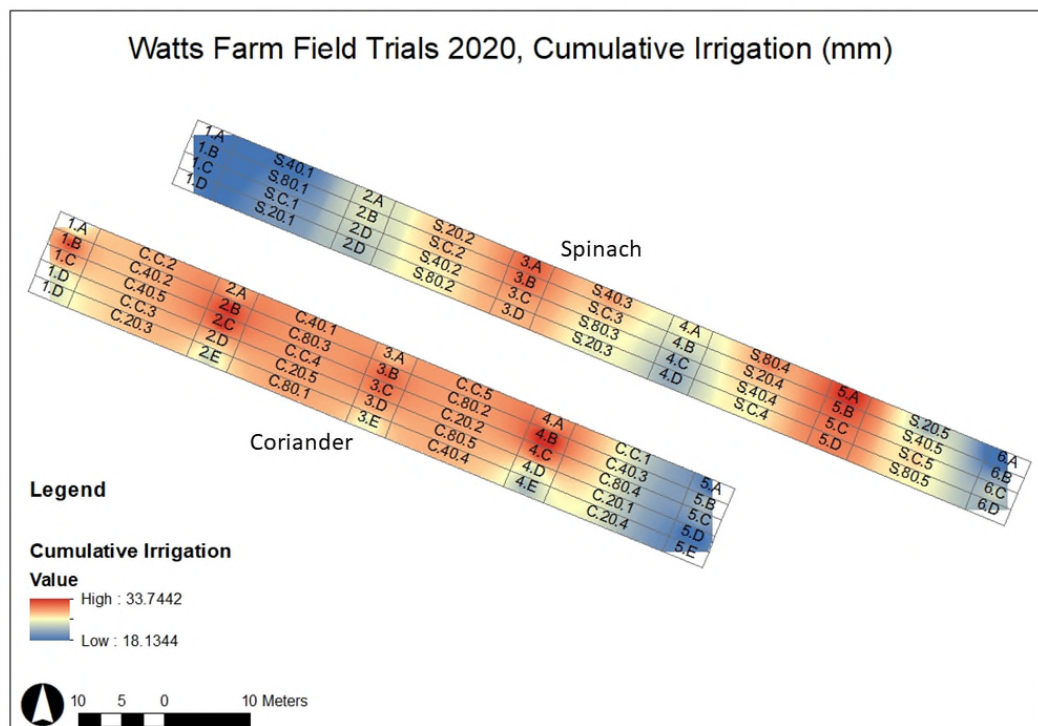


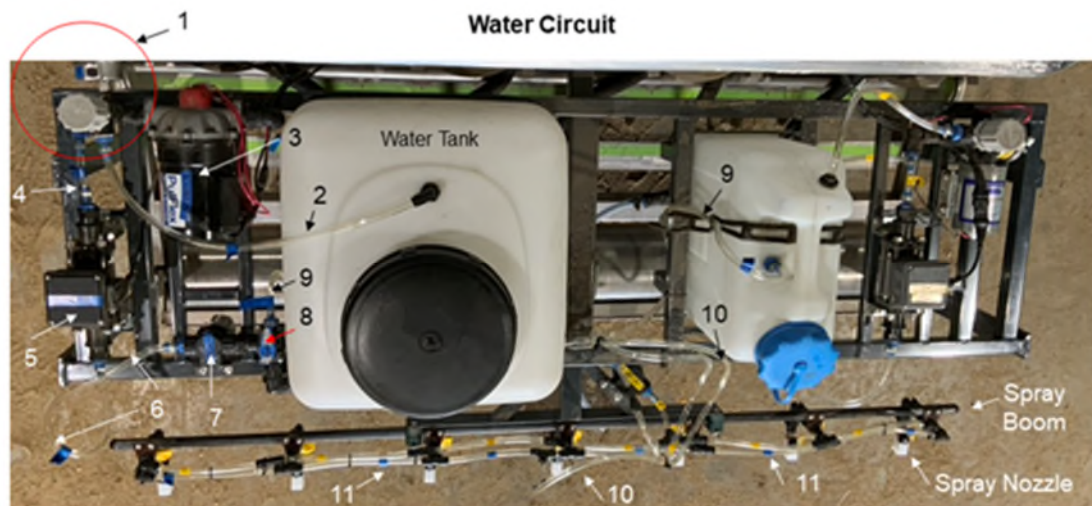
Figure 4.2 Heatmap of cumulative irrigation for the Spinach and Coriander field trials at Watts Farm during July-August 2020Smaller rectangles correspond to the 5.0 m buffer areas between 20 m experimental plots, where rain gauges were placed. In the plots, S=Spinach, C=Coriander. The second component of the label is the treatment. C=Control, 20, 40 and 80 correspond to PAM applications rates (kg ha⁻¹)

4.2.5 PAM application

The PAM investigated was SFA 30, a linear anionic concentrated suspension. SFA30 is copolymerised with sodium acrylate, has a charge density of 25 % and a molecular weight of 6×10^6 g mol⁻¹. The PAM polymer is suspended in an anionic suspension of ammonium nitrate in a liquid state.

The PAM was applied using a be-spoke innovative Dual-Fluid sprayer constructed by Pulvexper, Ramerupt, France, (<https://www.pulvexper.com/>) mounted on the back of the spider seed drill to keep to a minimum the number of passes. The sprayer consists of two parallel hydraulic circuits (Figure 4.3a and 4.3b) made of commercially available components. Water and PAM require separate pumps and are controlled by two flowmeters. More detailed information is in Appendix C

Water Circuit



- 1: Water PG & PRV Assembly
- 2: Water backflow tube to water tank
- 3: Water Pump
- 4: Tube from Water PG+PRV Assembly to Water Flow Meter
- 5: Water Flow Meter
- 6: Tubing from water flow meter to water filter
- 7: Water filter
- 8: Water flow direction valve, secured by elastic bands

- 9: Water flow tubing to washer head in PAM tank
- 10: Water tubing to main water feed tube (11) on spray boom
- 11: Main water feed tube (11) on spray boom
- 12: Water nozzle connector elbow assembly
- 13: Water tank drain circuit

PRV = Pressure Regulator Valve; PG = Pressure Gauge

Figure 4.3a Diagram of the Water Circuit of the PAM Sprayer used in Watts Farm for 2020 Field Trials.

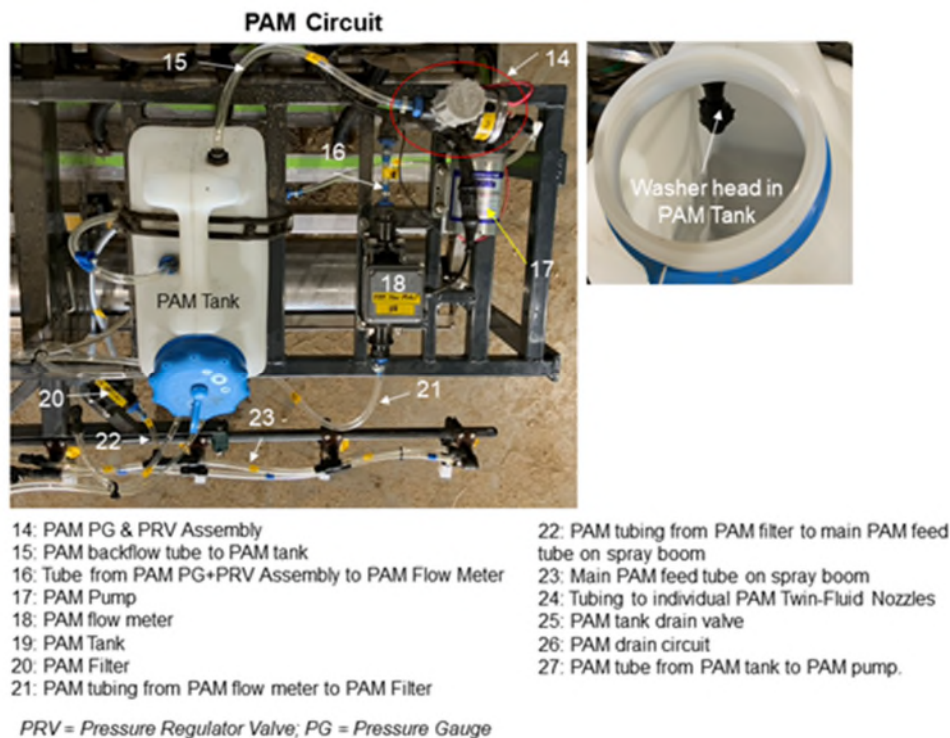


Figure 4.3b: Diagram of the PAM Circuit mounted on the sprayer used in Watts Farm for 2020 Field Trials

The two hydraulic systems (Figure 4.3) converge at the Dual-Fluid nozzle that facilitates the mixing of water and PAM outside the pipe system. The Dual-Fluid flat fan nozzle is a moulded piece of plastic that features two separate inlets and outlets, converging outside at a 45° angle. At the interface between the water and PAM, the PAM droplets are scattered by the water jet and then bounced off the exterior angled surface of the nozzle that then deflects them to the soil surface. Any non-homogeneity in the mixture of PAM and water is balanced by overlapping the nozzles' footprint. Mixing the PAM and water outside the tanks and pipework allows the sprayer to apply higher PAM concentrations compared to the traditional in-pipe mixing (ranging from a 0.1 to 1.0%) PAM to Water weight concentration kg kg^{-1} (Bjorneberg and Aase, 2000; Lentz, Sojka and Mackey, 2002; Yang, Tang and Feng, 2020).

4.2.6 Treatments

PAM was applied at 20, 40, and 80 kg ha⁻¹ using 600-1300 litres of water ha⁻¹. PAM and water flow rates were kept constant at 0.42 and 7.98 kg min⁻¹. The target application rates of 20, 40, and 80 kg ha⁻¹ were achieved by varying the speed of the sprayer to 6.0, 3.0 and 1.5 km hr⁻¹, respectively. The proportion between PAM and water is held constant while the amount of water applied increases with PAM application rate. The amount of water applied ranges from 0.03 and 0.2 l m⁻² at 20 and 80 kg m⁻² PAM application rates respectively. This volume of water was not considered enough to trigger any physiological response from the seed, and was therefore ignored when quantifying the volume of rainfall irrigational water.

4.2.7 Performance Metrics

4.2.7.1 Soil Moisture

For both the Coriander and Spinach trials, five randomly selected replicate soil moisture readings were measured in every plot using a ML3 Theta-probe 1 hr before, 24 hr and 48hr after each irrigation event. Time at measurement for each plot was recorded and coupled with prevailing weather conditions from the weather station. All soil moisture readings were undertaken between 8:10 to 10:30 am, as close to the centre of the seedbed as possible.

4.2.7.2 Splash Detachment

For each experimental replicated for both Trial 1 and Trial 2, five replicates of soil splash detachment were measured by placing a 0.10 x 0.1m nylon mesh held vertically above the soil surface by geotextile pins. Nylon mesh and splashed soil were immediately collected post each irrigation event and placed into pre-labelled tins (Figure 4.4). Subsequently, the nylon mesh and mass of splashed detached soil was oven dried at 105 °C for 24 hr. The mass of splash-detached soil was determined using a two-decimal places balance.

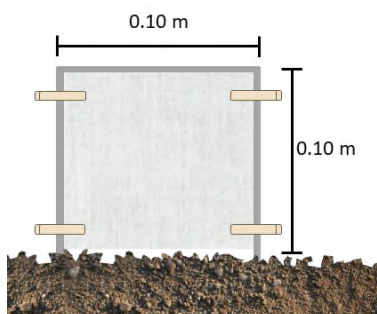


Figure 4.4 Diagram of experimental setup for capturing the mass of splash detached soil for each of the first three irrigation events adopted in the 2020 Field Trials.

4.2.7.3 Unsaturated hydraulic Conductivity

Unsaturated hydraulic Conductivity (HC) was measured using a Decagon mini-disc tension infiltrometer 24 hr after the first three irrigation events. The suction rate used was 2.0 cm, associated with medium textured soils. Between the crust and the perforated disc on the bottom of the infiltrometer, a fine layer of Garside Sand (Garside 80EW, Leighton Buzzard, UK) was placed to ensure optimum contact even in presence of irrigation drop craters. The mini-disc infiltrometer was carefully placed on the soil surface and if needed held in place by a geotextile pin. Elapsed time and the water level were recorded at predetermined time intervals up to 5 mins. If the drop on the infiltrometer was lower than the recommended 10 mm more time was allocated to the measurement until a 10 mm drop was reached. Data was then processed according to Zhang (1997). One day before the first irrigation event, four replicates of baseline HC were measured at random locations within the area of the trials and showed a mean infiltration rate of 45 mm h⁻¹.

4.2.7.4 Crop Emergence

From each experimental plot, daily high resolution images were captured using a digital SLR camera of 0.25m² areas delimited by a quadrat. In Trial 1, Coriander, one quadrat fitted three single-seeded rows, in Spinach, it was eight rows. The images were taken from five randomly selected fixed locations per plot, starting on the day of first plant detected and finished when the number of plants

stabilised. Between measurements, the quadrat position was marked by two flags on diagonally opposite corners, allowing repeated measures. These images were processed off-field using Fiji, the number of new plants per day was recorded manually.

4.2.7.5 Crop yield

Spinach Yield was modelled on the 0.25 m² quadrat used to capture emergence, linking virtually the emerged plants to the final fresh weight. The crop was manually harvested at 2 ±1 cm using a knife, as the motorised harvester did not provide sufficient accuracy and speed. Coriander grew much more than the markers used for the emergence area. Fresh weight was captured harvesting random 0.25 m² areas within each plot. In both cases fresh weight was measured using a two-digit scale under laboratory conditions, between 4 and 8 hours after harvest. The relatively small area and the harvesting method did not allow the fresh weight data to be safely converted to conventional yield (kg ha⁻¹) and hold a purely comparative value within the domain of this research. To minimise the multiplication of error, the fresh weight data was analysed and presented as g 0.25 m².

4.2.8 Statistical analysis

Normality of data was visually confirmed using plots of residuals versus fitted values. If the data were normally distributed, no transformation was required. Significant differences ($\alpha=0.05$) in the metrics investigated was determined by One Way ANOVA followed by *post-hoc* Fisher LSD analysis using Statistica version 13 (<http://statistica.io>).

4.3 Results and discussion:

4.3.1 Soil Splash Detachment

The first splash detachment collection event coincided with the 1st irrigation and occurred 2 days after seed drilling (DAD) in both crops. Trial 1, (Coriander), did not show significant differences in the mass of splash detached soil (g) between

treatments (Table 4.1), with a mean ($n=25$) values of 2.06, 2.16, 2.40 and 2.39 g for the Control, 20, 40 and 80 kg ha⁻¹ PAM treatments, respectively (Table 4.1). A similar pattern was recorded for the 2nd irrigation 6 DAD drilling with no significant difference observed between treatments although the mean mass of splashed soil decreased significantly (Table 4.1). Trial 1 plots were irrigated a third time 15 DAD. Again, no significant difference was observed between treatments (Table 4.1).

PAM application rate (kg ha ⁻¹)	Trial 1: Coriander			Trial 2: Spinach		
	Mass of splash detached Soil (g)					
	1 st	2 nd	3 rd	1 st	2 nd	3 rd
Control	2.06 ^a	1.01 ^a	1.89 ^a	1.24 ^{ab}	1.53 ^{ab}	1.73 ^b
20	2.16 ^a	0.83 ^a	2.00 ^a	1.68 ^b	1.62 ^{ab}	2.78 ^a
40	2.40 ^a	0.99 ^a	2.16 ^a	1.19 ^{ab}	2.11 ^b	2.98 ^a
80	2.39 ^a	0.83 ^a	1.95 ^a	0.95 ^a	1.20 ^a	2.23 ^{ab}

Table 4.1 Effect of PAM application rate (kg ha⁻¹) on mean (n=25) mass of splash detachment soil (g) for Trial 1 (Coriander) and Trial 2 (Spinach) for the 1st, 2nd and 3rd irrigation events.

Within each column, values followed by the same superscript letter are not significantly different ($\alpha=0.05\%$) following One-Way ANOVA and post-hoc Fisher LSD analysis. The 1st, 2nd and 3rd irrigation events occurred 2, 6 and 15 Days after Drilling (DAD), respectively.

In Trial 2, (Spinach) there is a general trend for the 80 kg ha⁻¹ PAM treatment to be associated with a lower cumulative mass of splash detached soil as compared with the Control, 20, and 40 kg ha⁻¹ treatments with values of 4.37, 4.50, 6.08 and 6.28 g, respectively. For the 1st irrigation event, the mass of soil captured by the voile was lower than for the 1st irrigation on Trial 1. However, the 2nd and 3rd irrigation events are associated with higher values of splash detached soil compared to Trial 1 (Table 4.1).

For the 1st irrigation event, (2 DAD) no significant difference in mass of splash detached soil was found between the Control and PAM treatments (Table 4.1). The lowest mass of splash detachment soil was associated with the 80 kg ha⁻¹ treatment. However, within treatment variability meant that this was not significantly different from the Control although it was significantly different from the 20 kg ha⁻¹ PAM treatment (Table 4.1). The average mass of splash detached soil across all treatments (n=100) soil detached was 1.26 (± 0.031) g.

For the 2nd irrigation event (6 DAD) no significant difference in mass of splash detached soil was observed between PAM treatments and the Control (Table 4.1). However, again there was a trend for the 80 kg ha⁻¹ PAM treatment to be

associated with lower splash detachment as compared with the Control and 20 and 40 kg ha⁻¹ PAM treatments. The 80 kg ha⁻¹ PAM treatment was associated with significantly lower (44% reduction) splash detachment as compared with the 40 kg ha⁻¹ PAM treatment (Table 4.1). The average mass of splash detached soil across all treatments (n=100) soil detached was 1.26 (±0.031) g.

In contrast for the 3rd irrigation, the Control is associated with significantly lower soil splash detachment as compared with 20 and 40 kg ha⁻¹ PAM treatments with values of 1.73, 2.78 and 2.98 g, respectively. The reduction in splashed soil compared to the previous two events, might be explained with a lack of free aggregates to be splashed: by the third irrigation, the soil surface is solidified and compacted into a cemented layer, and thus requires more kinetic energy to be detached from the raindrops. Conversely, the PAM treatments show a different pattern with the mass of splash detached soil captured on the voile significantly higher than the Control in the 3rd irrigation. This may in part be due to the fact that due to PAM addition, soil splash is associated with stabilised 'flocs' rather than primary particles. The PAM stabilised flocs may also adhere to the voile more effectively than the primary particles which are primarily quartz.

The efficacy of PAMs in stabilising and hence protecting soil aggregates from irrigation-induced erosion in field trial has been documented (Lehrsch, Lentz and Kincaid, 2005; McNeal *et al.*, 2017). The contrasting splash detachment response associated with Trial 2 might be the effect of different aggregate size distribution between the Trials due to field heterogeneity and/or due to PAM-soil interactions at a molecular level. Soil aggregates between 0.5 and 1 mm are the ones that benefit the most from PAM application, whereas aggregates < 0.5 mm do not provide pores large enough for PAM to permeate and stabilise them (Mamedov *et al.*, 2017). In addition, the efficacy of the anionic PAM investigated in this research might have been impacted by the lack of reactive colloidal clay surfaces (Mamedov *et al.*, 2010) in the soil which consists of 67%, 7.0% and of 6.4% low reactivity quartz, K-feldspar and plagioclase-feldspar minerals (Appendix E). Furthermore, the studies that validated PAM efficacy to mitigate soil splash were both obtained with alkaline soils (Chang *et al.*, 2019; Soltani-Gerdefaramarzi,

Ghezelseflue and Boroughani, 2019), which had pH of 8.3 and 8.6 respectively. The soil at the trials site in contrast had a pH of 5.7.

4.3.2 Unsaturated Hydraulic Conductivity (HC)

All the HC, displayed on Table 4.2, are less than the baseline HC value measured on the field of 45 mm h⁻¹. Generally speaking, in both trials PAM application is associated with lower HC after the 1st and 2nd irrigation events. The general decrease of HC overtime indicated the formation of a seal on the soil surface.

PAM application rate (kg ha ⁻¹)	Trial 1: Coriander			Trial 2: Spinach		
	Unsaturated hydraulic conductivity (mm hr ⁻¹)					
	1 st	2 nd	3 rd	1 st	2 nd	3 rd
Control	31.0 ^c	9.6 ^a	10.8 ^a	22.8 ^a	17.7 ^a	19.3 ^a
20	19.9 ^{ab}	5.7 ^a	11.7 ^a	23.4 ^a	15.8 ^b	19.7 ^a
40	22.7 ^b	8.8 ^a	12.5 ^a	22.5 ^a	15.2 ^{ab}	15.4 ^a
80	13.2a ^b	7.5 ^a	10.3 ^a	16.4 ^b	11.2 ^b	16.9 ^a

Table 4.2 Effect of PAM application rate (kg ha⁻¹) on mean (n=20) Unsaturated Hydraulic Conductivity (HC) for Trial 1 (Coriander) and Trial 2 (Spinach) for the 1st, 2nd and 3rd irrigation events.

Within each column, values followed by the same superscript letter are not significantly different ($\alpha=0.05\%$) following One-Way ANOVA and post-hoc Fisher LSD analysis. The 1st, 2nd and 3rd irrigation events occurred 2, 6 and 15 Days after Drilling (DAD), respectively.

In Trial 1, (Coriander), for the 1st irrigation event the PAM treatments were associated with significantly lower HC as compared with the Control (Table 4.2). No significant difference was observed between the PAM treatments with HC values for the 20, 40 and 80 kg ha⁻¹ PAM treatments of 19.9, 22.7 and 13.2 mm h⁻¹ respectively versus 30.97 mm h⁻¹ for the Control. This equates to between a

26.8 - 57.4 % reduction in HC for the PAM treatments as compared with the untreated Control, respectively (Table 4.2). In Trial 1 for both the 2nd and 3rd irrigation events no significant difference in HC was observed between the Control and PAM treatments (Table 4.2).

Trial 2, Spinach, showed a different trend. For the 1st irrigation event no significant difference in HC was observed between the Control and 20 and 40 kg ha⁻¹ PAM treatments with values of 22.8, 23.4 and 22.5, respectively (Table 4.2). In contrast, the 80 kg ha⁻¹ PAM treatment was associated with a significantly lower HC than all other treatments of 16.4 mm hr⁻¹. A similar trend was observed for the 2nd irrigation event with the 80 kg ha⁻¹ PAM treatment associated with significantly lower HC as compared with the Control and 20 kg ha⁻¹ PAM treatment (Table 4.2). For the 3rd irrigation vent in Trail 2, no significant difference in HC was observed between treatments.

The positive effect of PAM's on soil HC has been recorded from the early explorative studies (Weeks, E and Colter, William, 1952; Mitchell, 1986; Terry and Nelson, 1986). The findings of this study, contradict this with higher PAM applications rates being associated with a decrease in HC.

In furrow irrigation, PAMs were able to penetrate the aggregates in the soil surface and reduce their swelling, disaggregation. This reduced the mass of sediment transported offsite as flocculated sediment was deposited. The relationship between HC and PAM dosage is not linear and depends on the PAM formulation, soil texture and mineralogy and water electrolyte concentration (R. D. Lentz and Sojka, 1994b). The cases where PAM was most effective were characterised by a neutral to alkaline soil pH, prevalence of illites or smectites in the clay fraction (Mamedov *et al.*, 2010), prevalence of aggregates >0.5 mm in diameter (Lentz, 2015a), and use in combination with divalent cations, either supplied via gypsum or via tap water (Smith, Levy and Shainberg, 1990).

There are also several cases where PAM application does not have a significant effect on HC. As a flocculant polymer, PAM was found to reduce erosion but not runoff volume, with application rates (granules) as little as 2 to 3 kg ha⁻¹ in furrows

(Bjorneberg *et al.*, 2003a), and even slow down HC when mixed within the soil profile as granules at 40 to 80 kg ha⁻¹ (Ao *et al.*, 2016; Li, Xu and Ao, 2019a), when the PAM polymer architecture prevents penetration into soil aggregates (Ben-Hur and R Keren, 1997) or if the soil structure is already degraded (Mamedov *et al.*, 2017). A possible explanation for the lack of significant differences between treatments might either be the lack of soil aggregation (due to the high tillage intensity, low SOM % and high prevalence of non-reactive quartz) at the time of PAM application, and the pore-blocking effect that the hydrated PAM might have had in reducing the soil porosity at the immediate soil surface. The HC after the 2nd and 3rd irrigation events indicates that the effect of the PAM formulation adopted in this study on HC does not last more than two irrigations.

4.3.3 Volumetric Soil Moisture

Figure 4.5a shows a partial time series (29th July – 27th August 2020) representing the effect of PAM application rate on volumetric soil moisture (%) with the coriander seedbed (Trial 1). The results indicate that PAM application irrespective of application rate results in a higher volumetric soil moisture content than control after the 1st and 2nd irrigation events. The results also indicate that despite the significantly lower HC associated with the PAM treatments observed after the 1st irrigation event (Figure 4.5a) The PAM treated plots hold significantly higher soil moisture than the Control, with the difference in volumetric moisture content being significant also 48 and 36 hr after the 1st irrigation (Figure 4.5a).

The baseline (29th of July 2020) volumetric soil moisture values post PAM application and prior to the 1st irrigation from the ranged from 8.08 to 8.78 % (Figure 4.5a). The relatively low volumetric soil moisture content is explained by the land plot being characterised by a light soil worked twice by the seedbed former and once by the seed drill, all in late July, during a heatwave (Figure 4.1). After the 1st irrigation volumetric soil moisture content increases to up to 12-14 % and subsequently decreases to baseline values (*circa* 8%) 4 DAD. Similarly, the

2nd and irrigation events increase volumetric soil moisture content up to 23.51% and 18% respectively.

Volumetric soil moisture (%) 24 hrs (03/08/2020) after the 2nd irrigation (2/8/2020) showed a diverse response between treatments. The Control and 40 kg ha⁻¹ PAM treatments were associated with statistically similar mean (n=5) volumetric soil moisture with values of 13.3 and 13.1 % respectively. In contrast the 20 and 80 kg ha⁻¹ PAM treatments were associated with significantly higher volumetric soil moisture with values of 17.4 and 15.8 %. The 20 kg ha⁻¹ PAM treatment is associated with significantly higher volumetric moisture content than all other treatments 24 hrs after the 2nd irrigation with this trend continuing to the 3rd irrigation. Crucially, the 20 and 80 kg ha⁻¹ treatments are also associated with a slower rate of soil moisture loss from within the bed after the 2nd irrigation event than the Control which lasts until the 3rd irrigation (Figure 4.5a). On 10/08/2020 24 hr prior to the 3rd irrigation event (applied on the 11/08/2020), the 20 kg ha⁻¹ PAM treatment is associated with significantly higher volumetric soil moisture as compared with all other treatments (Figure 4.5a).

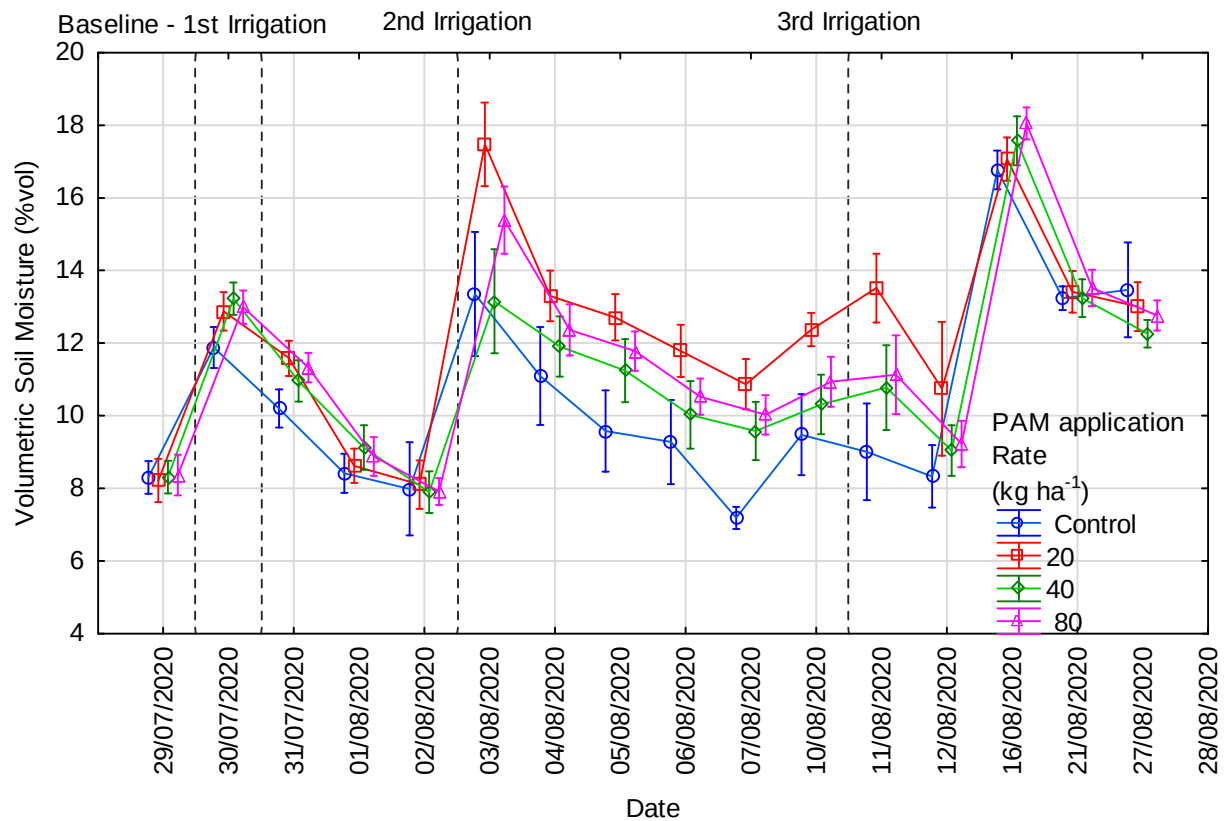


Figure 4.5a Effect of PAM application rate (kg ha^{-1}) on Volumetric Soil Moisture (%) on Trial 1, Coriander. Vertical bars denote 0.95 Confidence intervals. The vertical reference lines indicate when the baseline (0 DAD) Volumetric Soil Moisture was recorded and when Irrigations were applied

A spike in volumetric soil moisture content following the 3rd irrigation was not observed. This may be due to wind drift during irrigation resulted in a high percentage of water mm being delivered outside the trial. Daily volumetric soil moisture measurements were only taken two days after 3rd irrigation, but confirm the same trend observed after the previous irrigations, with the 20 kg ha^{-1} PAM treatment being associated with the highest volumetric soil moisture content of 13.5% followed by the 80 and 40 kg ha^{-1} PAM and Control treatments with values of 11.3, 10.8 and 9.4 %, respectively. Post the 3rd irrigation volumetric soil moisture readings do not represent continual daily monitoring. However, it is

possible to observe an increase due to rainfall events that occurred during this time (Figure 4.5a).

The results indicate that optimum PAM performance was associated with the 20 kg ha⁻¹ PAM treatment. However, this may in large part be due to two spatial variability factors as well as treatment performance. The first spatial variability factor is the heterogeneity in irrigation, that lead to one side of the trial receiving more water than the other, and therefore increasing volumetric soil moisture content (Figure 4.2). The second variability factor is the position of the experimental treatment replicates on the slope, and associated water logging of the plots. The precautions to avoid the edge effect on the field trials were not enough, and as a consequence excess irrigation and rainfall ran downslope. Furthermore, the unavoidable movement of people in the wheelings when the soil was wet (e.g during measurement of metrics), compacted them, enhancing runoff. The 20 kg ha⁻¹ PAM treatments did not outperform the other applications rates in terms of soil splash detachment or HC, and therefore is likely that statistically better performance in terms of volumetric soil moisture is in part a consequence of spatial variability within the trials.

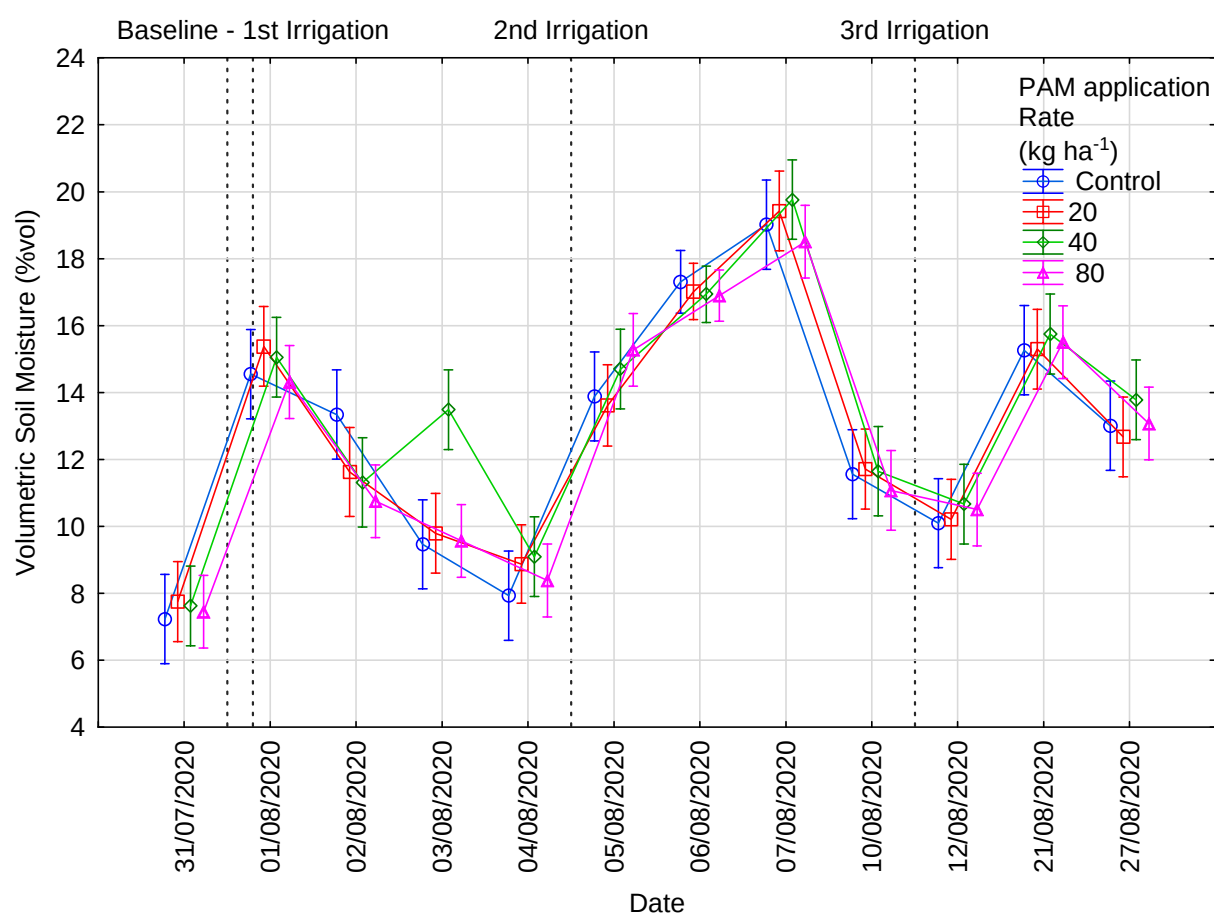


Figure 4.5b Effect of PAM application rate (kg ha⁻¹) on Volumetric Soil Moisture (%) on Trial 2, Spinach. Vertical bars denote 0.95 Confidence intervals. The vertical reference lines indicate when the baseline (0 DAD) Volumetric Soil Moisture was recorded and when the 1st, 2nd and 3rd irrigation events were applied. Vertical bars denote 0.95 confidence intervals.

For Trial 2 (Spinach) with the exception of the 40 kg ha⁻¹ PAM treatment on 03/08/20, no significant difference in volumetric soil moisture was observed between any of the PAM treatments or the Control (Figure 4.5b). The randomised block design mitigates the effect of slope and irrigation heterogeneity and confirms that the differences in volumetric soil moisture observed in Trial 1 were not a function of PAM application rate. The only exception is on 3/08/2020, where the 40 kg ha⁻¹ PAM treatment was associated with significantly higher volumetric soil moisture. This was due to the high values associated with a specific replicate (40.2) which had a mean volumetric soil moisture of 27.8 %, which was much

higher than the mean value for all other treatment replicates of 9.7 % which was, in line with the other treatments. A check on the raw data confirms that the high values are not due to irrigation heterogeneity but due to an instrument error.

4.3.4 Crop Emergence

Trial 1, Coriander emergence started 10 DAD and ended on 25 DAD (Figure 4.6a). Some of the upslope plots received less water during the 1st irrigation, and therefore emergence was delayed. The results indicate that there is no significant difference in emerge between treatments for any of the days sampled. All treatment eventually reached 100% (± 2) emergence, with the exception of the 80 kg ha⁻¹ PAM treatment which was associated with a final emergence of 92% compared to the target plant density.

In the Control treatment, 50% of emergence was achieved at 14 DAD. In comparison, the 40 and 80 kg ha⁻¹ PAM treatments were associated with a slightly faster 50% emergence, at 13.1 and 13.3 DAD, respectively whereas the 20 kg ha⁻¹ PAM treatments achieved 50% emergence at 14.8 DAD. This may have been due to excess water caused by higher volumetric water content (Figure 4.2). In terms of 75% emergence this was achieved at 18.0, 15.6, 15.8 and 16.9 DAD for Control, 20, 40 and 80 kg ha⁻¹ PAM treatments, respectively (Table 4.3).

The lack of significant difference in final plant count between PAM ARs can be explained by the magnitude of other factors, such as the position of the experimental plots in relation to slope (Figure 4.6b). Position 1 is at the base of the slope and receives all the water runoff from the plots upslope. Typically, this runoff water ponded for a few hours before infiltrating. Position 4 at the top of the slope upslope and did not receive much runoff from upslope. In addition, Position 4 received less water during the 1st irrigation (a mean value of 6.1 mm compared to the target irrigation depth of 12.0 mm). At 10 DAD the emergence on slope Position 4 is significantly higher than the downslope plots, suggesting that the higher temperatures and the longer solar exposure upslope might have accelerated germination and emergence (Table 4.3). At 13 DAD the trend is reversed.

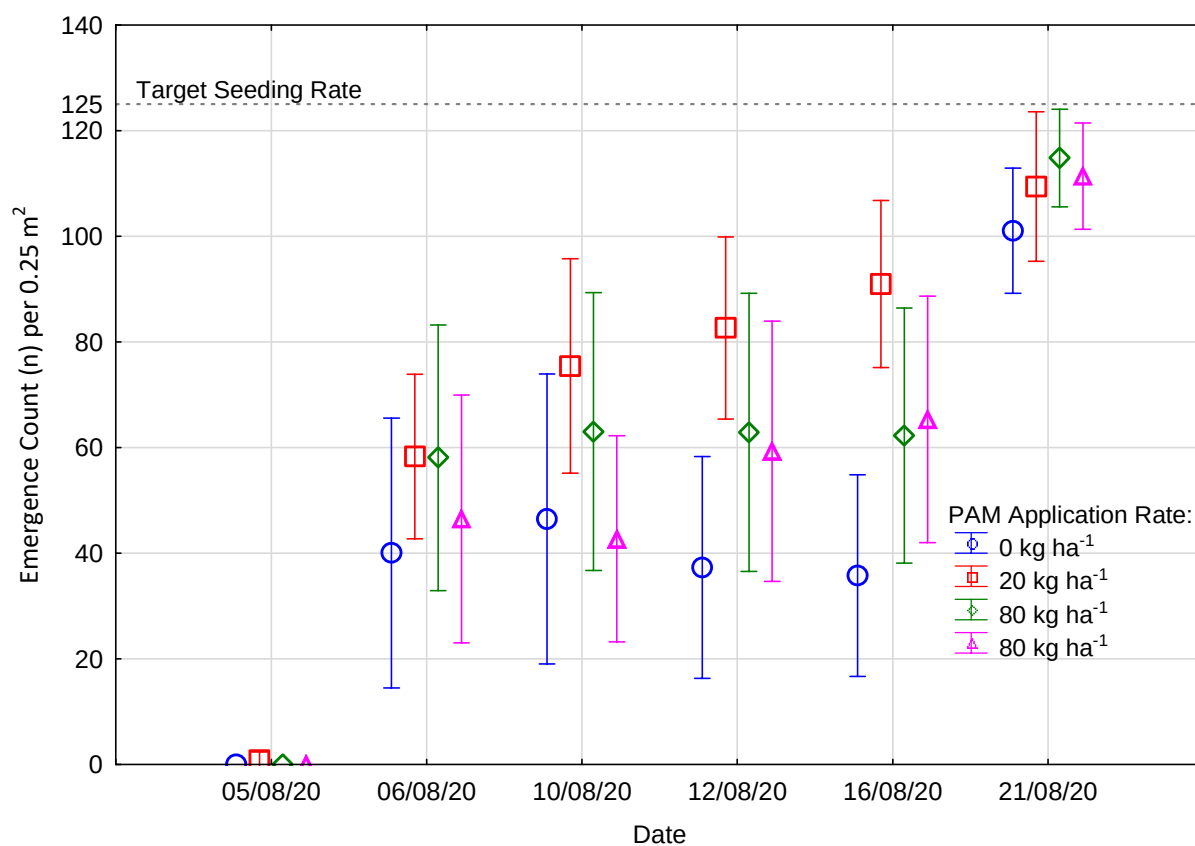


Figure 4.6a Effect of PAM application (kg ha⁻¹) on coriander emergence (count per 0.25 m²). Vertical bars denote 0.95 confidence intervals

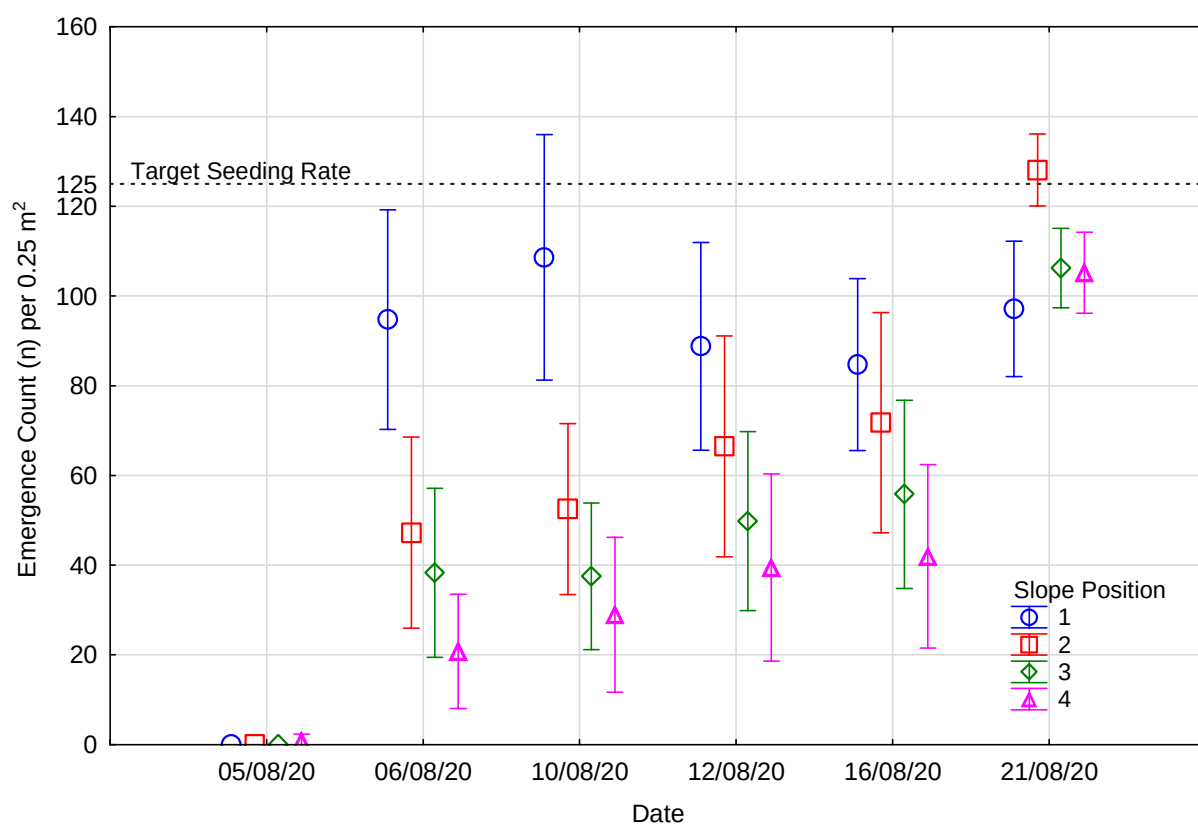


Figure 4.7b Effect of Slope Position on coriander emergence (count per 0.25 m⁻²). Vertical bars denote 0.95 confidence intervals. The graph shows all the population, not the Control Subset.

Slope Position	Coriander emergence (count per 0.25 m ²) at Day After Drilling (DAD)					
	10	13	14	16	20	25
1 (downslope)	0 ^a	93 ^c	108 ^b	89 ^b	84 ^a	98 ^a
2	0 ^a	50 ^b	55 ^a	66 ^{ab}	75 ^a	129 ^b
3	0 ^a	38 ^{ab}	39 ^a	51 ^a	57 ^{ab}	107 ^a
4 (upslope)	1 ^b	21 ^a	29 ^a	40 ^a	42 ^b	105 ^a

Table 4.3 Effect of Slope Position on coriander emergence (count per 0.25 m²).

Within each column, values followed by the same superscript letter are not significantly different ($\alpha=0.05\%$) following One-Way ANOVA and post-hoc Fisher LSD analysis. Target seeding rate for 0.25 m² is 125 plants

Spinach emergence started on 7 DAD and ended 12 DAD. No significant difference in emergence was observed between treatments for any day sampled (Figure 4.8a). For spinach, 50% emergence was achieved essentially simultaneously for all treatments at 10.2 DAD. Maximum emergence was reached at 12 DAD for all treatments. However, the final stand establishment was *circa* 75% of the seeding rate. This was due to “Damping Off” disease (Watts Farms; Personal Communication 2020), caused by one or more pathogenic soil fungi namely *Fusarium oxysporum*, *Pythium spp.* and *Rhizoctonia spp.* (Van West, Appiah and Gow, 2003)

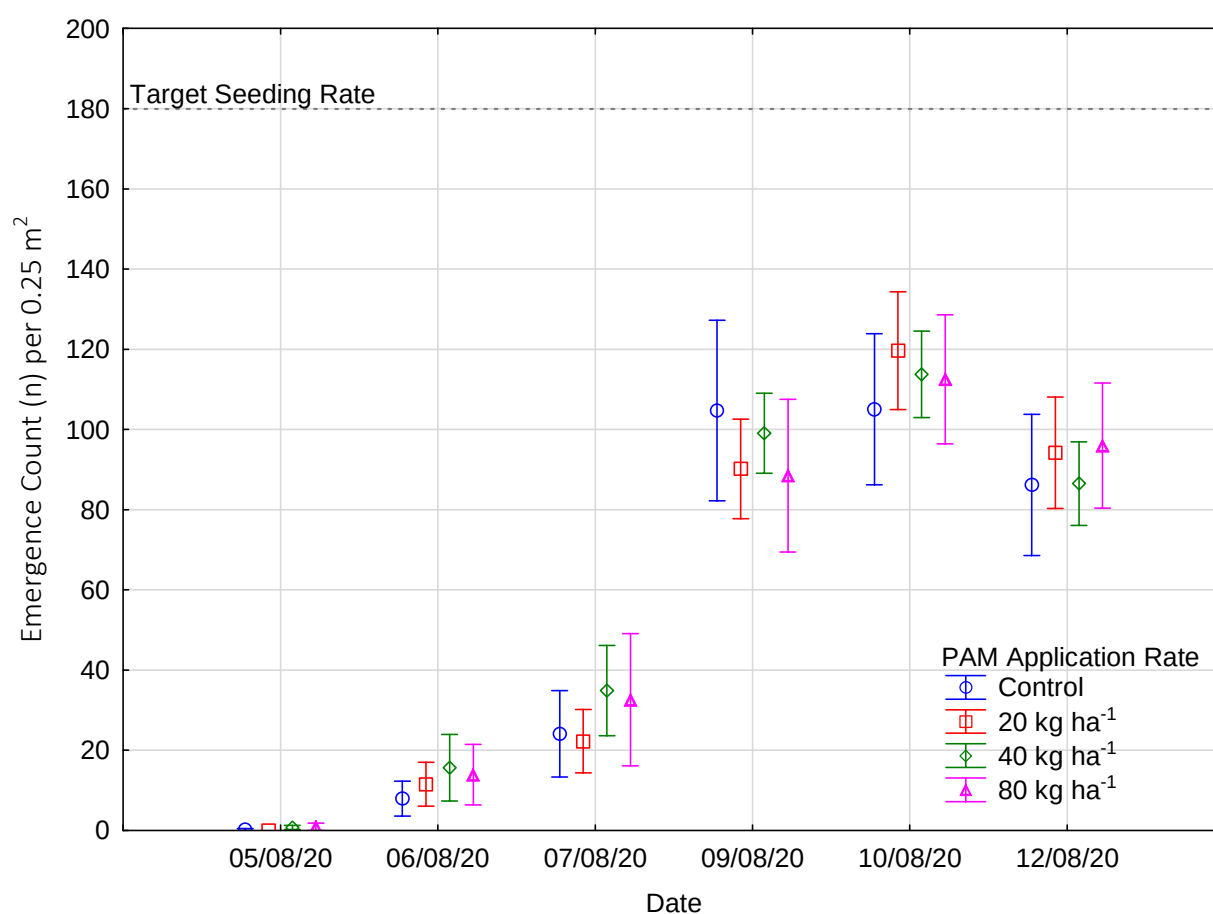


Figure 4.8a Effect of PAM application (kg ha⁻¹) on spinach emergence (count per 0.25 m²). Vertical bars denote 0.95 confidence intervals

Similarly to Trial 1 on coriander, Trial 2 on spinach was also affected by soil moisture dynamics related to the location of the experimental plots in relation to their position on the slope. All plots on Slope Position 1 (downslope) were characterised by early emergence, significantly higher at 7 DAD (1.3 plants 0.25 m⁻²). The biggest difference between treatments is 9 DAD, where slope Position 1 emergence counts were on average 54.5 plants per 0.25 m⁻², whereas average emergence counts for slope Positions 2, 3, 4 and 5 were 18.2, 31.1, 25.7 and 12.8 plants 0.25 m⁻² (Figure 4.9b). The positive relationship between soil moisture content and emergence count is visible at 12 DAD, where slope Position 1 emergence counts were significantly higher than Position 5 with values of 147 and 95 plants 0.25 m⁻².

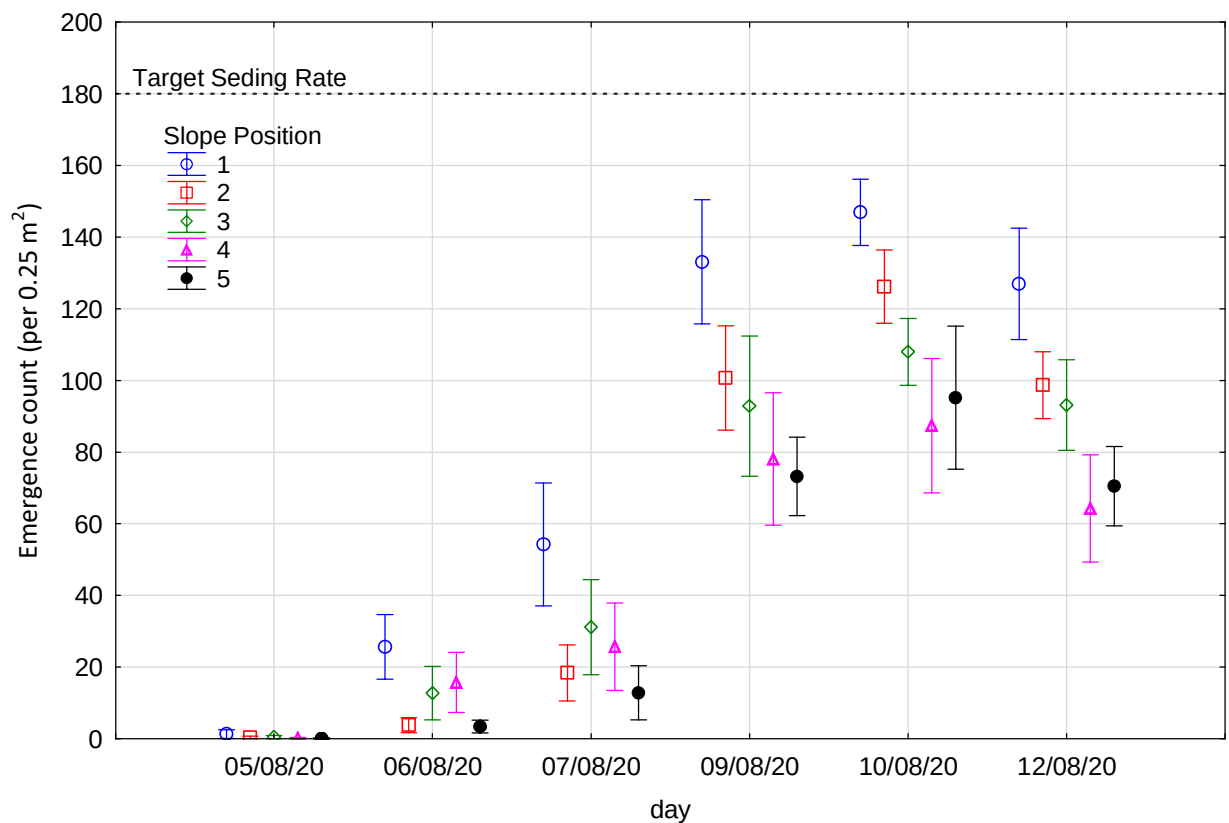


Figure 4.8b Effect of PAM application (kg ha^{-1}) on spinach emergence (count per 0.25 m^2). Vertical bars denote 0.95 confidence intervals

The current study confirms the observations made by Steinberger (1991), where 0.2% by weight of granular PAM was incorporated in the upper 10 cm of soil, and where the effect of PAM was outweighed by different environmental conditions (temperature and soil moisture). PAM effects on emergence and maize growth were out weighted by environmental conditions (Steinberger and West, 1991). A study on cotton emergence found that a 50 mg l^{-1} PAM solution hand poured on the soil was associated with significant emergence improvement under controlled laboratory conditions (Helalia and Letey, 1989). A fully replicate field trial in a semiarid rangeland in New Mexico evaluated hand-poured PAM at 10, 20 and 40 kg ha^{-1} application rates to enhance an array of local perennial grasses, with the most responsive species being Blue Panic (10 to 35% emergence on Control and 20 kg ha^{-1} respectively). In beetroot emergence, a 5% w/w solution of PAM (of a lower molecular weight than SFA30) was delivered using a flat fan nozzle at 700

to 1100 kg ha⁻¹. The emergence was 2.5 fold higher than the untreated control, but its application resulted in *circa* 70 m³ of water per ha (Lersch, 2005). In contrast, in the current study, only 600-1300 litres of water are required per ha. Delivering PAMs diluted in water at low concentrations, like Steinberger (1993), Lersch (2005) and Rubio (1989, 1992) with higher amounts of water may allow PAMs to infiltrate better into and stabilise soil aggregates than in the present study. However, the machinery and irrigation infrastructure constraints characterising the leafy green industry do not allow the application of a 50 mg l⁻¹ solution to achieve a target of 40 kg ha⁻¹ PAM active ingredient, because the volumes of water required would be excessive (ref. Chapter 6).

4.3.5 Yield at Harvest

In Trial 1, Coriander, the treatment associated with the highest fresh weight (FW) is 20 kg ha⁻¹ followed by the 40, Control and 80 kg ha⁻¹ treatments with mean (n=25) values of 1224, 1128, 820 and 656 g m⁻², respectively. The higher FW associated with the 20 kg ha⁻¹ treatment might be a consequence of the higher volumetric soil moisture content (Figure 4.5) associated with C20 treatments (Figure 4.2). The hot dry weather conditions (Figure 4.1) during the trial might have mitigated the waterlogging that was causing delay in emergence and might have resulted in a more favourable soil moisture, leading to higher FW. The two downslope slope positions (1 and 2) are associated with a lower FW compared to slope Position 3, which was associated with significantly higher FW yield regardless of PAM application (Table 4.4). In Trial 2, Spinach no significant difference in harvested yield (FW) was observed between treatments, with FW harvest values of 6424, 5932, 5932 and g⁻² for the Control and 20, 40 and 80 kg ha⁻¹ PAM treatments, respectively (Table 4.4). Spinach FW yield also shows the effect of slope position as the two downslope positions (Position 1 and 2) are associated with higher FW yield at harvest compared to the three upslope positions (Positions 3, 4 and 5), reflecting the emergence results (Table 4.4 and Figure 4.6b).

Trial 1: Coriander				Trial 2: Spinach			
Slope position	FW of sample (g)	PAM (kg ha ⁻¹)	FW of sample (g)	Slope Position	FW of sample (g)	PAM (kg ha ⁻¹)	FW of sample (g)
1	186 ^a	Control	205 ^{ab}	1	2296 ^b	0	1608 ^a
2	213 ^a	20	306 ^c	2	2767 ^b	20	1483 ^a
3	326 ^b	40	282 ^{bc}	3	1164 ^a	40	1655 ^a
4	236 ^{ab}	80	164 ^a	4	568 ^a	80	1504 ^a
				5	1115 ^a		

Table 4.4 Effect of PAM application rate (kg ha⁻¹) and slope position on Coriander and Spinach Fresh Weight (FW) yields at harvest.

Within each column, values followed by the same superscript letter are not significantly different ($\alpha=0.05\%$) following One-Way ANOVA and post-hoc Fisher LSD analysis. The 1st, 2nd and 3rd irrigation events occurred 2, 6 and 15 Days after Drilling (DAD), respectively.

4.4 Conclusions

The results of Trial 1 and Trial 2 indicate that PAM can be successfully applied using Dual-Fluid flat fan nozzles. The highest PAM application rate treatment of 80 kg ha⁻¹ was delivered using only 1.3 m³ of water ha⁻¹. Cleaning operations were completed on field, and the SFA 30 formula was relatively easy to clean, resulting in circa 1 hr of post-spraying cleaning and sprayer maintenance.

Spatial variability created by slope position and heterogeneous irrigation outweighed the effect of PAM on the performance metrics investigated. Firstly, failure in the prevention of irrigation-drive heterogeneity, lead to the setup of a completely randomised experiment Trial 1, that was partially corrected by changing Trial 2 into a randomised blocks design. Secondly, the underestimation of the edge effect on downslope plots affected the final result as well, especially combined with the reduced infiltration in the wheelings causing the downslope portion of the field to hold much more moisture than the section above. The land plot used for the trials was selected among a shortlist of diverse soils (ref. Chapter

2) as the most crust susceptible, and its properties might have exacerbated what would have been otherwise an acceptable slope, or a non-perfect irrigation pattern. Its mineralogy, dominated by Quartz and feldspar (67.4% quartz, 6.9% feldspar, 13.9% Illites+smectites) (Appendix E) might not have offered to PAMs the electrically charged areas where to anchor itself. Moreover, the aggregate size distribution might be less than the 0.5 mm diameter that was found to work better with PAMs. Future research exploring PAM performance should pay more attention to topology and irrigation. Co-application of PAM and water with divalent could assist in anionic SFA30 PAM sorption to the anionic charges of soil colloids.

4.5 References

Ao, C. *et al.* (2016) 'Efficacy of granular polyacrylamide on runoff, erosion and nitrogen loss at loess slope under rainfall simulation', *Environmental Earth Sciences*, 75(6). doi: 10.1007/s12665-015-5110-3.

Assouline, S. (2004) 'Rainfall-Induced Soil Surface Sealing: A Critical Review of Observations, Conceptual Models, and Solutions', *Vadose Zone Journal*, pp. 1–60.

Ben-Hur, M. and Keren, R. (1997) 'Polymer Effects on Water Infiltration and Soil Aggregation', *Soil Science Society of America Journal*, 61(2), p. 565. doi: 10.2136/sssaj1997.03615995006100020028x.

Le Bissonnais, Y. (1996) 'Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology', *European Journal of Soil Science*, 47(April), pp. 425–437. doi: 10.1111/j.1365-2389.1996.tb01843.x.

Bjorneberg, D. L. *et al.* (2003) 'Using polyacrylamide with sprinkler irrigation to improve infiltration', *Journal of Soil and Water Conservation*, 58(5), pp. 283–289.

Bjorneberg, D. L. and Aase, J. K. (2000) 'Multiple polyacrylamide applications for controlling sprinkler irrigation runoff and erosion', *Applied Engineering in Agriculture*, 16(5), pp. 501–504.

Bronick, C. J. and Lal, R. (2005) 'Soil structure and management: A review', *Geoderma*, 124(1–2), pp. 3–22. doi: 10.1016/j.geoderma.2004.03.005.

Chang, A. *et al.* (2019) 'Impact of raindrop diameter and polyacrylamide application on runoff, soil and nitrogen loss via raindrop splashing', *Geoderma*. Elsevier, 353(June), pp. 372–381. doi: 10.1016/j.geoderma.2019.07.026.

DEFRA (2020) *Agriculture in the United Kingdom 2019, Agriculture in the United Kingdom 1995*.

FAO (1993) 'Soil tillage in Africa: needs and challenges', in *Soil tillage in Africa: needs and challenges*. 1st edn. Rome, p. Soil Crusting and Sealing. Available at: <http://www.fao.org/3/t1696e/t1696e06.htm#TopOfPage>.

Helalia, A. M. and Letey, J (1989) 'Effects of Different Polymers on Seedling Emergence, Aggregate Stability and Crust Hardness', *soil Science*, 148(3), pp. 199–203.

Helalia, A. M. and Letey, J. (1989) 'Effects of different polymers on seedling emergency, aggregate stability, and crust hardness', *Soil Science*, 148(3), pp. 199–203. doi: 10.1097/00010694-198909000-00007.

Klute, A. (1986) *Methods of soil analysis*. 2nd edn. Madison: Soil Science Society of America.

LandIS (2022) *The Soils Guide*. Available at: <https://www.landis.org.uk/soilsguide/mapunit.cfm?mu=57110> (Accessed: 18 May 2022).

Lehrsch, G. A., Lentz, R. D. and Kincaid, D. C. (2005) 'Polymer and sprinkler droplet energy effects on sugar beet emergence, soil penetration resistance, and aggregate stability', *Plant and Soil*, 273(1–2), pp. 1–13. doi: 10.1007/s11104-004-7614-6.

Lentz, R. D. (2015) 'Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam', *Geoderma*. Elsevier B.V., 241–242, pp. 289–294. doi: 10.1016/j.geoderma.2014.11.019.

Lentz, R. D. and Sojka, R. E. (1994) 'Field results using polyacrylamide to manage furrow erosion and infiltration', *Soil Science*, 158(4), pp. 274–282. doi: 10.1097/00010694-199410000-00007.

Lentz, R. D., Sojka, R. E. and Mackey, B. E. (2002) 'Fate and Efficacy of Polyacrylamide Applied in Furrow Irrigation', *Journal of Environmental Quality*, 31(2), pp. 661–670. doi: 10.2134/jeq2002.6610.

Li, S., Xu, H. and Ao, C. (2019) 'Polyacrylamide and Rill Flow Rate Effects on Erosion and Ammonium Nitrogen Losses', *Water, Air, and Soil Pollution. Water, Air, & Soil Pollution*, 230(1). doi: 10.1007/s11270-018-4052-2.

Mamedov, A. I. *et al.* (2010) 'Polyacrylamide Effects on Aggregate and Structure Stability of Soils with Different Clay Mineralogy', *Soil Science Society of America Journal*, 74(5), p. 1720. doi: 10.2136/sssaj2009.0279.

Mamedov, A. I. *et al.* (2017) 'Aggregate Stability and Water Retention Near Saturation Characteristics as Affected by Soil Texture, Aggregate Size and Polyacrylamide Application', *Land Degradation and Development*, 28(2), pp. 543–552. doi: 10.1002/ldr.2509.

McNeal, J. P. *et al.* (2017) 'Application of Polyacrylamide (PAM) through Lay-Flat Polyethylene Tubing: Effects on Infiltration, Erosion, N and P Transport, and Corn Yield', *Journal of Environmental Quality*, 46(4), pp. 855–861. doi: 10.2134/jeq2016.08.0299.

Mitchell, a. R. (1986) 'Polyacrylamide application in irrigation water to increase infiltration', *Soil Science*, pp. 353–358.

Orts, W. J. *et al.* (2007) 'Use of synthetic polymers and biopolymers for soil stabilization in agricultural, construction, and military applications', *Journal of Materials in Civil Engineering*, 19(1), pp. 58–66. doi: 10.1061/(ASCE)0899-1561(2007)19:1(58).

Rubio, H. O. *et al.* (1989) 'Effect of polyacrylamide on seedling emergence of three grass species', *Soil Science*, 148(5), pp. 356–360. doi: 10.1097/00010694-

198911000-00006.

Rubio, H. O. *et al.* (1992) 'The effect of polyacrylamide on grass emergence in southcentral New Mexico', *Journal of Range Management*, 45(3), pp. 296–300. doi: 10.2307/4002981.

Smith, H. J. C., Levy, G. . J. and Shainberg, I. (1990) 'Water-Droplet Energy and Soil Amendments: Effect on Infiltration and Erosion', *Soil Science Society of America Journal*, 54(4), p. NP-NP. doi: 10.2136/sssaj1990.03615995005400040049x.

Soltani-Gerdefaramarzi, S., Ghezelseflue, N. and Boroughani, M. (2019) 'Using polyacrylamide to control soil splash erosion in rainfalls with variable intensity and duration', *Spanish Journal of Soil Science*, 9(3), pp. 212–222. doi: 10.3232/SJSS.2019.V9.N3.05.

Steinberger, Y. *et al.* (1993) 'The effect of synthetic soil conditioners on microbial biomass', *Arid Soil Research and Rehabilitation*, 7(3), pp. 303–306. doi: 10.1080/15324989309381360.

Steinberger, Y. and West, N. E. (1991) 'Effects of Polyacrylamide on Some Biological and Physical Features of Soil: Preliminary Results from a Greenhouse Study', *Arid Soil Research and Rehabilitation*, 5(1), pp. 77–81. doi: 10.1080/15324989109381267.

Stichele, V. and Young, S. (2012) *The relationship between supermarkets and suppliers : What are the implications for consumers ?*, *Consumers Internationals*.

Sumner, M. E. (2000) *Handbook of soil science*. London: CRC Press.

Terry, R. E. and Nelson, S. D. (1986) 'Effects Of polyacrylamide and Irrigation Method on Soil Physical Properties', *Soil Science*, 141(5), pp. 317–320. doi: 10.1097/00010694-198605000-00003.

Tisdall, J. M. and Oades, J. M. (1982) 'Organic matter and water-stable aggregates in soils', *European Journal of Soil Science*, pp. 141–163. Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1365->

2389.1982.tb01755.x/pdf%5Cnpapers2://publication/uuid/3E8FB6C5-61FC-4BB5-A25C-730C3743C544.

Wakindiki, I. I. C. and Ben-Hur, M. (2002) 'Soil Mineralogy and Texture Effects on Crust Micromorphology, Infiltration, and Erosion', *Wakindiki, I.I.C. Ben-Hur, M.*, 66, pp. 897–905.

Weeks, E. L. and Colter, William, G. (1952) 'Effect of synthetic soil conditioners on erosion control', *Soil Science*, 73(6), pp. 473–484. doi: 10.1097/00010694-195206000-00006.

Van West, P., Appiah, A. A. and Gow, N. A. R. (2003) 'Advances in research on oomycete root pathogens', *Physiological and Molecular Plant Pathology*, 62(2), pp. 99–113. doi: 10.1016/S0885-5765(03)00044-4.

Yang, K., Tang, Z. and Feng, J. (2020) 'Effect of co-use of fly ash and granular polyacrylamide on infiltration, runoff, and sediment yield from sandy soil under simulated rainfall', *Agronomy*, 10(3). Available at: <https://www.scopus.com/record/display.uri?eid=2-s2.0-85081648956&origin=resultslist&sort=plf-f&cite=2-s2.0-84960953223&src=s&imp=t&sid=d60d454df4ad7bcfb9dc2fb2d925e67c&sot=cite&sdt=a&sl=0&relpos=4&citeCnt=0&searchTerm=>.

Zhang, R. (1997) 'Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer', *Soil Science Society of America Journal*, 61(4), pp. 1024–1030. doi: 10.2136/sssaj1997.03615995006100040005x.

5 Effect of polyacrylamide (PAM) application on metrics of soil crusting and spinach (*Spinacea olearia*) and Coriander (*Coriandrum sativum*) emergence and yield: 2021 Field Trials

Abstract

Polyacrylamides (PAMs) have been used for decades to prevent aggregate breakdown and crusting, improve infiltration and control furrow erosion. However, their extreme viscosity when mixed with water, limits their ability to be applied to the immediate soil surface using conventional spray machinery. This study presents the results of a novel field application of PAM (SFA30) using dual-fluid nozzles applied at 0, 40, 80 and 120 kg ha⁻¹ using 2 m³ of water ha⁻¹, alone or PAM applied at 80 kg ha⁻¹ in combination with Calcium Nitrate (1.0 mol of Ca:1.0 mol of acrylic acid, the PAM's anionic co-polymer). The effect of PAM application on metrics of soil-crust formation, seedling emergence and stand establishment of coriander (*Coriandrum sativum*) (Trial 1) and spinach (*Spinacia oleracea*) (Trial 2 and 3) were quantified in separate randomised-block field trials established at Watts Farms, Kent, UK. Results for Trial 1 showed a significant 24, 41 and 59% decrease in splash detached soil from plots treated with 40, 80 and 120 kg ha⁻¹ PAM respectively as compared to the untreated control. No significant difference in hydraulic conductivity was observed between treatments. Emergence of coriander occurred significantly earlier and faster for plots treated with 80 and 120 kg ha⁻¹ PAM as compared to the 40 kg ha⁻¹ PAM treatment and the untreated control. Both the 80 and 120 kg ha⁻¹ PAM treatments were associated with significantly (>30%) greater final coriander fresh weight yield as compared with the untreated control. Trial 2 showed similar trends in yield as Trial 1, with a 47-39% increase in harvested biomass for plots treated with 80 kg ha⁻¹ of PAM and 80kg ha⁻¹ PAM+Ca respectively.

Finally, for Trial 3, PAM application in combination with a 50% reduction in irrigation pre-emergence did not significantly impact hydraulic conductivity, emergence or soil splash, as compared to a commercially irrigated control. The results of these trials indicate that SFA 30 can be spray applied to the soil surface

with significant benefits to emergence, final yield and water use efficiency in both commercially grown coriander and spinach.

5.1 Introduction

Globally, Spinach (*Spinacea olearia*) and Coriander (*Coriandrum sativum*) occupy a relevant portion of global cropped area, with 920,804 ha harvested for spinach in 2020 and 1,957,411 ha for Coriander, together with Anise, Fennel (FAO, 2021a). In the UK, leafy green salads for human consumption accounts for *circa* 70% of all horticultural cropped area, standing at 112,000 ha (DEFRA, 2021a). However, the production of leafy greens comes at a cost in terms of soil health. Conventional farm management relies on multiple crop cycles per year, typically 4 for Coriander, and 6 for Spinach (Watts Farm; Personal Communication, 2019). The short growth cycle associated with coriander (28 to 32 days) and baby leaf spinach (21 to 22 days) depending on variety, planting date and climatic factors, as well as planting schedules allow growers to maintain a continuous, supply of fresh, affordable produce to the market. As a consequence the soil is tilled numerous times per year, left bare at the beginning of every cropping cycle and irrigated up to three times (twice pre-emergence) before the development of 50% canopy cover, resulting in a mechanical and oxidative stress that doesn't allow the development of natural-occurring soil organic matter (SOM) a key factor in aggregate stability (Sumner, 2000; Pagliai, Vignozzi and Pellegrini, 2004; Giardini, 2012). Consequently, soil aggregates are unable to resist the Kinetic Energy (KE) associated with rainfall and multiple irrigation events occurring during the cropping cycle (Chapter 4). This results in the formation of structural seals and upon de-hydration, of structural crusts (Bresson and Boiffin, 1990; Armenise *et al.*, 2018).

The agronomic impact of these structural crusts are low infiltration rate (Hardie and Almajmaie, 2019) and emergence impedance (Awashwal and Thierstein, 1985). Conventional practices to promote soil structural regeneration such as mixed cropping, no tillage, cover crops aimed at establishing a complete Soil Organic Carbon Pool (Bronick and Lal, 2005; Lal, 2014) are not compatible with the fast-paced agronomy associated with intensive baby leaf spinach and

coriander production systems, which demand production at a price point that does not allow one crop per year (Stichele and Young, 2012).

Polyacrylamides (PAMs) have been used for decades as soil conditioners in agriculture and civil engineering. Their efficacy as a soil stabiliser is confirmed by numerous laboratory experimental evidence (Ben-Hur *et al.*, 1989a; Sojka *et al.*, 2007; Laker and Nortjé, 2019; Panova, Ilyasov and Yaroslavov, 2021), and to flocculate sediment in furrow irrigation systems (Levy *et al.*, 1992a; Trout, Sojka and Lentz, 1995; Lentz *et al.*, 2000). Compared to other synthetic soil conditioners, PAMs are used as an efficacy benchmark to trial other synthetic and bio-alternatives such as cellulose or guar gums (Lentz, 2015b). However, the very same properties that make PAMs so effective as soil conditioners (charge density, molecular weight, hygroscopicity) are also hindering their practical adoption. When in contact with water, PAM molecules unfold, attracted by the hydrogen bonds with water molecules (Hecker, 1998b). The long polymers (10^6 Mg mol⁻¹) increase viscosity of the liquid making pumping any mixture of PAM at a concentration higher than 6000 mg l⁻¹ impossible (Bjorneberg, 1998b). Beside field trials on furrow irrigation (Lentz *et al.*, 2000) there have been a handful of attempts at field application by broadcasting PAMs, using a PVC sleeve (McNeal *et al.*, 2017), sowing granular PAMs with a crop (Känkänen *et al.*, 2011) and via sprinkler irrigation (Ben-Hur, 2001). The lack of follow-up publications on field-application of PAM outside furrow irrigation suggests that PAM performs well in laboratory conditions, but its application is not easily scalable to the field, let alone to a commercial context.

The physical properties of PAMs are not the only constraint for successful mitigation of crust-related pre-emergence problems. The time window to apply the PAMs is also narrow, especially for spinach, characterised by a 4-5 day gap between seeding and emergence. The application of PAM would preferably be before the first irrigation which is required to activate the seed but is associated with the risk of crust formation and impeded seedling emergence (Chapter 2). Generally, PAMs applied as flocculants in agriculture have a linear structure, a charge density between 18 and 30% and a molecular weight of 1 to 2 10^6 g mol⁻¹. Previous research has demonstrated that PAM efficacy can be significantly

improved through the addition of cations to facilitate 'cation-bridging' between anionic PAMs and negatively charged exchange sites of soil colloids. Lu et al. (2002) observed that divalent cations (Ca^{2+} and Mg^{2+}) were 28 times more effective than monovalent cations (Na^+ , K^+) at facilitating PAM sorption. To promote 'cation-bridging' previous approaches have applied typically 20 to 40 kg ha^{-1} of PAM as granules or dissolved in water in conjunction with <2.0 mm granular gypsum previously incorporated to the soil profile at typically 4000 kg ha^{-1} (Ben-Hur *et al.*, 1989a; Chaudhari and Flanagan, 1998; Abrol *et al.*, 2013; Muluaem *et al.*, 2021). Abrol et al. (2013) substituted gypsum with 40 mm of a 0.02 mol solution of CaCl_2 misted onto the surface after the application of granular PAM with consequential reduction in erosion and runoff.

The aim of this study was to critically evaluate the efficacy of the innovative application of a commercially available PAM SFA30, using Twin-Fluid flat fan nozzles to promote soil stabilisation and improve crop emergence, yield and metrics of crop quality in baby leaf spinach and coriander. This was addressed under the following research objectives. To quantify whether the application of PAM results in positive changes in selected metrics of soil crusting, improved coriander crop emergence and final yields in a commercial context. In particular, to investigate whether higher application rates could trigger a mulching effect by effectively creating a polymer barrier between the soil and rain or irrigation drop impacts.

The second objective was to verify whether mixing Calcium Nitrate with the water component of the PAM spray application has an effect on selected metrics of soil crusting, spinach emergence metrics and yield.

The final objective was to evaluate the efficacy of PAMs to improve water use efficiency by eliminating one of the two pre-emergence irrigations as compared to current management practices.

5.2 Materials and methods

5.2.1 Location and Field Trial Design

Three separate field trials took place during August-October 2021 at Southfleet, Kent, (51°24'43.4"N 0°18'32.2"E), on a commercial farm (Watts Farm)

specialising in intensive baby leaf spinach and field grown herb production. The soil is an association between a Calcaric Cambisol and a Calcaric Endoleptic Cambisol, a well-drained, calcareous, fine silty, and often very stony (LandIS, 2021). It is a sandy clay loam (C=28.6; Z=19.6; S=55.5) (Marshall and Holmes, 1979). The soil has a pH of 6.0, a Soil organic matter content via Loss On Ignition (LOI) of 3.24% and a Cation Exchange Capacity of 0.036 cmol kg⁻¹ (pH, BS ISO 10390:2005; LOI (Klute, 1986) Particle Size Distribution, ISO 11277:2009; Cation Exchange Capacity, BS 7755-3.12:1996). The climatic conditions (Figure 5.1) during the trial period were monitored using a Delta-T weather station WSTN (GP1-27-51) located >200 m from the field trials that recorded humidity, wind speed and direction, solar radiation and rainfall.

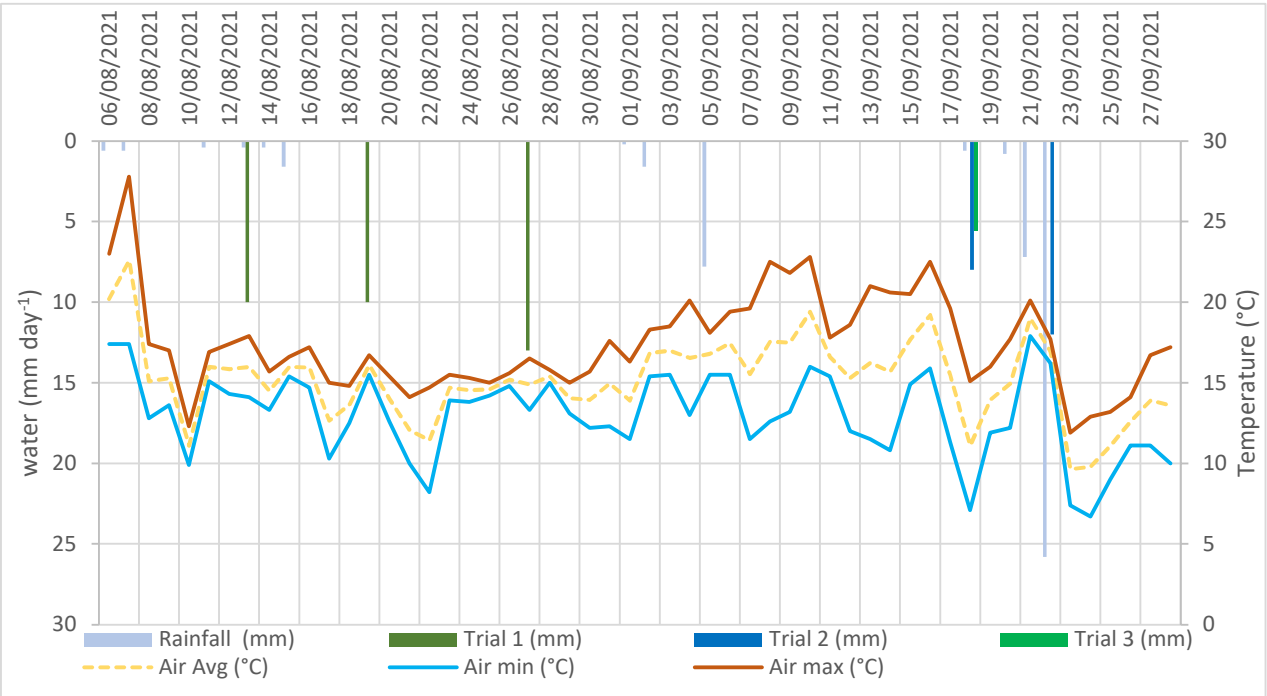


Figure 5.1 Climatic conditions prevailing during the experimental field Trials (August-October 2021). The vertical bars represent rainfall and irrigation divided by Trial.

The three trials (Table 5.1) were established as randomised block designs, where the experimental plot consisted of a 15 m long, 1.8 m wide seedbed, separated at either end by a 5 m buffer area. All measurements were taken in the central 10 m of each plot. All treatments were repeated in quintuplicate. Information about the number and treatments are available in Table 5.1:

Experimental Trial	Crop	PAM application rate (kg ha ⁻¹)					No. of irrigations	No. of randomised blocks
		0	40	80	80+Ca ¹	120		
1. Polymeric Film	Coriander	x	x	x	/	x	3	5
2. Effect of Calcium Nitrate ¹ addition on PAM efficacy	Spinach	x	/	x	x	/	3	5
3. Effect of PAM on WUE ³	Spinach	x	/	x	/	x	2	3

Table 5.1 Summary of replicated field trials undertaken during August-October 2021 at Watts Farms, Kent, UK.

1 Calcium Nitrate applied in water component of Twin-Fluid application at a ratio of 1.0 mol of Ca:1.0 mol of acrylic acid **2** Trial 3 had two plots removed due to non-uniform irrigation post-seeding. **3** WUE = Water Use Efficiency.

5.2.2 Conventional commercial agronomic management of coriander and spinach at Watts Farms, Kent, UK: A phenology-driven approach

The spinach and coriander cropping season in the UK starts usually in the second half of April and ends in the first half of November (Watts Farm; Personal Communication, 2019). Figures 5.2 a and b detail the current agronomic practices adopted by Watts Farms for spinach and coriander.

For coriander, seeding rate decreases with the progression of the season. While the seeding rate along a drill line is set as 85 seeds per linear m⁻¹ across the entire season, the number of drill lines grouped together and separated by 0.15 – 0.2 m, decreases to two, and then to a single as the season progresses resulting in 7*3=21 rows in early season, 7*2=14 rows in June-July and 7*1=7 rows from August. This practice allows wind to flow through the crop to limit the incidence of mildew, and enables the crop to develop thicker stems that promote post-harvest shelf-life (Watts Farm; Personal Communication, 2019). For Trial 1, seven single rows were drilled in the 1.8 m wide seedbed. Planting density for spinach was constant throughout the season and was set at 18 rows per 1.8 m wide seedbed with a seeding rate of 40 plants per linear m⁻¹. Dry spinach seeds weigh 1.5 ±0.2 g (Ziaf et al., 2017). Spinach emergence can occur 4 -5 days post-drilling depending on the variety (Watts Farm; Personal Communication, 2019) and environmental conditions (e.g. soil moisture and temperature). Coriander has an emergence period ranging between 9-14 days post drilling, the weight of the 1000 coriander seeds is typically 8.72 g at 7-10% moisture content (Coşkuner and Karababa, 2007). The longer time span between seeding and emergence and the lighter seed dry-weight, denoting a

lower energy stock in the endosperm, are risk factors in ensuring a homogenous emergence in coriander. The longer period between seeding and emergence for coriander as compared with spinach exposes the soil to a longer drying period after the first post-seeding irrigation (Figures 5.2a and b), increasing risk of crust formation. Secondly the lighter weight of coriander seeds does not feature the energy storage necessary for the proliferation of the cells responsible for the increase in turgor pressure associated with larger seeds, like spinach (Coşkuner and Karababa, 2007). As a consequence, coriander is more prone to emergence issues on crust susceptible soils. Coriander phenology, however, allow the seed to enter a temporary dormancy state whenever the hypocotyl cannot pierce through the crusted soil surface, that can be reactivated following an additional irrigation (Watts Farm; Personal Communication 2020). Typically, both coriander and spinach are given a 2nd irrigation pre-emergence, based on a visual assessment of the 'crust-status' and moisture content of the seedbed. In spinach, linear cracks along the drill lines, caused by the aggregated turgor pressure of the cotyledons are used as a trigger for this pre-emergence irrigation. For coriander, a small knife is used to remove the surface crust in order to quantify the degree of seed germination. For both crops, the trigger for the 3rd irrigation is the development of the first two true leaves, as the moisture draws from the soil surface between 2nd and 3rd irrigation (Figures 5.2a and b), the root system develops vertically to depth rather than horizontally. Harvest is undertaken manually for coriander, and mechanically for spinach using a spinach harvester. Both spinach and coriander seeds were drilled using a spider-precision drill that works one bed at the time. A steel roller suspended on the back of the seed drill gently compressed the seedbed post-drilling to ensure good soil-seed contact.

DAD ^a	Scheduled operations	Crop Phenology
0	Drilling followed by first irrigation	Seed
1		
2		
3		
4	Pre-emergence pesticides applied	
5	2nd irrigation around seed chitting	Germination
6		Emergence
7		
8		
9		
10	*Additional irrigation/rainfall event	
11		
12		
13		Two true leaves
14	3rd irrigation at two true leaves	
15		
16		
17		
18		
19	*Additional irrigation/rainfall event	
20	Pesticide Application	
21		
22		
23		Stem Extension, rapid growth
24	*Additional irrigation/rainfall event	
25		
26	Pesticide Application	
27		
28	*Additional irrigation/rainfall event	
29		
30		
31	Pesticide Application	
32	*Additional irrigation/rainfall event	
33		
34		
35	Harvest	Commercial maturity

Table 5.2a Coriander Estimated Growing Timeline according to Current Practices. Where multiple cells display the same colour-code without further labels, the phenology stadium is assumed to be reached within that days' range. a DAD=Day after Drilling

DAD ^a	Scheduled operations	Crop Phenology
0	Drilling followed by first irrigation	Seed
1		
2	Pre-emergence pesticides applied	Germination
3		Emergence
4	2nd irrigation just before emergence	
5		
6		
7		
8		Two true leaves
9		
10		
11	3rd irrigation at start of two true leaves	
12		
13		
14		Circa 50 % canopy cover
15	*Additional irrigation/rainfall event	
16	Pesticide Application	
17		
18		Circa 75 % canopy cover
19	*Additional irrigation/rainfall event	
20		
21		
22	Pesticide Application	
23	*Additional irrigation/rainfall event	
24		
25	Harvest	Commercial maturity

Table 5.2b Spinach Estimated Growing Timeline according to Current Practices. Where multiple cells display the same colour-code without further labels, the phenology stadium is assumed to be reached within that days' range. ^a DAD=Day after Drilling

In both crops, the seeding and 1st irrigation are conventionally undertaken within the first 24hrs. However, PAM application increased this time, resulting in a one day longer cycle, due to the physiological activation of the seeds being postponed 24hrs.

5.2.3 Soil Management

For both crops, at the beginning of the growing season, the field was subsoiled perpendicularly to the future seedbed orientation to avoid any interference between the subsoiler tramlines and future cultivated beds. The formation of the seedbed consists in a GPS-guided double pass. A rotor blade breaks the aggregates on the seedbed surface, whilst the sides are excavated and stabilised by the action of two-faced mouldboards and discs. The second pass was undertaken 24hrs prior to drilling.

5.2.4 Irrigation

The irrigation schedule for the three field trials followed the crop phenology-oriented approach adopted by Watts Farms. All the plots were irrigated 24 h after seeding, and irrigation were scheduled at key phenological stages, as shown in Figure 5.2a and 5.2b, and were assessed by daily monitoring and were applied on the dates reported on Table 5.2.

A Briggs Chassis VR5 hose-reel operated at 5⁶ Pa (5.0 atm) pressure at the farm pump with a programmed moving front of 60 ±15 m h⁻¹ was used to apply the scheduled irrigation on the three experiments. The irrigation boom was fitted with Komet KPT Twister nozzles (Komet Austria GmbH), characterised by a 9 m radius at the ground (D50 Undisclosed by Komet). An irrigation technical error on the first irrigation of Experiment 3 applied on 9th September 2021 resulted in anomalous irrigation applied on two of the five randomised blocks, and their exclusion from the data analysis.

For each experiment, irrigation homogeneity was monitored using three rain gauges placed in the plots. This resulted in 40 and 45 rain gauges for Experiment 1 and 2 and 3, respectively.

The total amount of water delivered in average to every plot (mm) is shown in Table 5.1, the average mm and time of delivery of the irrigations is shown in Figure 5.1. ANOVA was used to ensure there was no significant difference ($\alpha < 0.05$) in mm delivered to the treatments within the same experiment.

Trial	1. Polimeric Film			2. Calcium-aided PAM			3. Water Scarcity	
Phenology	PD	Pre Em	2 nd TL	PD	Pre Em	2 nd TL	PD	Pre Em
Irrigation →	1 st	2 nd	3 rd	1 st	2 nd	3 rd	1 st	2 nd
Treatment (kg ha ⁻¹) ↓	13/08/2021	19/08/2021	27/08/2021	09/09/21 ^a	18/09/2021	22/09/2021	09/09/2021	18/09/2021
0	10.5	9.8	13.6	- ^a	12.9	7.4	5.3	5.6
20	9.5	9.6	13.2	- ^a	12.1	7.6	4.9	5.4
80	10.5	9.3	12.5	- ^a	12.7	8.6	5.35	5.8
120	10.2	9.8	13.4					
Std Err.	0.2	0.22	0.33		0.24	0.29	0.39	0.43

Table 5.3 Irrigation calendar and mean irrigation depth (mm) applied to the 2021 Field Trials.

^aData not available. PD = Post-drilling; Pre Em = Pre-emergence; 2nd TL = Second true leaf stage. Std Err. = Standard Error

5.2.5 PAM characteristics and delivery

The PAM investigated in the 2021 Field Trials (SFA30) is a linear anionic concentrated suspension, with a molecular weight of 6.0×10^6 g mol, and is copolymerised with sodium acrylate, for a charge density of 25%. The PAM polymer is preserved in a concentrated anionic suspension of ammonium nitrate in a liquid state, and occupies 30% of its volume. PAM was applied using a bespoke sprayer constructed by Pluvex, France (Appendix C), mounted on the back of the frame of a seed driller available at Watts Farm. The sprayer consists of two parallel hydraulic circuits made of commercially available Tee-Jet and John Quest components, propelled by two separate pumps, and controlled by two flowmeters. The two hydraulic systems converge at a twin fluid nozzle that incorporates outlets for both water and PAM. The twin fluid flat fan nozzle is a moulded piece of hard plastic that features two separate inlets and outlets, converging outside at a 45° angle. At the interface between the water and PAM, the PAM droplets are scattered by the water jet and then bounced off the exterior

angled surface of the nozzle that then deflects them to the soil surface. Any non-homogeneity in the mixture of PAM and water is balanced by overlapping the nozzles' footprint. Mixing the PAM and water outside the sprayer tanks and pipework allows the sprayer to apply higher PAM concentrations to the immediate soil surface compared to the traditional in-pipe mixing.

5.2.6 PAM application

The aim of PAM application is to protect the soil from breakdown associated with rain and irrigation drop impacts and the crop from the agronomic impacts associated with crusting. The best window for its application is between seeding and the 1st irrigation event. Typically, this 1st irrigation is applied between 24 and 48hrs after seeding. For each experiment, a single PAM application was delivered 24hrs after seeding and 24hrs before the 1st irrigation. PAM and water flow rates were kept constant at 0.42 and 7.98 kg min⁻¹. The target PAM application rates were achieved by varying the speed of the sprayer. Therefore, the relative proportions of PAM and water is held constant for each PAM application rate. The settings on the sprayer's flowmeter were calculated as follows:

5-1 Application Rate as a function of Flowrate, Width of sprayed area and Sprayer speed

$$Application\ Rate(kg\ ha^{-1}) = \frac{Flow\ Rate_{Nozzles}}{width_{sprayed\ area}(m) * Speed(km\ h^{-1})} \quad 5.1$$

Experiment 2 required the addition of Calcium cations to the water. Calcium in the form of Calcium Nitrate (Ca(NO₃)₂, at 95% purity) was added to the water tank to allow simultaneous application with PAMs. The final mixture of water and PAMs just outside the nozzle contained the same number of Ca cations and OH-carboxyl groups on the PAM. The Ca(NO₃)₂ concentration was calculated based on the following assumptions. PAM flow rate is 0.42 kg min⁻¹. The PAM trialed, SFA 30, contains 50% of active Polyacrylamide of which the anionic monomer constitutes 30% of total weight. This equals to 0.875 mol min⁻¹ of reactive oxygen exchange sites on the PAM applied available for calcium cations to form 'bridges' to soil colloids. Consequently, this was set as the *target flow (mol min⁻¹)*.

Assuming that the molecular weight of $\text{Ca}(\text{NO}_3)_2$ is 135 g mol^{-1} the target flow rate was determined following equation 5.2:

5-2 Calcium Nitrate Target Flow rate

$$\begin{aligned} \text{Flow}_{\text{Ca}(\text{NO}_3)_2} [\text{g min}^{-1}] &= \text{Molar weight}_{\text{Ca}(\text{NO}_3)_2} [\text{g mol}^{-1}] * \text{target flow} [\text{mol min}^{-1}] = 5.2 \\ &= 115.5 \text{ g min}^{-1} \end{aligned}$$

The flow at the water pump is estimated at 7.98 kg min^{-1} and target $\text{Ca}(\text{NO}_3)_2$ concentration is therefore 1.4%, as shown in equation 5.4.

5-3 Concentration of Calcium Nitrate solution in the Water tank

$$\text{Ca}(\text{NO}_3)_2 \text{ concentration} = \frac{0.115 [\text{kg min}^{-1}]}{7.98 [\text{kg min}^{-1}]} * 100 = 1.4\% \quad 5-3$$

5.2.7 Metrics evaluating PAM effects in mitigating soil structural crusting and facilitating crop emergence

For each experiment, soil moisture was measured using a ML3 Theta-probe 1 hr before, 24hrs and 48hrs after each irrigation event. All measurements were collected at the centre of the seedbed, and in the central 10 m of the experimental plot, at least 0.5 m from where other metrics were collected. Time of measurement for each plot was recorded and coupled with weather conditions from the weather station to match anomalous values with atmospheric events. Soil moisture measurements were replicated in quintuplicate for each experimental plot.

5.2.7.1 Splash Detachment

Soil splash was quantified following a modified funnel method similar to the one developed by (Gorchichko, 1976). A pre-weighted 110 mm diameter Camlab 1171056 Grade 601 filter paper was folded and placed in a 95 mm diameter Nalgene funnel. This was partially inserted into the seed bed. Prior to insertion, soil of the same equivalent volume as the funnel was carefully removed and a 0.4m long, 10 mm wide drain created with a metal rod under each funnel to prevent backwash and soil contamination from under the funnel. The upper rim of the funnel emerged 5 mm above the bed surface to avoid the collection of soil contamination via sheet flow. Soil splash measurements were replicated in

quintuplicate for each experimental plot. For Trial 1-3 soil splash was captured for all irrigation events.

5.2.7.2 Hydraulic Conductivity (HC)

Hydraulic Conductivity (HC) of the immediate soil surface was measured in quintuplicate for each experimental plot using a Decagon mini-disc Infiltrometer 24hrs after all irrigation events applied to each Trial, following the methodology described in Chapter 4.

Emergence for both coriander and spinach was collected linearly. Five randomised areas in the plot were marked by flags, every flag was counted as the starting point of a 0.5 m length of drill line. Emerging seedlings were counted daily starting on the day where the first seedling had emerged. Due to the fast emergence associated with spinach, emergence was captured twice daily as required, before and after the 1st irrigation on Day 4 for Trial 2 and on 6 DAD for Trial 3. Emergence count was stopped once plant counts stabilised for more than two days for coriander and continued through to two true leaf stage for spinach, where factually both emergence and stand establishment were recorded.

5.2.8 Yield Quality and Quantity

At the time of harvest, wind had blown out most of the emergence marker flags for the coriander plots. Consequently, yield data was recorded from 5 randomly locations within each plot. Conversely, the emergence marker flags for spinach, were still in the ground during harvest, allowing yield data to be obtained by harvesting the same drill line segments used to measure emergence. All harvested plant samples were brought back to the laboratory and fresh weight (FW) determined using a two decimal place scale. The relatively small area and the harvesting method do not allow the fresh weight data to be safely analysed as conventional yield (kg ha^{-1}) and hold a purely comparative value within the domain of this research. To minimise the multiplication of error, the fresh weight data is analysed and presented as $\text{g } 0.25 \text{ m}^2$.

Quality check (QC) samples were collected from each experimental plot and consisted of a 1.0 kg sub-sample taken from a harvested unit from each experimental plot. This was sent to Watts Farm's Packhouse and subjected to

standard QC protocols. One harvested unit for coriander consisted of 18 hand harvested commercial bunches. For spinach each QC check harvested unit consisted of a 0.50m length of full seedbed-width which was sufficient to half-fill a standard harvest box. The presence of the QC indicators was subsequently quantified in percentage (%) terms. And the crop is finally subjected to a final judgment by the operator (pass/fail). The Damage Criteria linked to Manhandling after harvest were ignored for the scope of this analysis.

5.2.9 Statistical analysis

Normality of data was visually confirmed using plots of residuals versus fitted values. If the data were normally distributed, no transformation was required. One Way and Repeated Measures ANOVA was undertaken using Statistica version 14 (<http://statistica.io>) Homogenous groups were computed using *post-hoc* Fisher LSD analysis with $\alpha=0.05$.

5.3 Results and discussion

5.3.1 Splash Detachment

Splash detachment results are reported on Figures 5.2a, 5.2b and 5.2c. All PAM application rate treatments for Trials 1-3 significantly decreased splash detachment for the 1st irrigation. Splash detachment then settled in the consecutive irrigation, showing mostly no significant difference between treatments.

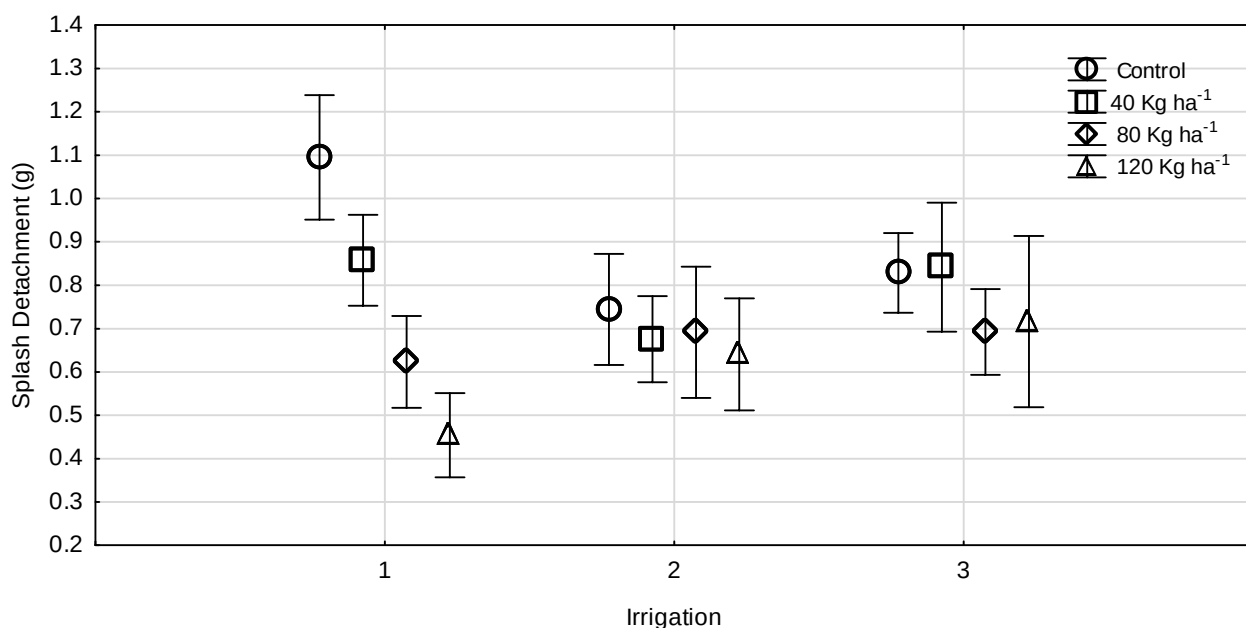


Figure 5.2a Effect of PAM application rate (kg ha⁻¹) on mean (n=25) mass of splash detachment soil (g) for Trial 1 (Coriander). Vertical bars denote 0.95 Confidence intervals.

For the 1st irrigation of Trial 1 (Figure 5.2a) increasing PAM application rate from 40, 80 and 120 kg ha⁻¹ resulted in significant 24, 41 and 58% reductions in soil splash as compared with the untreated control, respectively. In 80 and 120 kg ha⁻¹ treated plots, the aggregates were still present and distinguishable after the rainfall. No difference between treatments after second irrigation, with all treatments ranging between 0.64 and 0.71 g. Similarly, after irrigation 3, there is no significant difference within treatments, with values ranging between 0.70 and 0.89 g, slightly higher than irrigation 2 but not significantly. These data suggest that soil surface stabilised after the first irrigation. A post hoc at $\alpha=0.05$ shows how after the initial spike after irrigation 1, on Splash from irrigation 2 and 3 (0.76 and 0.87 g) belong to the same homogenous group in Control. Same trend in reverse (lower initial splash detachment and stabilisation at higher values) is observable for 120 kg ha⁻¹, where after the initial 0.45 g, soil detachment stabilised at 0.64 and 0.84 g after 2nd and 3rd Irrigation respectively. Significant difference only occurred between 1st and 2nd irrigation for 40 kg ha⁻¹ and no significant difference at all were associated to 80 kg ha⁻¹ splash detachment events (0.72, 0.68 and 0.68 g for 1st, 2nd and 3rd irrigation).

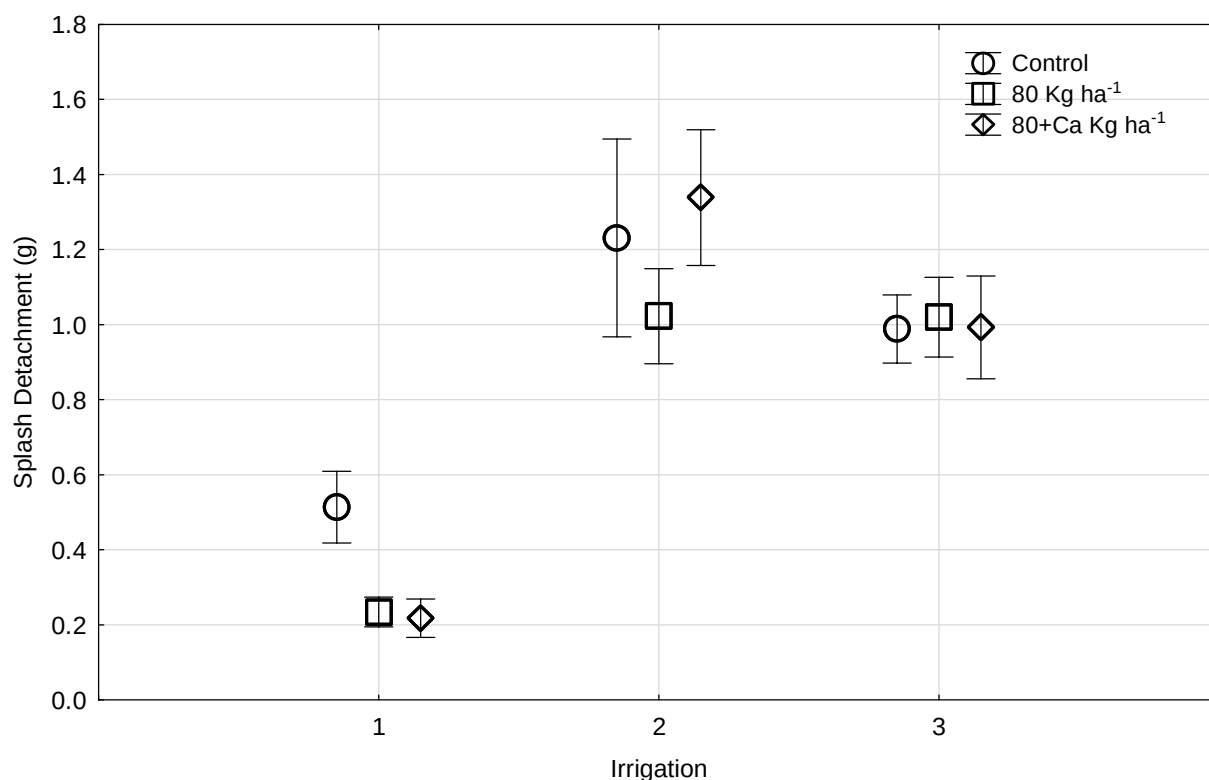


Figure 5.2b: Effect of PAM application rate (kg ha^{-1}) on mean ($n=25$) mass of splash detachment soil (g) for Trial 2 (Spinach – Calcium addition). Vertical bars denote 0.95 Confidence intervals.

Similarly, for the 1st irrigation of Trial 2 (Figure 5.2b) increasing PAM application at 80 kg ha^{-1} and $80+\text{Ca kg ha}^{-1}$ treatments resulted in significant 41.6 and 43.7% reductions in the mass of splash detached soil as compared with the untreated control. No significant difference, however, was observed between the 80 kg ha^{-1} and $80+\text{Ca kg ha}^{-1}$ after the first irrigation vent. After the second irrigation the significant difference between the two PAM treatments 1.32 and 1.03 (associated with 80 kg ha^{-1} of PAM only and 80 kg ha^{-1} of PAM+Ca) however the wide standard error associated with Control (1.25 g) confirms that there is no significant difference between Control and any of the treatments. The 3rd irrigation shows how the homogenisation of the splash detachment after consecutive irrigation is now stable for the three treatments, 0.97, 1.02 and 1.00 g (Control, 80 kg ha^{-1} of PAM only and 80 kg ha^{-1} of PAM+Ca, respectively) all belong to the same homogenous group.

The lower mass of splash detached soil observed Trial 2 and 3 for the 1st irrigation event as compared with Trial 1 can be explained by the soil conditions at the time of seed drilling and consequently PAM application. Trial 2 and 3 were postponed twice due to adverse weather conditions and were then seeded in the first window of opportunity available. This meant that the soil was rolled while its moisture content was high enough for the soil to behave in a plastic state, and created a seedbed characterised by a flat surface rather than a dusty and aggregated surface that associated Trial 1. This suggests that splash detachment on bare compacted soil is less than on soil that has been worked at a lower moisture content.

Trial 3 demonstrated similar results to Trial 1 with for the 1st irrigation, significant reductions in the mass of splash detached soil associated with increasing PAM application. However, no significant difference in mass of splash detached soil was observed between the 80 and 120 kg ha⁻¹ PAM treatments with values of 0.22 and 0.15 g respectively (Figure 5.2c). The mass of splash detached soil in Trial 3 is even lower than the other spinach trial (Trial 2) due to an anomaly in the irrigation boom speed, that made it deliver less water than the designed 12 mm. This anomaly made the last two plots in each experimental block unsalvageable. As with Trial 1 and 2, the mass of splash detached soil increased in the 2nd irrigation with no significant difference observed between PAM treatments and the untreated control. After the second irrigation, no significant difference is observed between control and treatments (0.94, 1.00 and 0.89 g associated respectively with Control, 80 and 120 kg ha⁻¹, respectively) these values are within 0.1 g range Test 2's third irrigation results. The two simultaneous trials had received some atmospheric rain, particularly between the 20th and 23rd of September (Figure 5.1).

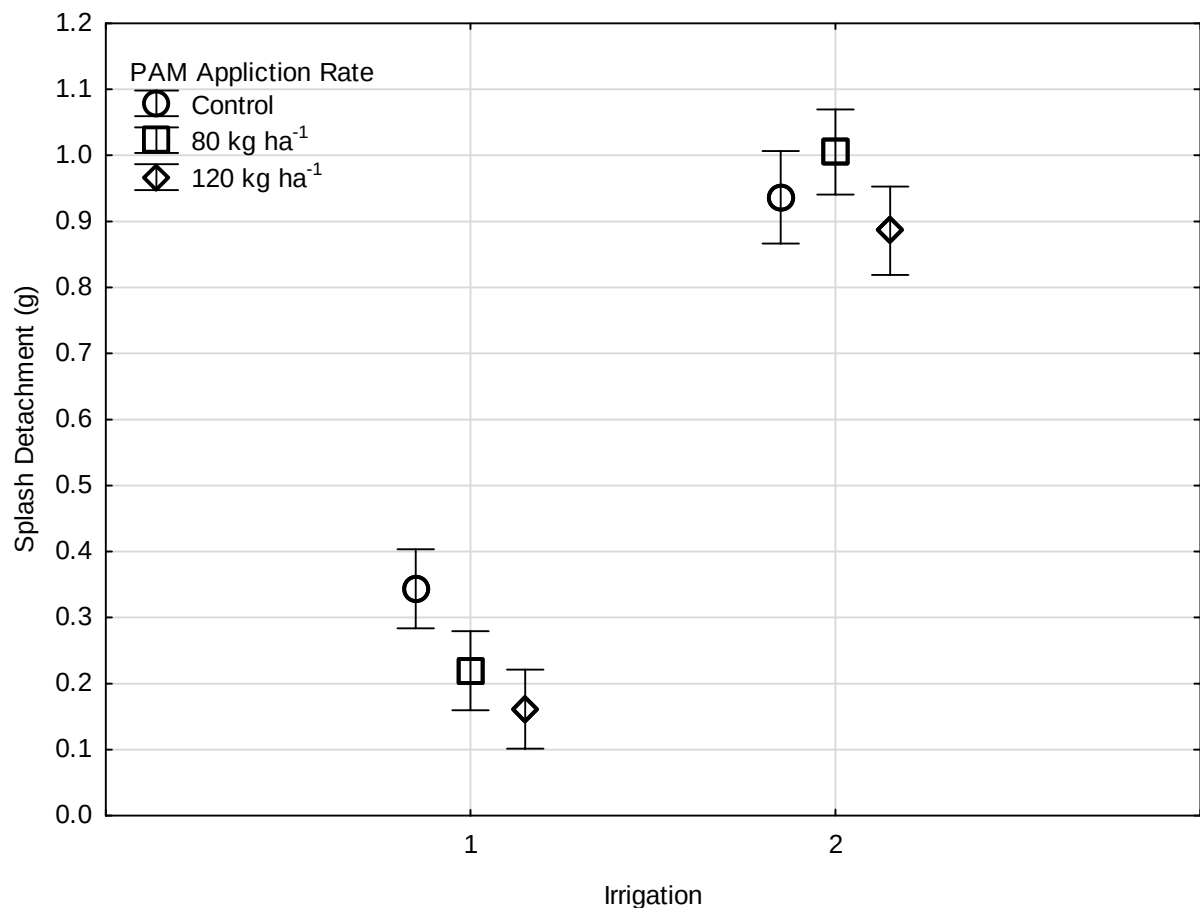


Figure 5.2c: Effect of PAM application rate (kg ha⁻¹) on mean (n=15) mass of splash detachment soil (g) for Trial 2 (Spinach – WS). Error bars denote 0.95 Confidence Intervals.

5.3.2 Hydraulic Conductivity

Hydraulic Conductivity results are reported on Figures 5.3 a, b and c. Data from the 2020 field trial (Chapter 4) showed a negative association between PAM application rate (kg ha⁻¹) and HC after the 1st irrigation event only. Similar, to what was observed in for splash detachment, the 1st irrigation for the 2021 Trials 1-3 present the clearest trends. However, the trends visible for the 1st irrigations in Figure 5.4a and b, cannot be considered significant within the treatment's variability.

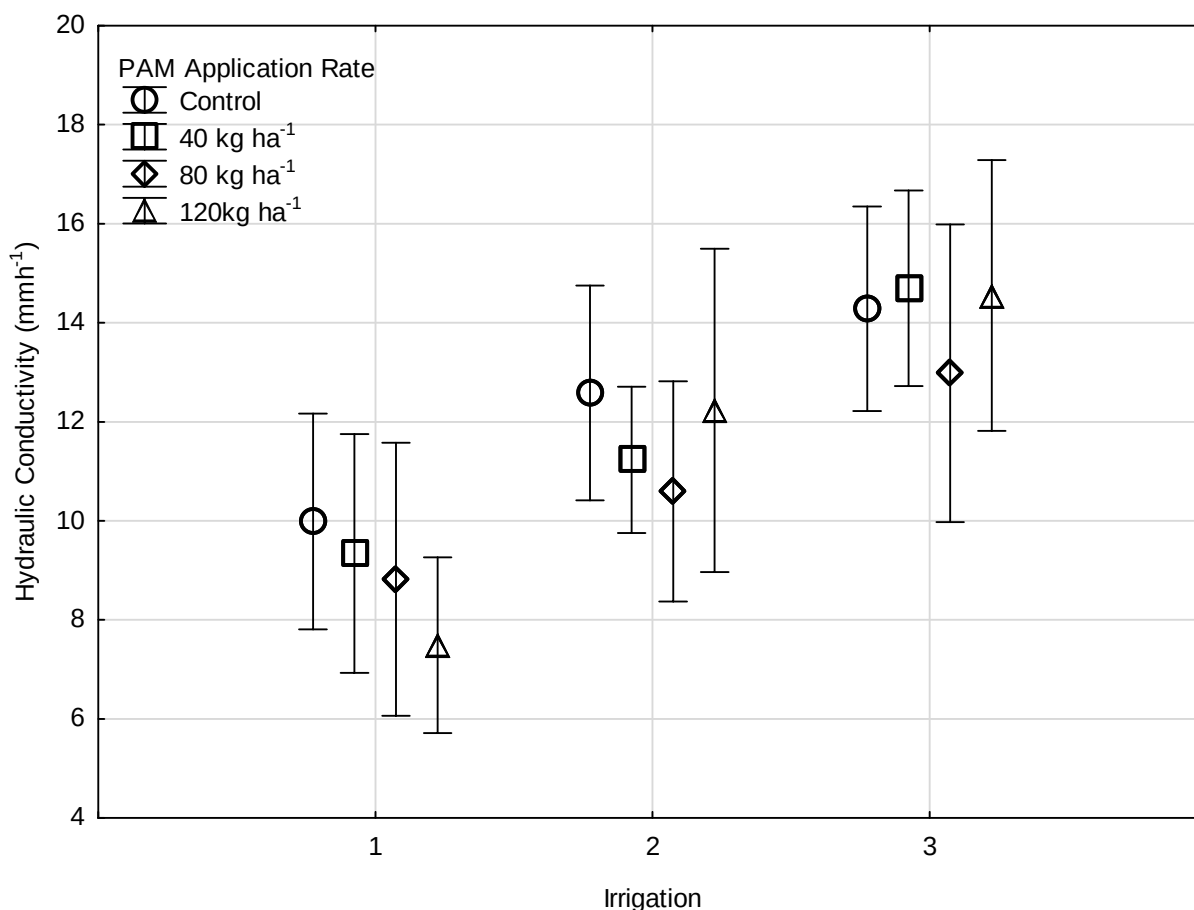


Figure 5.3a Effect of PAM application rate (kg ha^{-1}) on mean ($n=25$) hydraulic conductivity (mm ha^{-1}) for Trial 1 (Coriander). Error bars denote 0.95 Confidence Intervals.

Although not significantly different, there is a trend for HC values associated with the 1st irrigation event of Trial 1 to be negatively associated with increasing PAM application rate (Figure 5.3a), confirming observations from 2020 Trials. After the first irrigation, HC is at 10.0, 9.8, 9.0 and 7.4 mm ha^{-1} associated with control, 40, 80 and 120 kg ha^{-1} respectively. After the second irrigation, no significant differences were observed between treatments, with mean HCs ranging between 12.6, 11.3, 10.6, and 14.5 mm ha^{-1} associated with increasing PAM application rates. After the 3rd irrigation, the overall HC values increased, with 14.2, 14.6 13.0 and 14.5 mm ha^{-1} associated respectively with Control, 40, 80 and 120 kg ha^{-1} . The general trend for an increase of HC between the 1st, 2nd and 3rd irrigation events may in part be explained with the hot and dry weather (Figure 5.1) that occurred between the 13 – 27th August 2021 which allowed the formation of

dehydration cracks in the surface crust. For the 2nd and 3rd irrigation events, no significant difference in HC was observed between the PAM treatments (irrespective of application rate) and the untreated controls.

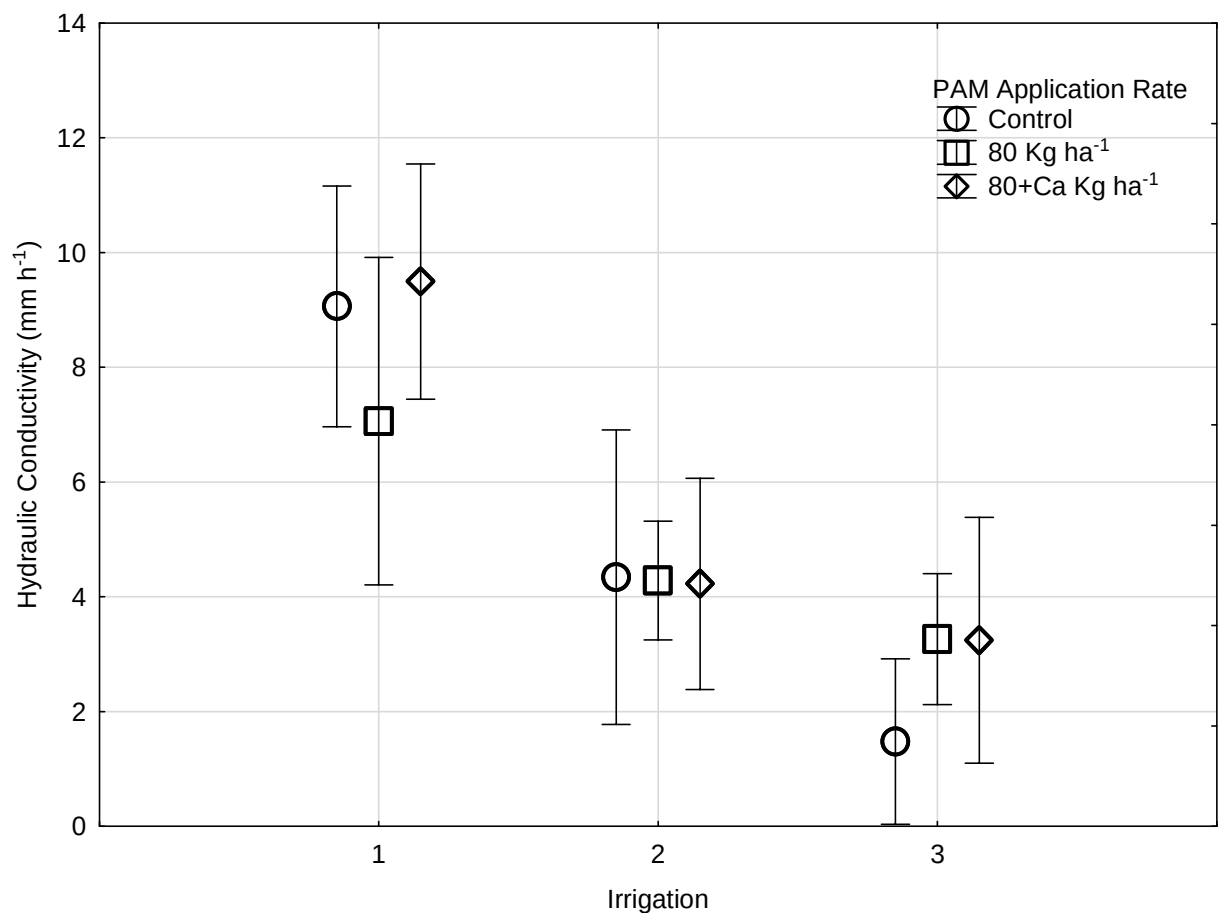


Figure 5.3b Effect of PAM application rate (kg ha^{-1}) on mean ($n=25$) Hydraulic Conductivity (mm hr^{-1}) for Trial 2, Calcium-aided PAM. Error bars denote 0.95 Confidence Intervals.

For Trial 2 an opposite trend in HC between the 1st, 2nd and 3rd irrigation events was observed as compared to Trial 1 (Figure 5.3 c). Trial 2 is characterised by a general trend for decreasing HC from the 1st to 2nd and 3rd irrigation events. This may in part be due to the higher degree of soil sealing (hydrated structural crust) caused by the irrigations (Table 5. 2) and by the rainfall events that occurred in that period, in particular, 24 hrs after the 2nd irrigation (Figure 5.1). However, HC after the 3rd irrigation shows PAM-treated plots having a higher HC, although not significant. Possibly, PAM-treatments helped in mitigating the loss in HC, in an effect that might have been masked by environmental noise.

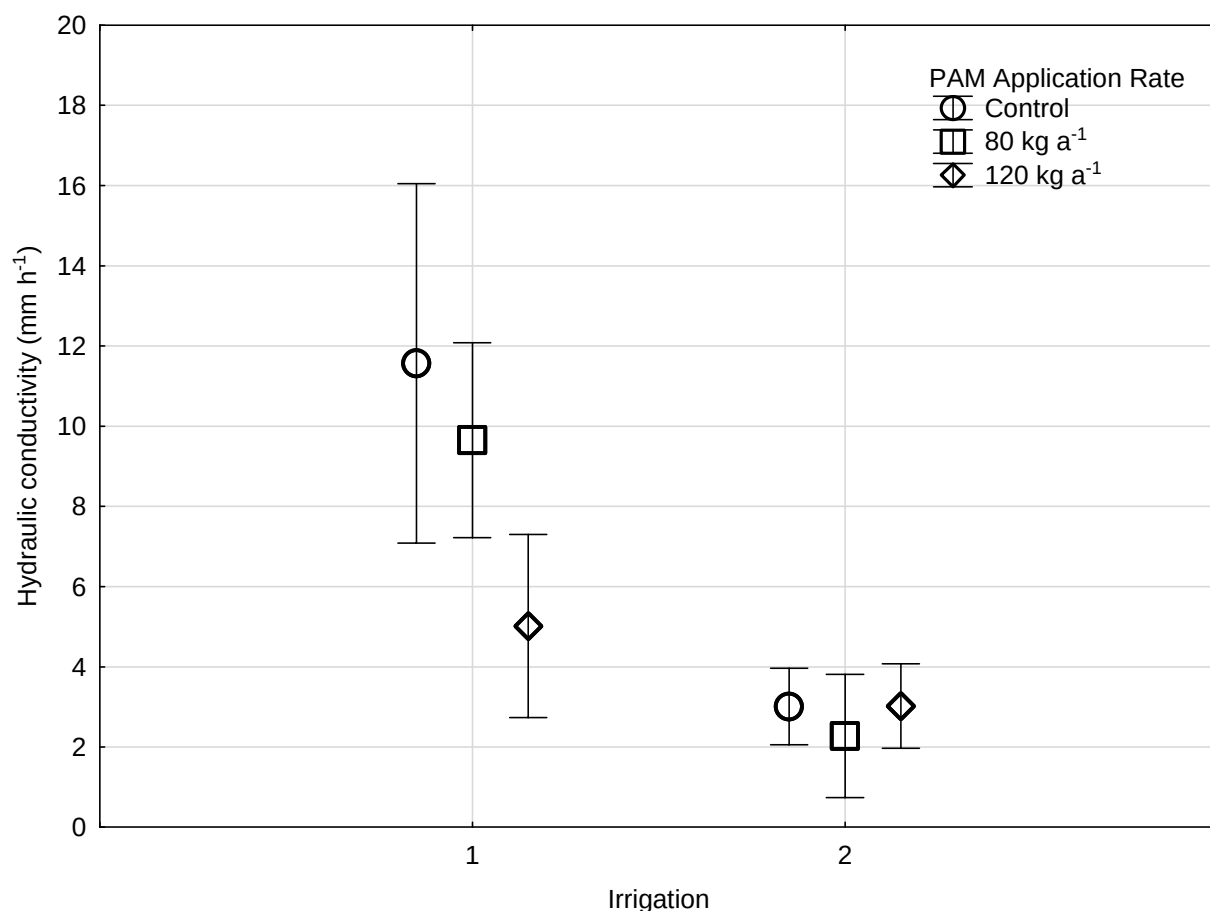


Figure 5.3c: Effect of PAM application rate (kg ha⁻¹) on mean (n=15) Hydraulic Conductivity (mm hr⁻¹) for Trial 3, Water Scarcity Spinach. Error bars denote 0.95 Confidence Interval.

For the 1st irrigation of Trial 3 the 120 kg ha⁻¹ PAM treatments was associated with a significantly lower HC as compared with the Control and 80 kg ha⁻¹ PAM treatments with values of 5.02, 11.6 and 9.64 mm hr⁻¹, respectively (Figure 5.4c). For the 2nd irrigation event no significant differences in HC conductivity were observed between the Control and 80 and 120 kg ha⁻¹ PAM treatments with HC values of 3.01, 2.27 and 3.12 mm hr⁻¹, respectively. This implies a stabilised soil surface crust, where HC was influenced in part by the rainfall event on the night of the 26th of August following the 2nd irrigation and before the HC measurements were made on the 27th of August 2021 (Figure 5.1).

5.3.3 Emergence

Coriander and spinach emergence results for Trial 1 and Trial 2-3 are reported in Figures 5.4a, b and c. The values are reported as number of seeds per m⁻² and compared against the target commercial seeding density of Watts Farms.

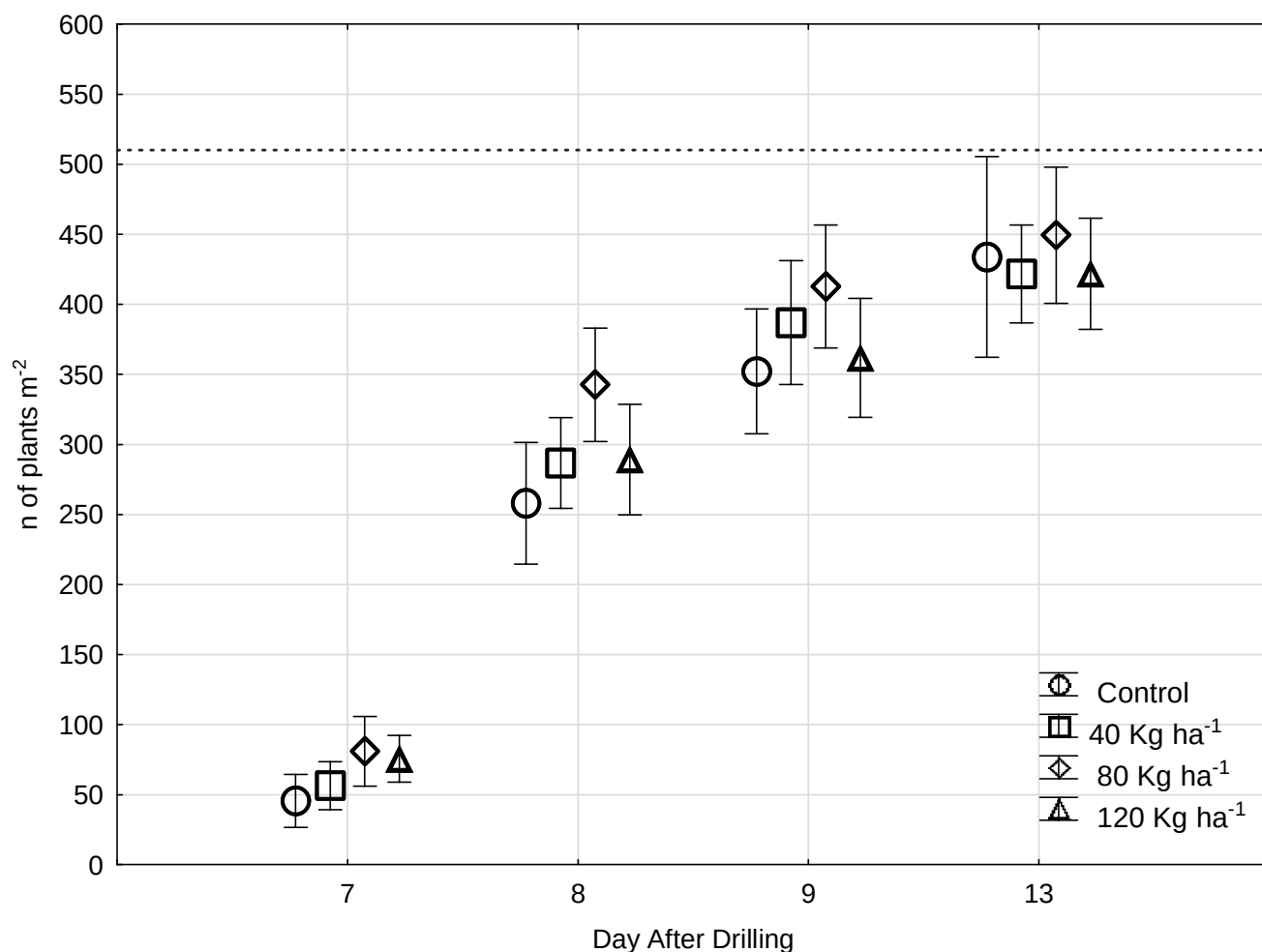


Figure 5.4a Effect of PAM application rate (kg ha⁻¹) on mean (n=25) emergence (No. plants m⁻²) for Trial 1 (Coriander). Error bars denote 0.95 Confidence Intervals.

In Trial 1, coriander, emergence started 7 days after drilling (DAD) and was considered completed 13 DAD, when the emergence count stopped increasing (Figure 5.5a). The majority of the seedlings emerged during the night between 7 and 8 DAD with stabilisation in planting density of circa 430 plants m⁻² 13 DAD. At 13 DAD no significant difference in the No. plants m⁻² was observed between the Control and PAM treated plots irrespective of application rate.

The 80 kg PAM ha⁻¹, was the best performing treatment in terms of seedling emergence with significantly higher emergence rates on 8 DAD as compared with the untreated Control with values of 342 and 258 plants m⁻² respectively. A similar but non-significant trend was observed for 7 and 9 DAD with emergence values for the Control and 80 kg ha⁻¹ PAM treatment of 46 and 81 at 7 DAD and 352 and 412 plants m⁻² at DAD 9 respectively. The 80 kg ha⁻¹ PAM treatment allowed a faster and more homogenous emergence, without affecting the final plant count 13 DAD.

Contrary to expectation, the application of PAM at 40 and 120 kg ha⁻¹ did not result in a significant difference in coriander seedling emergence for 7, 8, 9 or 13 DAD (Figure 5.5a). However, a positive though not significant trend was observed between the Control and 40 and 80 kg PAM ha⁻¹ treatments (Figure 5.4a). On 7 and 8 DAD, this trend is not observed for the 120 kg ha⁻¹ PAM treatment despite having shown the best performance for splash detachment (Figure 5.2a). The inversion in this observed trend might be in part explained by the trend for a decrease in HC associated with increased PAM application rate for the 1st irrigation of Trial 1 (Figure 5.4a). In conventional practice, the formation of a soil seal on the seedbed after the 1st irrigation is a desirable phenomenon as the reduced porosity associated with the seal slows water evaporation from the bare soil and helps to retain soil moisture promoting seed germination. Soil moisture readings (data not shown), however, show no significant difference between treatments. In addition, the weather during 7 – 13 DAD for Trial was characterised by rains and relatively low solar radiation (Figure 5.1). This resulted in reduced evaporation rate from the soil. PAM application at 120 kg ha⁻¹ may have created as intended, a polymeric film that through re-hydration of the PAM caused reduced HC. This may have resulted in a slower development of the coriander seedlings, especially before the 2nd irrigation 8 DAD, that homogenised HC values between treatments.

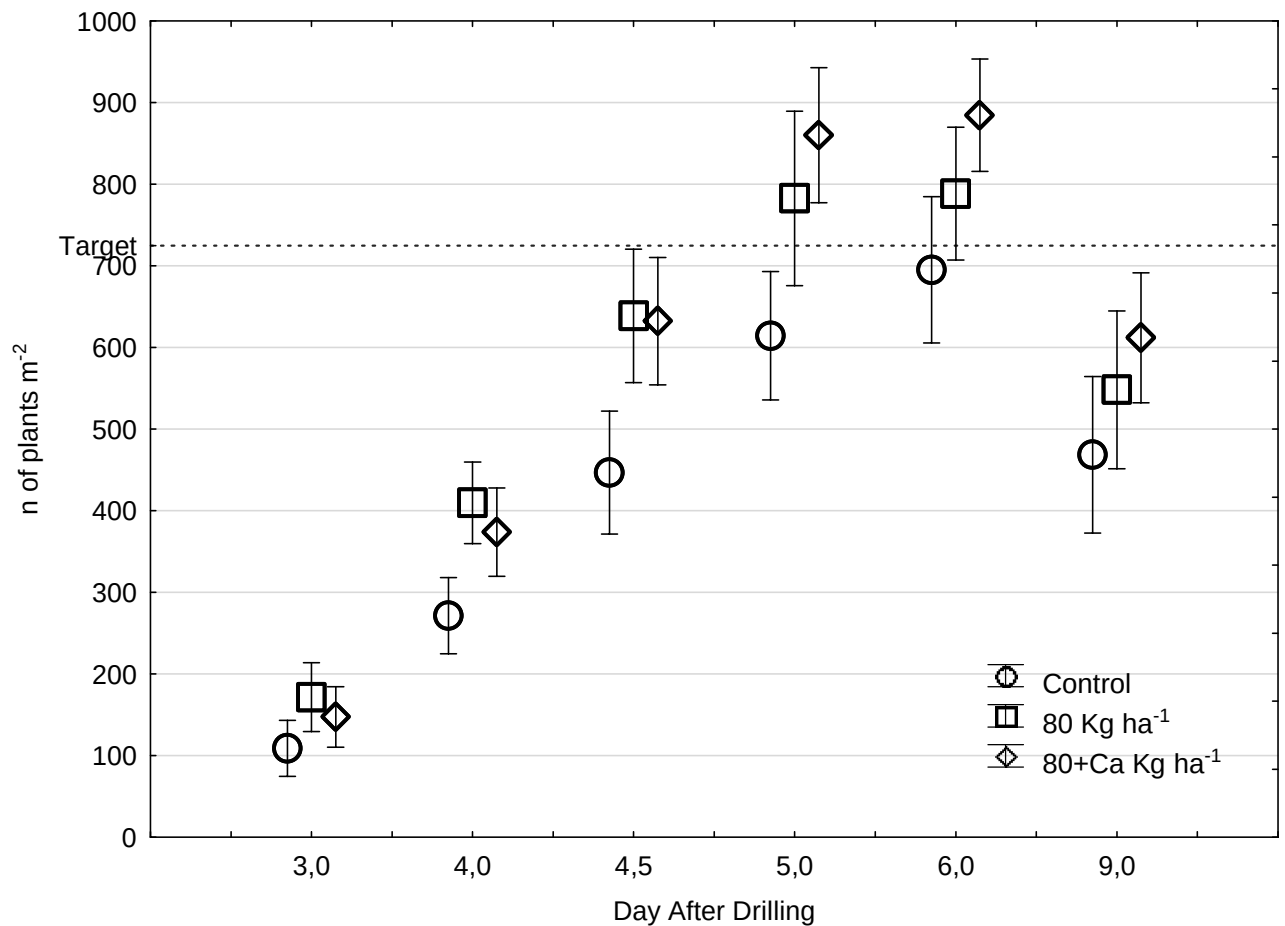


Figure 5.4b Effect of PAM application rate (kg ha⁻¹) on mean (n=25) emergence (No plants m⁻²) for Trial 2, Calcium-aided PAM. Error bars denote 0.95 Confidence Intervals

Figure 5.5b shows the emergence and stand establishment of spinach in Trial 2. Emergence started 3 DAD and was considered completed 5 DAD. The highest increase in emergence occurred between morning and afternoon of 4 DAD, before and after the 2nd irrigation. Critically, for 4 and 4.5 DAD, the 80 and Ca+80 kg ha⁻¹ PAM treatments were associated with significantly higher emergence as compared with the Control with values of 271 and 409 and 374 and 447 and 639 and 632 plants m⁻², respectively. At 4.5 DAD this equates to a significant +58 and 66% increase in spinach emergence for the 80 and Ca+80 kg ha⁻¹ PAM treatments compared to the Control.

By 5 DAD, for PAM-treated plots the number of spinach plants emerged exceeded the Watts Farms, target seeding rate of 725 plants m⁻². At 5 DAD, the Ca+80 kg ha⁻¹ PAM treatment is associated with significantly higher emergence

as compared with the Control with values of 860 and 614 plants m⁻² respectively. At 5 DAD, no significant difference in emergence was observed between the 80 kg ha⁻¹ PAM treatment and the Control or between the PAM treatments (Figure 5.5b). At 6 DAD, across all treatments, *circa* 32±2% of plants, wilted before reaching the two true leaves stage. Visual observation of the symptoms confirmed the cause to be an infection known in the industry as ‘Damping-Off’ (Van West, Appiah and Gow, 2003; Watts Farms; Personal Communication 2021). Damping-off is caused by one or more pathogenic soil fungi namely *Fusarium oxysporum*, *Pythium* (several species), and *Rhizoctonia solani*. However, the significantly higher seedling emergence associated with the 80 and Ca+80 kg ha⁻¹ PAM treatment as compared with the Control 4.5, 5 and 6 DAD is still observed although only significant at the 90% confidence interval. The final stand establishment numbers are 469, 548 and 611 plants m⁻² associated with Control, 80 and Ca+80 kg ha⁻¹ PAM respectively, well below the target density of 725 plants m⁻².

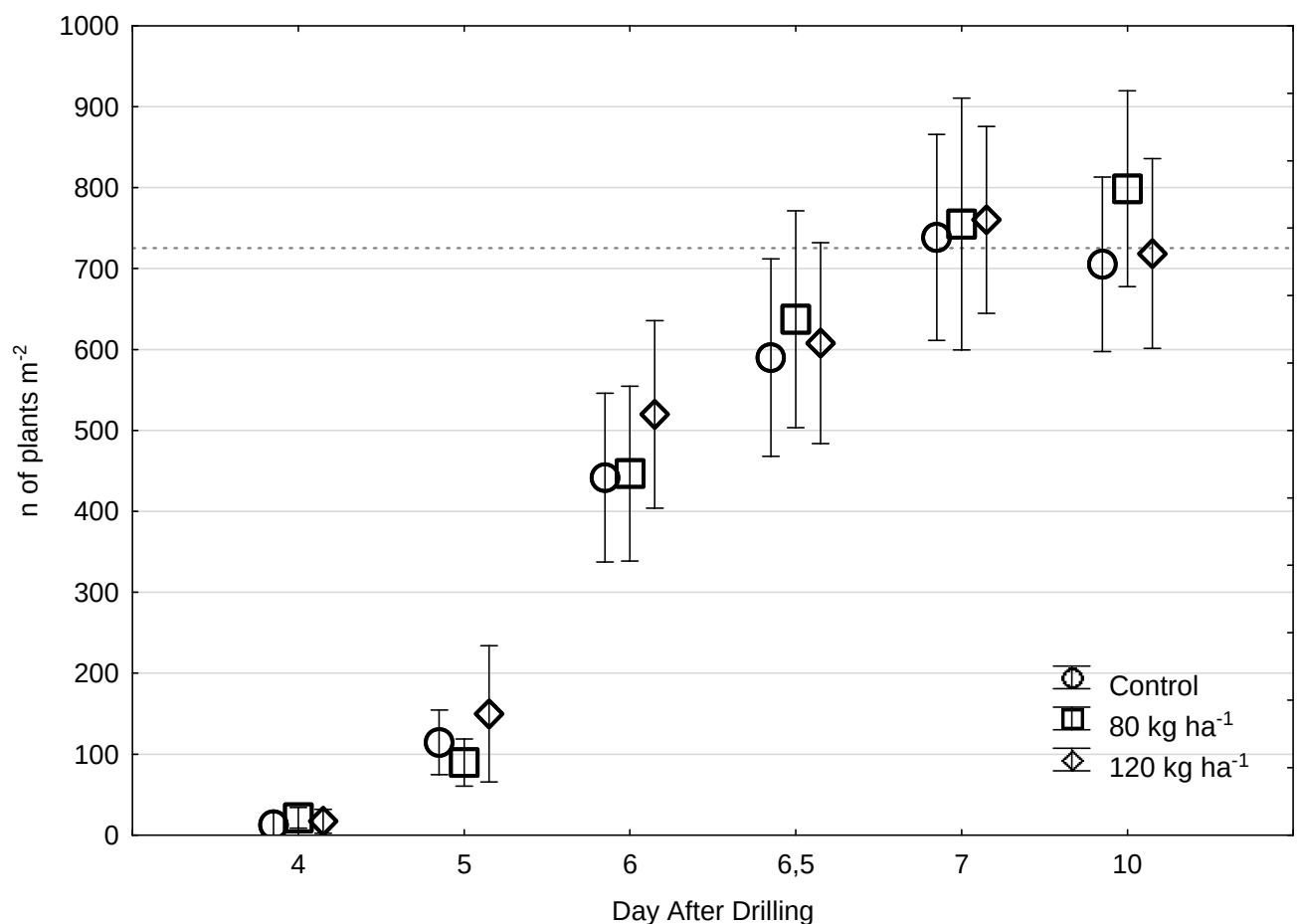


Figure 5.4c Effect of PAM application rate (kg ha⁻¹) on mean (n=15) emergence (No plants m⁻²) for Trial 3, Water Scarcity Spinach. Error bars denote 0.95 Confidence Intervals.

For Trial 3, Water Scarcity spinach emergence was delayed by 24hrs as compared with Trial 2 (Figures 5.4b and 5.4c). However, in contrast to Trial 1 and 2, the application of PAM did not result in any significant increase in crop emergence. Critically the omission of a 2nd irrigation (Pre emergence) did not result in 'Damping-Off' symptoms and a subsequent reduction in stand establishment as was observed in Trial 2. Trial 2 and 3 were held simultaneously within the same land plot. The storm occurred just after Trial 2's second irrigation might have worked as an additional irrigation for Trial 3, factually supplying the soil moisture necessary for emergence, and allowing the soil seal not to cement into a crust. A trend is observable between 5 and 6 DAD characterised by a higher plant count associated with 120 kg ha⁻¹ treatment 149 versus Control's 114 at 5 DAD, and 520 and 441 plants m⁻² associated with 120 kg ha⁻¹ and Control respectively. The incidence of damping off is observable at 10 DAD for Control and 120 kg ha⁻¹ with a circa 35 plants incidence, (=0.5% of total plant count).

5.4 Yield and Yield Quality

Harvest results for Trials 1-3 are displayed on Figures 5.6a, b and c.

The results from Trial 1 indicate that PAM application at 80 and 120 kg ha⁻¹ results in significant 31 and 27% yield increases as compared with the Control, (Figure 5.6a) with FW biomass values of 585.6, 566 and 445.5 g m⁻², respectively. The increase in harvested biomass may in large part be associated with the earlier and high emergence rate observed for the PAM treatments (Figure 5.5a).

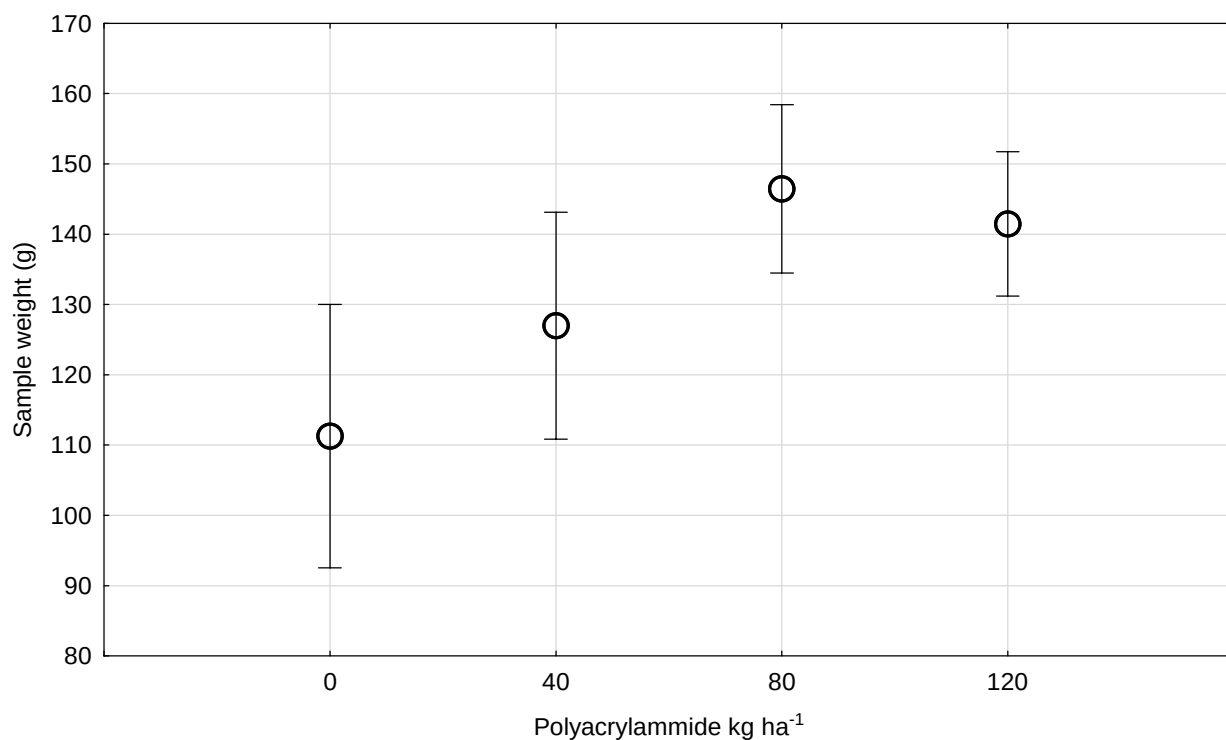


Figure 5.5a Effect of PAM application rate (kg ha⁻¹) on mean (n=25) coriander fresh weight (FW) biomass (g) for Trial 1 (Coriander). Error bars denote 0.95 Confidence Intervals.

One fresh weight sample consists of the 18 hand-harvested commercial bunches.

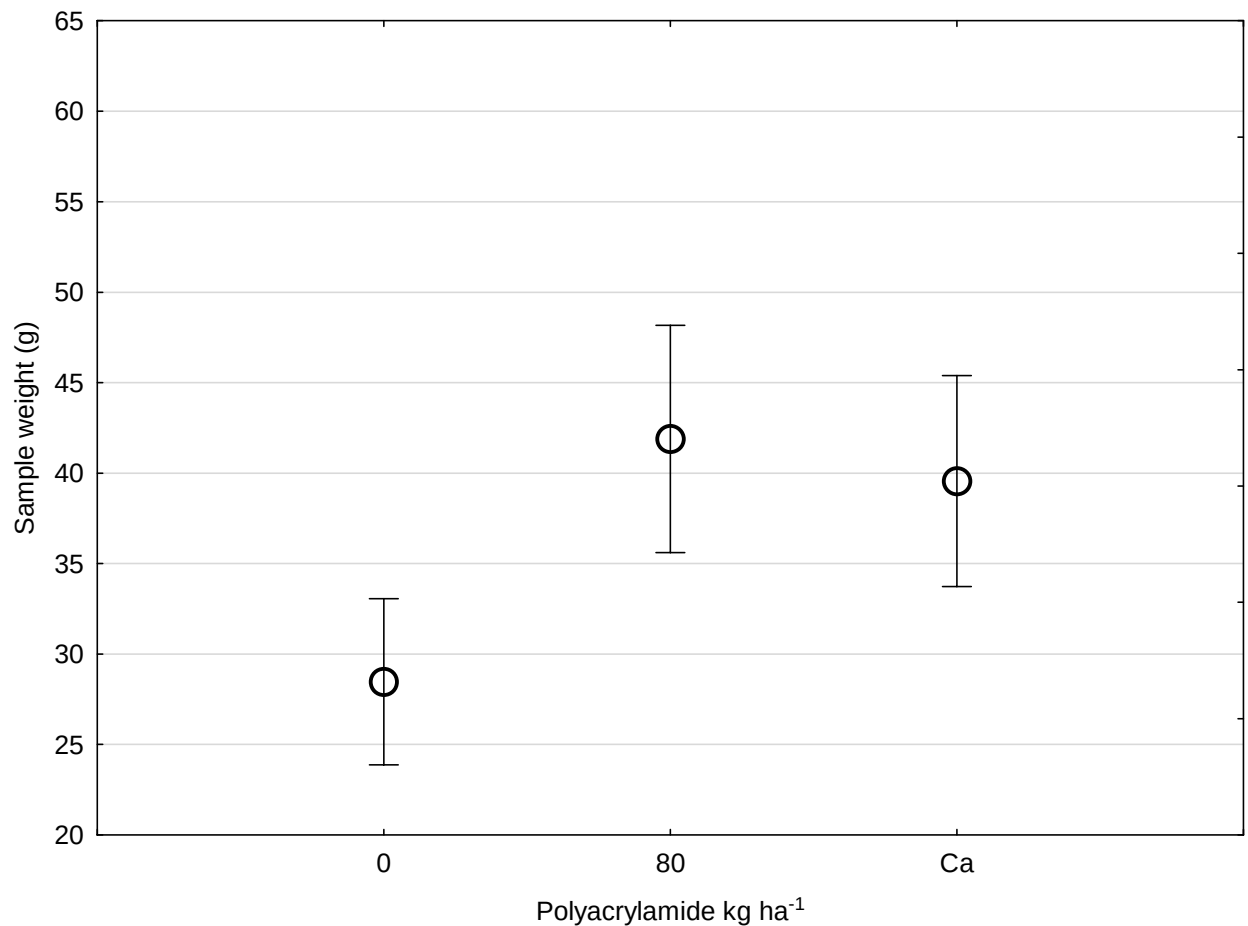


Figure 5.5b Effect of PAM application rate (kg ha⁻¹) on mean (n=25) coriander fresh weight (FW) biomass (g) for Trial 2, Ca Aided Spinach. Error bars denote 0.95 Confidence Intervals.

One fresh weight sample consists of the biomass harvested from 0.50 m single drill line.

In Trial 2, both the 80 and Ca+80 kg ha⁻¹ PAM treatments are associated with significantly higher FW biomass as compared to the untreated Control (Figure 5.6b) with values of 167.6, 160, and 114g m⁻², respectively. This equates to a 39-47% increase in harvested biomass for the PAM treatments. However, no significant difference in yield was observed between the 80 and Ca+80 kg ha⁻¹ PAM treatments. The higher yield observed in the PAM treatments may in large part be due to the significantly greater coriander seedling emergence at 4 and 4.5 DAD, associated with the 80 and Ca+80 kg ha⁻¹ PAM treatments.

Further, the significant difference in yield between the Control and PAM treatments might be due to the impact of the PAM treatments on 'Damping-off' which affects plants at the 2nd true leaf stage. The harvest-ready crop did not show any 'Damping-off' symptoms. Most of the QC defects were due to either physical damage, with 1% of damaged leaves or due to over maturity, characterised by the presence of floral stems (Table 5.4) which were mostly associated with the PAM-treated plots. The presence of floral stems is an indication of over-maturity and might be caused by the earlier emergence associated with the PAM treated plots. This indicates that on PAM treated plots spinach is potentially ready for harvest one or two days earlier than conventional practice.

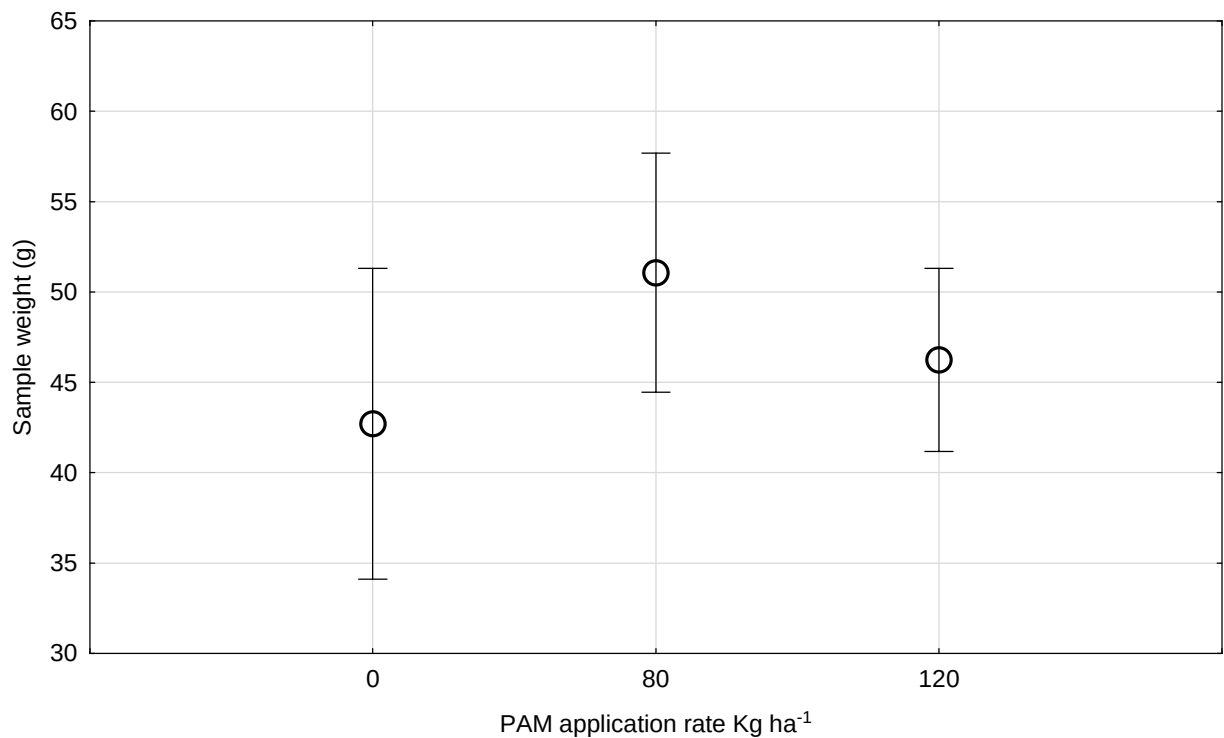


Figure 5.5c: Effect of PAM application rate (kg ha⁻¹) on mean (n=15) coriander fresh weight (FW) biomass (g) for Trial 3, Water Scarcity Spinach. Error bars denote 0.95 Confidence Intervals.

One fresh weight sample consists of the biomass harvested from 0.50 m single drill line.

For Trial 3, no significant difference in spinach harvest was observed between the Control and PAM treated plots (Figure 5.6c). However, there is a general trend for an increase in yield following PAM application at either 80 and 120 kg ha⁻¹, that reflects the trends observed for coriander in Trial 1 and spinach in Trial 2. No significant difference in spinach FW biomass being observed between the 80 and 120 kg ha⁻¹ PAM treatments. The high degree of variability within treatment associated with the Control may in part mask the positive influence of PAM application on spinach yield observed in Trial 2. No significant difference in product quality was observed between the Control and PAM treatments (Table 5.4).

All samples passed the Quality Check (QC), as shown in Table 5.4. Coriander in particular did not have any defects on any of the unit samples and will not be shown as a table. The lack of defects likely depends on the professional harvesters that have helped with QC sampling. Without any prompting they might have manually discarded any defective stem or leave, sending clean produce for QC analysis. However, anecdotal evidence of quality measurement carried on by the scientist confirm the homogeneity of the crop.

Trial	PAM (KG ha ⁻¹)	Breakdown	Physical damage	Yellowing on edges	Over maturity	Discolouration	Weeds, Roots	Pests	Total Defects (%):	Pass Y/N
Ca Aided Spinach (n=25)	control	free	0.40	0.00	0.20	0.00	1.00	0.20	1.80 ^a	Y
	80	free	0.20	0.00	0.80	0.40	1.00	0.00	2.40 ^a	Y
	Ca-80	free	0.67	0.00	0.67	0.00	1.00	0.00	2.33 ^a	Y
Water Scarcity Spinach (n=15)	0	free	0.33	0.00	0.67	0.33	0.67	0.00	1.33 ^{ab}	Y
	80	free	0.33	0.00	1.00	0.33	0.67	0.00	2.00 ^b	Y
	120	free	0.33	0.00	0.00	0.00	0.67	0.00	0.33 ^a	Y

Table 5.4 Effect of PAM application rate (KG ha⁻¹) on mean quality check metrics (%) Post-hoc Fischer LSD Trial was performed independently for all Trials. Trial one did not have any variance, being all sample without defects. Different letters denote different homogenous groups ($\alpha=0.05$).

5.5 Conclusions

The innovative Dual Fluid PAM spray application on the sprayer achieved a homogenous PAM application at a commercial scale. The polymeric mesh created on the soil surface protects it against splash erosion. This effect has found to be constant with time, as the PAM-treated plots kept the splash losses low throughout the consecutive irrigations.

The agronomic effects consist of a higher biomass at commercial maturity, driven by a quicker emergence (Trial 1) or a better stand establishment (Trial 2).

The yield improvements associated with PAM application do come, however, with a cost associated to machinery, machinery hourly cost and Polyacrylamide polymer. The costs connected with PAM application will be addressed in the next chapter.

5.6 References

- Abrol, V. *et al.* (2013) 'Efficacy of dry granular anionic polyacrylamide (PAM) on infiltration, runoff and erosion', *European Journal of Soil Science*, 64(5), pp. 699–705. doi: 10.1111/ejss.12076.
- Armenise, E. *et al.* (2018) 'Soil seal development under simulated rainfall: Structural, physical and hydrological dynamics', *Journal of Hydrology*. The Authors, 556, pp. 211–219. doi: 10.1016/j.jhydrol.2017.10.073.
- Awashwal, N. . and Thierstein, G. . (1985) 'Characteristics , Impedance To Seedling Emergence , Methods of Crust Manage- Ment As Well As Measures of Encouraging Emergence Through the Crust Have Been Gathered and Discussed , in Order To Provide an Insight Into the Problem of Soil Crusting and Its Im', *Soil & Tillage Research*, 5(1985), pp. 289–302.
- Ben-Hur, M. *et al.* (1989) 'Polymers as soil conditioners under consecutive irrigations and rainfall', *Soil Science Society of America Journal*, 53(4), pp. 1173–1177. doi: 10.2136/sssaj1989.03615995005300040030x.
- Ben-Hur, M. (2001) 'Soil conditioner effects on runoff and potato yield under sprinkler irrigation', *Agronomy Journal*, 93(5), pp. 1156–1163. doi: 10.2134/agronj2001.9351156x.
- Bjorneberg, D. L. (1998) 'Temperature, concentration, and pumping effects on

PAM viscosity', *Transactions of the American Society of Agricultural Engineers*, 41(6), pp. 1651–1655. doi: 10.13031/2013.17340.

Bresson, L. M. and Boiffin, J. (1990) 'Morphological characterization of soil crust development stages on an experimental field', *Geoderma*, 47(3–4), pp. 301–325. doi: 10.1016/0016-7061(90)90035-8.

Bronick, C. J. and Lal, R. (2005) 'Soil structure and management: A review', *Geoderma*, 124(1–2), pp. 3–22. doi: 10.1016/j.geoderma.2004.03.005.

Chaudhari, K. and Flanagan, D. C. (1998) 'Polyacrylamide effect on sediment yield, runoff, and seedling emergence on a steep slope', in *ASAE Annual International Meeting*. Orlando, FL.

Coşkun, Y. and Karababa, E. (2007) 'Physical properties of coriander seeds (*Coriandrum sativum* L.)', *Journal of Food Engineering*, 80(2), pp. 408–416. doi: 10.1016/j.jfoodeng.2006.02.042.

DEFRA (2021) 'Farming Statistics Final Crop Areas , Yields , Livestock Populations and Agricultural Workforce at 1 June 2012 , United Kingdom', (December), pp. 1–30. Available at: <https://www.gov.uk/government/statistics/farming-statistics-final-crop-areas-yields-livestock-populations-and-agricultural-workforce-at-1-june-2021-uk>.

FAO (2021) *FAOSTAT*. Available at: <https://www.fao.org/faostat/en/#home> (Accessed: 15 December 2021).

Giardini, L. (2012) *L'agronomia per conservare il futuro*. Patron.

Gorchichko, G. . (1976) 'Device for determining the amount of soil splashed by raindrops', *Soviet soil science*. Available at: <https://agris.fao.org/agris-search/search.do?recordID=US201301283343>.

Hardie, M. and Almajmaie, A. (2019) 'Measuring and estimating the hydrological properties of a soil crust', *Journal of Hydrology*. Elsevier, 574(April), pp. 12–22. doi: 10.1016/j.jhydrol.2019.04.031.

Hecker, R. (1998) 'The Characterisation of Polyacrylamide Flocculants.pdf'.

Känkänen, H. *et al.* (2011) 'Applying granulated and hydrated hydrophilic polymers at sowing to sustain seedling establishment of spring turnip rape', *Journal of Agricultural Science*, 149(5), pp. 567–577. doi: 10.1017/S0021859611000013.

Laker, M. C. and Nortjé, G. P. (2019) 'Review of existing knowledge on soil crusting in South Africa', *Advances in Agronomy*, 155, pp. 189–242. doi:

10.1016/bs.agron.2019.01.002.

Lal, R. (2014) 'Soil conservation and ecosystem services', *International Soil and Water Conservation Research*, 2(3), pp. 36–47. doi: 10.1016/S2095-6339(15)30021-6.

Lentz, R. D. *et al.* (2000) 'Irrigating with polyacrylamide (PAM) - Nine years and a million acres of experience', in Evans, R. G., Benham, B. L., and Trooien, T. P. (eds) *National Irrigation Symposium*. Phoenix, Arizona: American Society of Agricultural Engineers, pp. 161–169.

Lentz, R. D. (2015) 'Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam', *Geoderma*. Elsevier B.V., 241–242, pp. 289–294. doi: 10.1016/j.geoderma.2014.11.019.

Levy, G. J. *et al.* (1992) 'Polymers' effects on infiltration and soil erosion during consecutive simulated sprinkler irrigations', *Soil Science Society of America Journal*, 56(3), pp. 902–907. doi: 10.2136/sssaj1992.03615995005600030037x.

Marshall, J. D. M. and J.W, H. (1979) *Soil Physics*. Cambridge: Cambridge University Press.

McNeal, J. P. *et al.* (2017) 'Application of Polyacrylamide (PAM) through Lay-Flat Polyethylene Tubing: Effects on Infiltration, Erosion, N and P Transport, and Corn Yield', *Journal of Environmental Quality*, 46(4), pp. 855–861. doi: 10.2134/jeq2016.08.0299.

Muluaalem, T. *et al.* (2021) 'Examining the Impact of Polyacrylamide and Other Soil Amendments on Soil Fertility and Crop Yield in Contrasting Agroecological Environments', *Journal of Soil Science and Plant Nutrition*. Journal of Soil Science and Plant Nutrition, 21(3), pp. 1817–1830. doi: 10.1007/s42729-021-00482-4.

Pagliai, M., Vignozzi, N. and Pellegrini, S. (2004) 'Soil structure and the effect of management practices', in *Soil and Tillage Research*, pp. 131–143. doi: 10.1016/j.still.2004.07.002.

Panova, I. G., Ilyasov, L. O. and Yaroslavov, A. A. (2021) 'Polycomplex Formulations for the Protection of Soils against Degradation', *Polymer Science - Series C*, 63(2), pp. 237–248. doi: 10.1134/S1811238221020065.

Sojka, R. E. *et al.* (2007) 'Polyacrylamide in Agriculture and Environmental Land Management', *Advances in Agronomy*, 92(04), pp. 75–162. doi: 10.1016/S0065-2113(04)92002-0.

Stichele, V. and Young, S. (2012) *The relationship between supermarkets and*

suppliers : What are the implications for consumers ?, Consumers Internationals.

Sumner, M. E. (2000) *Handbook of soil science*. London: CRC Press.

Trout, T. J., Sojka, R. E. and Lentz, R. D. (1995) 'Polyacrylamide effect on furrow erosion and infiltration', *Transactions - American Society of Agricultural Engineers*, 38(3), pp. 761–766. doi: 10.13031/2013.27889.

Van West, P., Appiah, A. A. and Gow, N. A. R. (2003) 'Advances in research on oomycete root pathogens', *Physiological and Molecular Plant Pathology*, 62(2), pp. 99–113. doi: 10.1016/S0885-5765(03)00044-4.

Ziaf, K. *et al.* (2017) 'Pericarp loosening and reduced lipid peroxidation enhances spinach seed performance and biomass production under normal and saline conditions', *Pakistan Journal of Agricultural Sciences*, 54(2), pp. 299–309. doi: 10.21162/PAKJAS/17.3711.

6 Polyacrylamide (PAM) spray application in intensive horticulture: an analysis of costs

Abstract

Intensive field-based leafy green cultivation is a high input/high output industry, justified by the relatively high price per kg: 1.72 £ kg⁻¹ for coriander and £1.45 kg⁻¹ for baby leaf spinach (DEFRA, 2022) and by the possibility of having multiple crops per year. With multiple crop cycles per year, and a 21-28 day period between seeding and harvest, farming leafy greens impacts soil structure, reducing its resilience. When these soils are subject to rainfall and/or irrigation, the agronomic consequence is the formation of a crust, that reduces water-use efficiency and impedes crop emergence. Polyacrylamides (PAMs) are long carbon chains characterised by areas of different electrical density, and are very effective at binding with soil colloids, flocculating sediment and in the case of aggregates, stabilising them.

This research investigated a novel dual-fluid nozzle spraying method, developing, testing and implementing it in a field-scale context, with positive results in terms of reducing soil splash and improving emergence and yield. In order to implement this new technology at a commercial scale it needs to be both practical and economically viable. This study investigated the cost of applying PAM applications (40, 80 and 120 kg ha⁻¹) in a commercial context. The results indicate that per unit (kg) fresh produce costs (£) per kg decreased in association with PAM application. For conventionally irrigated coriander unit cost per kg decreased from the non-PAM treated control value of 0.55 £ kg⁻¹ to 0.52, 0.48 and 0.51 £ kg⁻¹ for 40, 80 and 120 kg ha⁻¹ PAM application rates, respectively. These equate to cost savings of 5, 13 and 8%, respectively. For conventionally irrigated spinach per unit fresh produce costs per kg significantly decreased from 0.56 to 0.45 and 0.42 £ kg⁻¹ associated with an 80 kg ha⁻¹ PAM + Calcium treatment and 80 kg ha⁻¹ of PAM only treatment respectively. These equate to cost savings of 20 and 25% respectively. Optimising the sprayer and the delivery method could decrease costs. This study also estimated the cost reductions of

PAM application resulting from different strategies in the technical improvement of the sprayer, highlighting what additional cost benefit would be achieved with (1) retrofitting the sprayer on the back of a seed drill, (2) optimising the sprayer's water use.

6.1 Introduction

Intensive field grown leafy green production is a high input/high output industry, justified by the relatively high price per kg (.72 £ kg⁻¹ for coriander and £1.45 kg⁻¹ for baby leaf spinach (DEFRA, 2022)) and by the typical practice of cultivating multiple crops per year (DEFRA, 2020 Personal Communication Watts Farms). The structure of the agricultural market in developed country generally consists of a disproportional number of producers, and a handful of major retailers (DEFRA, 2020b). This structure creates competition among farmers, pursuing higher yields and lowering the prices of their offers to obtain a supply contract from a retailer (Nicholson, 2012). This commercial pressure exerted on the producers results in affordable fresh produce that facilitates the transition towards a high micronutrient-dense diet (FAO, 2017).

The previous chapters have explored the effects of a single Polyacrylamide (PAM) spray application on two intensively farmed high micro-nutrient dense crops, Spinach (*Spinacea oleacea*) and coriander (*Coriandrum sativum*), with significant improvements in emergence and final yield. For coriander, a yield uplift of +31% was achieved at a PAM application rate of 80 kg ha⁻¹. Similarly, for conventionally irrigated spinach a yield uplift of +47% was achieved for both the 80 kg ha⁻¹ PAM + Calcium treatment and 80 kg ha⁻¹ of PAM only treatments, respectively. In addition, a +19% yield uplift was reported for spinach grown under modified irrigation (water scarcity conditions, equal to one less irrigation than the control during establishment) with PAM applied at 80 kg ha⁻¹. However, practicality and efficacy are necessary but not sufficient requirements to allow the transit of this novel PAM application strategy to commercial implementation. PAM application also needs to be cost-effective.

This study critically evaluates whether the spray application of PAMs using a Dual-Fluid nozzle is economically viable in the context of intensive leafy green production. The aim is to evaluate the incorporation of a single PAM application post-drilling in the crop management, quantify its costs and compare these costs with conventional practice. Crop performance data is used to evaluate the economic performance benefits of the treatments investigated.

6.2 Methodology

The analysis concentrates on the in-field spinach and coriander production costs from soil preparation to harvest. It does not include transport from the field to the cold store and packhouse, post-harvest storage, quality control checks, or packaging. The output is expressed as unit (kg) production costs (£) per hectare (ha) and unit production costs cost (£) per kg.

The production unit adopted in this economic analysis is 1.0 ha. Production units of this size are not common at Watts Farm, Kent, UK (51°24'44.80"N, 0°18'27.22"E), where production units tend towards fragmentation into smaller units. However, it allows standardisation and direct comparison between treatments investigated. The assumption produces a few distortions, such as four-hour-long irrigations, when in practice an irrigator run at Watts Farms does not take more than two hours. The result of this particular distortion on the economic appraisal is an understatement of the cost of the irrigation, because 1.0 ha is virtually going to be covered by one "pull" only, excluding all the preparation time usually associated with shorter pulls. Since modelling irrigation costs and timings of differently shaped 1.0 ha production units goes beyond the scope of this economic appraisal, and since this distortion has a precautionary effect on the hypothesis verification, this study will consider one irrigation event as a single, 40m-wide pull of total net duration of 4.55 hr.

Yield values are calculated by combining the 2021 field trial results with the average yield for spinach and coriander in late season (Personal Communication from Watts Farm, November 2021). The sample size collected on the field trial corresponds to a 0.50 m-long single strip of crop and was considered too little to

be multiplied to kg ha^{-1} without multiplying statistical errors. Therefore, a treatment specific PAM Application Coefficient was applied based on the average later season commercial Watts Farms yield data for 2021 (Table 6.1). The PAM + Ca 80 kg ha^{-1} treatments applied to conventionally irrigated spinach (Trial 2, 2021) were designed using an analytical grade Calcium Nitrate, whose commercial value is not compatible with agronomic economic appraisal. Moreover, the PAM + Ca 80 kg ha^{-1} did not result in any significant agronomic difference compared to the 80 kg ha^{-1} PAM-only treatment. Therefore, the inclusion of the Calcium Nitrate costs are not covered in the economic evaluation at this time.

Total Estimated Yield per treatment 2021 Field Trials	¹PAM application (kg ha^{-1})	¹PAM Application Coefficient	²Average late season yield (kg ha^{-1})	Total estimated yield (kg ha^{-1})
Coriander	0 (Control)	1.00 ^b	7500	7500 ^b
	40	1.14 ^{ab}	7500	8550 ^{ab}
	80	1.31 ^a	7500	9825 ^a
	120	1.27 ^a	7500	9525 ^a
³ Spinach	0 (Control)	1.00 ^a	7400	7400 ^a
	80 + Ca	1.39 ^b	7400	10286 ^b
	80	1.47 ^b	7400	10878 ^b
⁴ Spinach	WS 0 (Control)	1.0 ^a	7400	7400 ^a
	WS 80	1.19 ^a	7400	8806 ^a
	WS 120	1.08 ^a	7400	7992 ^a

Table 6.1 Total Estimated Yield per treatment.

Source Legend: ¹Data from the 2021 Field Trial. To the same superscript letter belong to the same homogenous group, derived from yield's Fischer Post Hoc in Chapter 5; ²Personal Communication from Watts Farm; ³Conventional irrigation ⁴Modified irrigation (water scarcity (WS)).

6.2.1 Production costs

The production of leafy greens is characterised by multiple growing cycles per year. Therefore, some preparatory soil works such as pre-season tillage and optional hoeing are undertaken once per year, whereas seedbed formation and seed drilling are repeated at the beginning of each cropping cycle (the latter are

included in the *seeding* costs). The economic appraisal considers this difference and divides the pre-season machinery operation by the number of crop cycles on an individual production unit (1.0 ha). The cost of 1 ha of crop per one cycle is quantified in Equation 6.1, where n is the number of cycles per year.

6-1 Costs categories associated with PAM spraying

$$total\ cost[\pounds\ ha^{-1}] = \frac{1}{n}(soil\ preparation) + seeding + fertilisation + irrigation + PAM \quad 6.1$$

It is assumed that the actual working capacity ($hr\ ha^{-1}$) of machinery (given in Table 6.3) is not based on the actual machinery speed as it also includes a typical number of turns required to complete field operations. Travel to and from field is not included in the calculation, whereas the setup time for the irrigation (connecting the irrigator to the hydraulic system, unfolding the coil and boom) is counted.

Variable costs of inputs are updated to the early months of 2021 (Table 6.2). Fertiliser requirements are modelled on the average yield and Watts Farms commercial practice which was applied to the trial plots. Treatment characteristics and crop management requirements that affect the costs (e.g. water requirements, PAM application rate (AR) ($kg\ ha^{-1}$) are also made explicit. Herbicide was not applied to the trials because of potential health risk for the scientist during measurements. Being the costs applied on the 2021 yield results, to avoid estimating the herbicide effect on the 2021 crop yield, its application cost is not included in the appraisal.

Category	Variable Costs	Quantity/Cost per unit	
¹ Seed	Coriander Seed	610	£ ha ⁻¹
	Spinach Seed	1334	£ ha ⁻¹
² Fertiliser	Coriander N	121	Kg ha ⁻¹
	Coriander P	80.7	Kg ha ⁻¹
	Coriander K	135	Kg ha ⁻¹
	Coriander total fertiliser cost	205	£ ha ⁻¹
	Spinach N	124	Kg ha ⁻¹
	Spinach P	82.8	Kg ha ⁻¹
	Spinach K	138	Kg ha ⁻¹
	Spinach total fertiliser cost	138	£ ha ⁻²
¹ Irrigation Per crop cycle	Water cost	3.72	£ m ⁻³
	Irrigation depth for three irrigations	40	mm
	Irrigation depth for WS treatment	20	mm
³ PAM	Cost	2.0	£ kg ⁻¹

Table 6.2 Variable costs of inputs for coriander and spinach in 2021

Source: ¹Watts Farms; ²(Alastair, 2021) ³SNF

The second set of economic costs are associated with machinery operations and personnel (Table 6.3). The machinery costs are given per hr, and include the driver's cost to the company, machinery's depreciation cost, maintenance, and fuel costs. The values listed were provided by Watts Farms, and checked against John Nix's Pocketbook (Graham, 2021) for consistency.

Category	Fixed Costs	Value	Unit
Land Preparation	^{1,2} Pre-season tillage	55.57	£ ha ⁻¹
	^{1,2} Hoeing	46.40	£ ha ⁻¹
	¹ Seedbed preparation (x2 passes)	67.62	£ ha ⁻¹
Seed Drilling	¹ Drill speed coriander	4.0	km hr ⁻¹
	¹ Drill speed spinach	7.0	km hr ⁻¹
	¹ Working capacity of seed drill	1	Seedbed
Irrigation	¹ Set up	1.	hr
	^{1,4} Irrigator speed	55	m hr ⁻¹
	^{1,2} Tractor	36.0	£ hr ⁻¹
	¹ Irrigator coil costs	43.2	£ hr ⁻¹
	^{1,4} Boom width (working capacity)	40	m

Category	Fixed Costs	Value	Unit
	^{1,4} Irrigations Coriander	3	No.
	^{1,4} Irrigations Spinach (PAM + Ca)	3	No.
	^{1,4} Irrigations Spinach (WS)	2	No.

Table 6.3 Fixed Costs of associated with coriander and spinach production in 2021

Source: ¹Watts Farms; ²Nyx Handbook; ³SNF; ⁴Derived from 2021 fieldwork

The cost of one irrigation is the sum of the volumetric cost of water, the setup and the Briggs Irrigator's cost. The water requirements are obtained by multiplying irrigation depth and surface irrigated by the water's cost m^{-3} . One irrigator can cover 40 m, equivalent of 20 seedbeds. The number of seedbeds covered per run determined the working capacity of the Briggs Irrigator, which, moving at a working speed of 60 m hr^{-1} to achieve a target speed of 55 m hr^{-1} was able to cover 1ha in 4:38 hrs, the net working capacity of the irrigator. Multiplying the net working capacity by the hourly cost of the Briggs Irrigator, gave the cost of irrigation ($\text{Cost}_{\text{irrigator}}$) addendum. The total cost of irrigation was calculated using Equation 6.2.

6-2 Cost Breakdown of one irrigation

$$\text{Irrigation } [\text{£ ha}^{-1}] = \text{Cost}_{\text{water}} + \text{Cost}_{\text{setup}} + \text{Cost}_{\text{Irrigator}} \quad \mathbf{6.2}$$

The setup cost is the hourly cost of a tractor driver operator times the average time that is necessary to move the irrigator from the adjacent land parcel, connect it to the hydraulic system on the final location, drag the coil and the boom across the field and open the boom.

Soil preparation costs were given per hectare, therefore this is simply the sum of tillage and hoeing costs. The value obtained being divided by the number of crop cycles.

Seeding includes the seedbed formation, seeder hourly cost, and the costs of seeds ha^{-1} . Unlike soil preparation, preparations for seeding need to be repeated at every crop cycle. The main components of these costs are the seeds, and the

machinery. The seed driller spaces the seeds using foam rolls that are able to distance the seeds as they drop from the seed reservoir, into tubing that inserts the seed under the soil surface. The entire system is mechanic, and the net working speed of the driller depends on the seed's diameter and how worn the foam rolls are that space the seeds. Given the potential error associated with costing this element and its limited relevance on PAM costings, this study considered the average speed of the driller to be 6 km hr⁻¹ for both spinach and coriander.

6.2.2 PAM costings

The operational costs of the PAM sprayer are comparable to any other sprayer and include set up, loading, PAM spray application and post-spray cleaning (shown in Table 6.4).

Category	Parameter		Unit
Sprayer's Settings	Water flow rate	6.00	l min ⁻¹
	PAM flow rate	0.42	kg min ⁻¹
	Speed 40 kg ha ⁻¹	3.0	km hr ⁻¹
	Speed 80 kg ha ⁻¹	1.5	km hr ⁻¹
	Speed 120 kg ha ⁻¹	1.0	km hr ⁻¹
	PAM tank volume	50	l
	Water tank volume	100	l
Fixed Labour Requirement	Preparation time	0.75	hr
	Cleaning time	1.5 - 2.5	hr
	Time per Tank Refill	0.05	hr
Accessory costs	Sprayer	55.44	£ hr ⁻¹

Table 6.4 PAM sprayer characteristics affecting operational costs associated with PAM spray application Source: All the values were derived from the 2021 Fieldwork.

The work capacity is based on observations made during the 2020 (Chapter 4) and 2021 (Chapter 5) field trials, and so are all the other costs and timings beside the hourly cost of the machinery. The total costs associated with the PAM application (Total Costs_{PAM}) were based on Equation 6.3

6-3 Cost Breakdown of one PAM application

$$Total\ Costs_{PAM} = PAM + fixed\ labour + Water + (net\ working\ capacity + refill\ time)hourly\ cost \quad 6.3$$

The fixed costs are linked to the sprayer routine checks and setup, plus its cleaning afterwards, they are independent of the quantity of PAM delivered. For the current prototype, which combines the seed drill with PAM sprayer, the working speed ($ha\ hr^{-1}$) is dictated by the PAM application rate $kg\ ha^{-1}$ as PAM flow rate was kept constant. The net working capacity is the time it takes to spray a linear hectare, a $1.8*5555\ m$ strip which equivalent to $1\ ha$, and is calculated as shown in Equation 4:

6-4 Net working Capacity

$$Net\ working\ capacity[hr\ ha^{-1}] = linear\ hectare / Speed_{Tractor} \quad 6.4$$

Where tractor speed is dictated by PAM application rate. The refill times are modelled on the water tank only. PAM refill time is assumed to be negligible. The $50\ l$ tank requires 1 to 2 refills to cover one ha, depending on the application rate (AR), assuming that PAM can be refilled at the same time as water. The number of water refills, are higher due to the limited tank volume. The water volume necessary to deliver PAMs is calculated as in Equation 6.5:

6-5 Volume of water required per hectare

$$Water\ [m^3\ ha^{-1}] = flow_{water} * \frac{linear\ hectare}{speed_{sprayer}} \quad 6.5$$

Where *Water* is the volume of water required per hectare, and $Speed_{sprayer}=Speed_{tractor}$ from equation 6.4. As Equation 6.5 shows, the amount of water delivered is dependent on the speed of the sprayer ($Speed_{sprayer}$). The water requirements as per summer 2021 were $0.67, 1.33$ and $2.00\ m^3\ ha^{-1}$ for $40, 80$ and $120\ ka\ ha^{-1}$ respectively, corresponding to 7, 14 and 20 refills. The PAM sprayer was originally designed to be retrofitted to the seed driller, as they have the same working width. However, during the 2020 and 2021 field trial, seed

drilling and PAM application were undertaken separately because it was not possible to synchronise the spraying and seeding speeds. Resulting in an increase in PAM application costs.

6.3 Results and Discussion

An array of economic scenarios are presented. The baseline economic scenario is a cost analysis of current management practices. It is not exhaustive, however, it provides a benchmark threshold to compare other crops and management practices to. An economic appraisal of the PAM application used during the field trials is also presented, breaking down the cost into categories and also considering the potential effect on costs of technical improvements to the sprayer.

6.3.1 Baseline scenario: no PAMs

For the Control treatments without PAM application, the cost of cultivating 1.0 ha of coriander and spinach based on the 2021 field trial treatments was 4122, 4140 and 3532 £ ha⁻¹ for Coriander, Spinach and Water Scarcity Spinach. The total estimated yield for the coriander and the spinach treatments was 7500 for Coriander and 7400 kg ha⁻¹ for Spinach regardless of water application, and the unit cost was 0.55, 0.56 and 0.48 £ kg⁻¹ for Coriander, Spinach and Water Scarcity Spinach, as shown in Table 6.5.

Trial	yield (kg ha ⁻¹)	cost ha ⁻¹	cost kg ⁻¹
Coriander	7500	4122	0.55
Spinach	7400	4140	0.56
Spinach Water Scarcity	7400	3532	0.48

Table 6.5 Baseline costs associated with Control Treatment for all 2021 Trials

A Baseline Scenario of PAM-treated plots

This economic evaluation considered all costs listed in Tables 6.1-6.4. PAM application costs range between £354 and £786 ha⁻¹ depending on application rate (Table 6.6). Table 6.6 shows the variation of costs connected with a PAM application as delivered during the 2021 field trial, accompanied with a breakdown of the three components: PAM polymer, Water and Machinery use

Trial	PAM (kg ha ⁻¹)	Total Crop Costs ^{1,2}		Baseline	Total PAM costs ⁵	Breakdown of PAM application costs		
						PAM product	Water	Machinery
		ha ⁻¹	kg ⁻¹			GBP ha ⁻¹	GBP ha ⁻¹	GBP ha ⁻¹
Coriander	0	4122	0.55	4122				
	40	4476	0.52		354	80	2.48	272
	80	4692	0.48		570	160	4.96	405
	120	4908	0.52		786	240	7.44	539
Spinach ³	0	4140	0.56	4140				
	Ca 80	4628	0.45		487	160	2.48	406
	80	4630	0.43		490	16	4.96	406
Spinach Water Scarcity ⁴	WS 0	3532	0.48	3532				
	WS 80	4022	0.46		490	16P0	4.96	406
	WS 120	4318	0.54		786	240	7.44	539

Table 6.6 Cost breakdown of PAM application for the coriander and spinach trials conducted in 2021 as compared with the respective untreated controls

¹Data from the 2021 Field Trial; ²Personal Communication from Watts Farm; ³Conventional irrigation ⁴Modified irrigation (water stress (WS)); ⁵SNF. For each trial, Yield (kg ha⁻¹), Total crop cost (£ ha⁻¹) and Total unit cost (£ kg⁻¹) values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and post-hoc Fisher LSD analysis based on the 2021 yield data for each treatment (Ref. Chapter 5).

Coriander showed a cost kg⁻¹ reduction with all PAM application rates (AR), due to a yield increase, which was significant for 80 and 120 kg PAM ha⁻¹. The cost kg⁻¹ decreased from 0.55 to 0.48 and 0.52 £ kg⁻¹ for 80 and 120 kg PAM ha⁻¹ plots (-13 and -7% respectively). Conventionally irrigated Spinach showed a significant decrease from 0.56 to 0.45 and 0.43£ kg⁻¹ for Calcium-enhanced PAM and PAM only, both at 80 kg ha⁻¹ (-20 and -24% respectively). Water Scarcity Spinach however, had a lower baseline cost and showed a 5% decrease at 80 kg PAM ha⁻¹ and a 13% increase at 120 kg PAM ha⁻¹, corresponding to an increment from 0.48 to 0.46 and 0.54 £ ha⁻¹ respectively.

6.3.2 Isolating compressible cost categories and testing them in different scenarios

PAM application costs represent 9.2 – 19.3% of the total crop cost, ranging from £354 - £786 depending on Application Rate (Table 6.6, PAM Total Costs). In addition to the variation of production costs, Table 6.6 also offers a breakdown of PAM-related costs that can be used to identify potential for additional optimisation of the process.

Polyacrylamides are used extensively as a waste-water treatment flocculant and are commercially widely available. As a consequence, although it is being applied in a novel way, it benefits from a well-established production and logistics system that can support PAM delivery without the initial costs associated with setting up a new production line. The costs are therefore known and easy to predict. This “commodity status” is not compressible and allows PAM to have a unit cost as low as 2.0 £ kg⁻¹ (spoken communication from SNF, May 2022). The cost of PAM product application accounts for 23, 29 and 31% of the total PAM application cost. The other two cost categories, water use and machinery (Table 6.6) are areas where improvements in costs savings could be made.

Machinery costs (hourly rate times number of hrs required to apply each treatment per ha) represented the major component of cost associated with PAM application, at £272, £405 and £539 for 40, 80 and 120 kg ha⁻¹ respectively (Table 6.6). This equates to 69 - 77 % of the overall PAM application related costs, inversely proportional to AR.

Water use costs are negligible, due to the low volume needed for spraying operations, which ranges from 0.67 to 2 m³ with the current setup (= 2.4 to 7.4 £ ha⁻¹). However, the small dimensions of the water tank on the current PAM sprayer prototype, require the machine operator to stop up to twenty times per ha to refill the water tank, resulting in a loss in working capacity of 0:33, 1:06 and 1:35 hrs ha⁻¹ for the 40, 80 and 120 kg PAM ha⁻¹ treatments respectively. This increase in labour time, results in a cost of £30, £62 and £92 for the 40, 80 and

120 kg PAM ha⁻¹ treatments respectively (= 10.3, 12.0 and 12.6% of the PAM application cost, depending on PAM's AR).

6.3.3 Opportunity for Optimisation

Three potential opportunities for optimisation of PAM application costs are considered, (1) fitting the sprayer on the back of the seed drill to reduce the number of machinery passes, (2) optimising nozzle water use efficiency, and (3) increasing working capacity by working more seedbeds in a single pass.

6.3.4 Cost saving scenario 1: Retrofitting the PAM sprayer to the seed drill

During the 2021 field trials, the priority was to obtain a homogenous layer of PAM and water, therefore the sprayer operated at a low speed (1.0 – 3.0 km hr⁻¹) and flow (Table 6.4), resulting in spraying times of between 2.41 to 7.22 hr ha⁻¹ depending on the speed of the sprayer and cumulative refill time. The net savings are calculated by multiplying the net working capacity [hr ha⁻¹] by the hourly cost of the sprayer (£ hr⁻¹). The potential cost savings that could be achieved by retrofitting the PAM sprayer to the seed drill are shown by comparing Table 6.6 and 6.7.

Retrofitting the sprayer on the back of the seed drill optimises the working hours of the tractor driver and increases the working speed (to circa 4-7 km hr⁻¹), on a premise that the sprayer is still broadcasting a homogenous layer of PAM at higher sprayer speeds, resulting in savings in machinery costs of 158, 261 and 363.4 £ ha⁻¹ for 40, 80 and 120 kg PAM ha⁻¹ respectively. These savings in machinery costs correspond to 45, 46 and 47% of the total cost of PAM application compared to the baseline scenario.

Test	Treatment	Total Crop Costs ^{1,2}		Baseline	Total PAM costs ⁵	Break down of PAM application costs		
		ha ⁻¹	kg ⁻¹			PAM Polymer	Water	Machinery
		£ ha ⁻¹	£ kg ⁻¹	£ ha ⁻¹	£ ha ⁻¹	£ ha ⁻¹	£ ha ⁻¹	£ ha ⁻¹
Coriander	Control	4122	0.55	4122				
	40	4318	0.51		197	80.00	2.48	114
	80	4432	0.45		310	160.00	4.96	145
	120	4545	0.48		423	240.00	7.44	176
Spinach ³	Control	4140	0.56	4140				
	Ca 80	4368	0.42		227	80.00	2.48	145
	80	4370	0.40		230	80.00	4.96	145
Spinach Water Scarcity ⁴	WS Control	3532	0.48	3532				
	WS 80	3762	0.43		230	80.00	4.96	145
	WS 120	3955	0.49		423	240.00	7.44	176

Table 6.7 Cost breakdown of PAM application with a sprayer retrofitted on the back of a seed driller, the Baseline costs are associated with the Conventional practices in Place at Watts Farms

¹Data from the 2021 Field Trial; ²Personal Communication from Watts Farm; ³Conventional irrigation ⁴Modified irrigation (water stress (WS)); ⁵SNF. For each trial, Yield (kg ha⁻¹), Total crop cost (£ ha⁻¹) and Total unit cost (£ kg⁻¹) values followed by the same letter are not significantly different (p<0.05) following One-Way ANOVA and post-hoc Fisher LSD analysis based on the 2021 yield data for each treatment (Ref. Chapter 5).

The reduction in cost is seen in the unitary price, which decreases from 0.55 (Control) to 0.51, 0.45 and 0.48 £ kg⁻¹, for 40, 80 and 120 kg PAM ha⁻¹ on Coriander, whereas for Conventional Spinach, the costs decrease from 0.56 £ kg⁻¹ for Control, to 0.42 and 0.40 £ kg⁻¹ for Ca-PAM and PAM only, as shown in Table 6.7 (-23 and -28% respectively). The reduction in machinery costs did not reverse the trend shown in Water Scarcity Spinach, characterised by a drop in costs for 80 kg PAM ha⁻¹ but by an increase for the 120 kg PAM ha⁻¹ treatments (-10 and +5% respectively corresponding to 0.43 and 0.49 £ kg⁻¹ versus Control's 0.48). The Water Scarcity Spinach, which had one less irrigation event (608 £ ha⁻¹ per irrigation event) decreased the base line production cost per ha. As a consequence, to be cost effective, PAM had to meet the lower unitary cost

caused by one less irrigation, causing the treatment not to be effective, with such small variations of yield.

6.3.5 Cost Saving Scenario 2: Optimisation of Water Use During PAM Application

This scenario builds on the improvements suggested in Scenario 1. The sprayer is retrofitted on the back of the seed driller, and an improvement in the water use efficiency of the nozzle, allowing homogenous PAM broadcast onto the soil surface at faster speeds (4-6 km h⁻¹).

While the co-applied water required to carry PAM to the soil has a negligible volumetric cost, it has logistical challenges. Beyond the hourly costs associated with the refill time required by the current prototype, the requirement for co-applied water implies the need for a water source near the field plot to which PAM is to be applied. If this is not available transporting a portable reservoir (e.g. IBC) to the field may be required, or changes in irrigation infrastructure (e.g. instillation of a mains tap closer to the irrigation pipes). All of these actions and decisions have a cost implication.

As a consequence, the main improvement associated with this scenario would be the quantity of water needed per kg of applied PAM, associated with better setup and cleaning procedures of the sprayer after use. For example, improvements could include increasing the water tank dimension to 0.25 m³ and the PAM tank to 0.1 m³. This scenario assumes an improvement of water use by 20% and of the sprayer setup and cleaning times from 2.5 to 1.5hr.

For consistency with the previous scenarios, this iteration still assumes a 1.0 ha plot and not a smaller sized plot more common in Watts Farm. Consequently, there will be a need to refill the tank. Table 6.8 shows the cost projection of Scenario 2.

Test	Treatment	Total Crop Costs ^{1,2}		Baseline	Total PAM costs ⁵	Break down of PAM application costs				
		ha ⁻¹	kg ⁻¹			£ ha ⁻¹	£ ha ⁻¹	PAM Polymer	Water	Machinery
Coriander	Control	4122	0.55	4122						
	40	4230	0.50		178	80.00	2.48	95		
	80	4395	0.45		273	160.00	4.96	108		
	120	4490	0.47		368	240.00	7.44	120		
Spinach ³	Control	4140	0.56	4140						
	Ca 80	4331	0.42		190	80.00	2.48	108		
	80	4333	0.40		193	80.00	4.96	108		
Spinach Water Scarcity ⁴	WS Control	3532	0.48	3532						
	WS 80	3725	0.42		193	80.00	4.96	108		
	WS 120	3900	0.49		368	240.00	7.44	120		

Table 6.8 Cost breakdown of PAM application for a sprayer fitted on the back of a seed driller, and characterised by an improved water-use efficiency (Scenario 2)

¹Data from the 2021 Field Trial; ²Personal Communication from Watts Farm; ³Conventional irrigation ⁴Modified irrigation (water stress (WS)); ⁵SNF. For each trial, Yield (kg ha⁻¹), Total crop cost (£ ha⁻¹) and Total unit cost (£ kg⁻¹) values followed by the same letter are not significantly different (p<0.05) following One-Way ANOVA and post-hoc Fisher LSD analysis based on the 2021 yield data for each treatment (Ref. Chapter 5).

Compared to Scenario 1, in Coriander, the decrease in cost per unit would be 0.01 £ for 80 and 120 kg ha⁻¹ only (ca. 2% of total costs). For the 2021 PAM treatments applied to coriander this would result in a reduction per unit costs from the Control value of 0.55 £ kg⁻¹ to 0.50, 0.45 and 0.47 £ kg⁻¹ for the 40, 80 and 120 kg PAM ha⁻¹ treatments, respectively (Table 6.8). This equates to -8, -19 and -15% reduction in per unit costs for the 40, 80 and 120 kg PAM ha⁻¹ respectively. For the 2021 Conventionally Irrigated Spinach treatments, unitary costs would decrease from 0.56 £ kg⁻¹ in the Control to 0.42 and 0.40 £ kg⁻¹ for the 80 and 80+Ca kg PAM ha⁻¹ treatments (Table 6.8). Whereas for the Water Scarcity Spinach it would drop from 0.48 to 0.42 £ kg⁻¹ for 80 kg PAM ha⁻¹ but increase to 0.48 £ kg⁻¹ for 120 kg PAM ha⁻¹ treatment. Costs savings associated with the higher application rate treatments are greater due to a reduction in the number of

times the tank has to be refilled. The optimised refill time would further decrease the Machinery costs to 95.48, 107.80 and 120.12 £ ha⁻¹ (Table 6.8), halving PAM application costs, 50, 52 and 53% compared to the Base Scenario for the 40, 80 and 120 kg PAM ha⁻¹ treatments, respectively.

The water tank dimensions is key, especially if the sprayer is to be retrofitted on a seed driller. The optimal number of refills is ≤ 4 , as this corresponds to the number of times needed to refill the seeder. The second key challenge would be to ensure an even PAM application at the same working speed as the seed driller.

For example, increasing the working speed to the average speed of the seeder at Watts Farm (5 km h⁻¹) would require the sprayer to be able to deliver 2 to 5 times the amount of water and PAM mixture in order to achieve the target ARs. Alternatively, the additional application rate could be achieved using multiple nozzles, arranged in two or three rows. However, this design would increase the sprayer's bulk and weight, affecting its practicality.

6.3.6 Cost saving scenario 3: Increasing boom width to cover multiple beds

Retrofitting the sprayer to the back of a seed driller, limits its working capacity to a single seedbed row. Scenario 3 shows the costs associated with detaching the sprayer from the seed driller and increasing its boom length, and therefore working capacity, to four seedbeds, corresponding to a boom width of 8 m. In this scenario working capacity can be increased without having to increase the speed of the sprayer, which implies not doing and nozzle development.

Scenario 3 is based on having a 0.25 m³ water tank and 0.1 m³ PAM tank. The sprayer speed would be equivalent to Scenario 1 (3, 1.5 and 1 km hr⁻¹ for 40, 80 and 120 kg PAM ha⁻¹ respectively). With an optimised 1.5 hr setup and cleaning time.

Extending the boom width affects the working capacity of the sprayer. If one linear hectare equals to a 5555 m long strip, with a 4-seedbeds boom, one linear hectare equals to a 1388 m long strip, (excluding wheelings). At a travel speed

consistent with Scenario 1, working time would be reduced from 1.85-5.56 hr ha⁻¹ to 0.46- 1.39 hr ha⁻¹ resulting in a machinery cost between 119 (40 kg ha⁻¹) and 197£ ha⁻¹ (120 kg ha⁻¹) (Table 6.9) corresponding to 25, 51 and 77 £ ha⁻¹ of machinery costs excluding cleaning and tank refills. All the results are showed in Table 6.9.

Test	Treatment	Total Crop Costs ^{1,2}		Baseline	Total PAM costs ⁵	Break down of PAM application costs		
		ha ⁻¹	kg ⁻¹			PAM Polymer	Water	Machinery
		ha ⁻¹	kg ⁻¹	£ ha ⁻¹	£ ha ⁻¹	£ ha ⁻¹	£ ha ⁻¹	£ ha ⁻¹
Coriander	Control	4122	0.55	4122				
	40	4323	0.51		206	80.00	2.48	118
	80	4445	0.45		323	160.00	4.96	158
	120	4567	0.48		445	240.00	7.44	197
Spinach ³	Control	4140	0.56	4140				
	Ca 80	4380	0.43		240	160.00	2.48	158
	80	4383	0.40		243	160.00	4.96	158
Spinach Water Scarcity ⁴	WS Control	3532	0.48	3532				
	WS 80	3775	0.43		243	160.00	4.96	158
	WS 120	3977	0.50		445	240.00	7.44	197

Table 6.9 Cost breakdown of PAM application using a sprayer covering 4 seedbeds (Scenario 3)

¹Data from the 2021 Field Trial; ²Personal Communication from Watts Farm; ³Conventional irrigation ⁴Modified irrigation (water stress (WS)); ⁵SNF. For each trial, Yield (kg ha⁻¹), Total crop cost (£ ha⁻¹) and Total unit cost (£ kg⁻¹) values followed by the same letter are not significantly different (p<0.05) following One-Way ANOVA and post-hoc Fisher LSD analysis based on the 2021 yield data for each treatment (Ref. Chapter 5).

Scenario 3 shows the same trends but slightly different costs as the previous scenarios. The unitary cost decreases for every PAM-treated plot excluding WS Spinach applied at 120 kg ha⁻¹. Coriander associated costs drop from 0.55 to 0.51 and 0.45 £ ha⁻¹ (80 and 120 kg PAM ha⁻¹ respectively) equivalent to Scenario 2, for the optimal single seedbed layout. Machinery cost is still the most relevant variable, contributing to 59, 48 and 44% of the total costs connected with PAM application (equal to 118, 157 and 197 £ ha⁻¹ for 40, 80 and 120 kg PAM ha⁻¹

respectively). The Machinery costs are comparable to the ones from Scenario 2 (Figure 6.1), characterised by the same water tank capacity and nozzle behaviour. The maximum difference is circa £21 £ ha⁻¹, making this scenario a good alternative if the nozzle improvements theorised in Scenario 3 are not attainable.

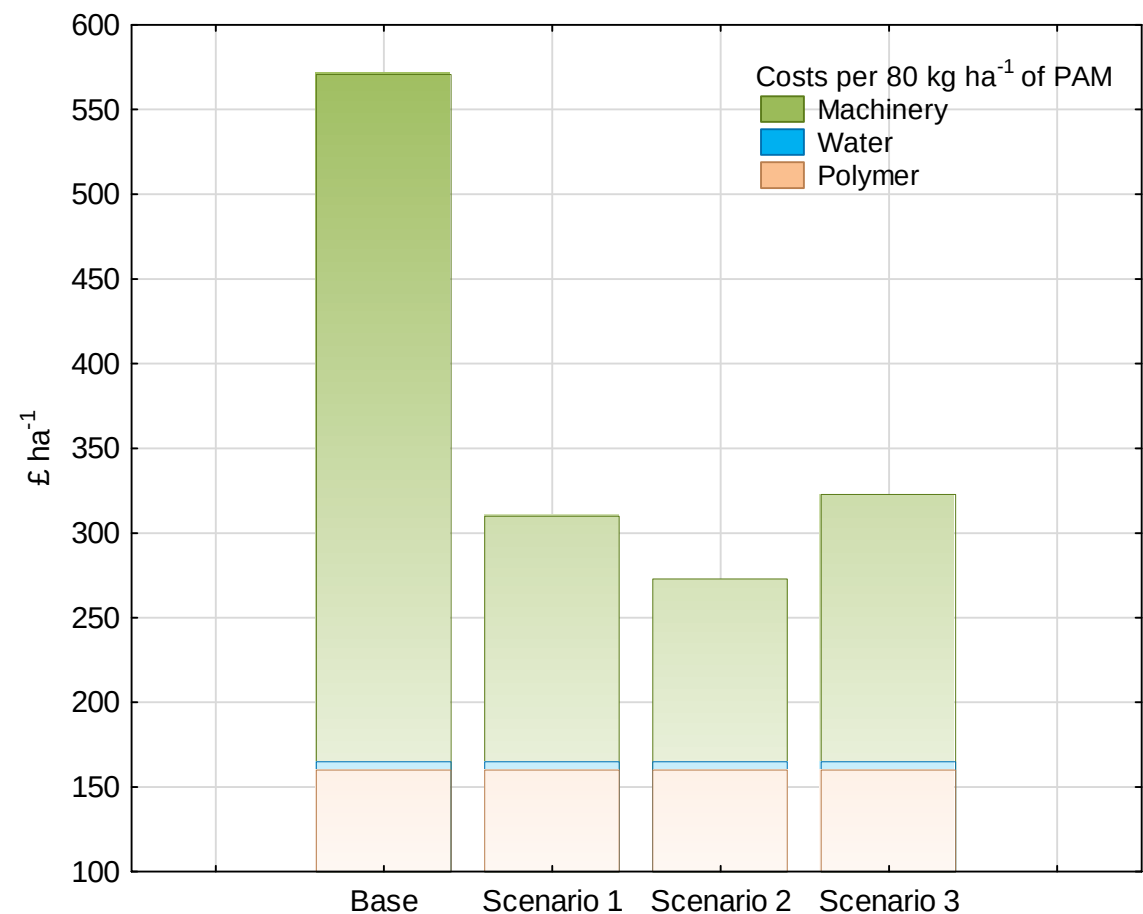


Figure 6.1 Cost comparison between scenarios associate with 1 ha of PAM application at 80 kg ha⁻¹. The costs associated with the prototype used in 2021 correspond to the baseline.

Moreover, having the sprayer run as an autonomous piece of equipment, whilst increasing running time, fits within the current workforce specialisation in place in WattsFarm, where Seed Drillers and Pesticide Spraying are operated by different personnel (WattsFarm, Spoken Communication, 2020).

6.4 Conclusions

Chapter 5 demonstrated that the spray application of PAM is practical in a commercial setting, and contributes to significant improvements in emergence homogeneity, stand establishment and yield. This economic analysis confirms that PAM application also has financial benefits to the farmer. The cost improvements modelled on the three optimisation scenarios can help to quantify the magnitude of future improvements both on the sprayer's design, and on the nozzle. PAM's efficacy and efficiency are strongly linked to additional costs, like cleaning and maintenance due to the hygroscopic nature of the PAM, that requires a different handling approach from the operator, and cannot separate from a design that prioritise safety and ease of use. Machinery costs were found to be the most easily modified PAM-related costs.

This economic appraisal also suggests that the application of PAM may also have relevance in relation to water use efficiency in an arid and semiarid context, where costs connected with water volume and logistics might increase the price per irrigation.

Polyacrylamide production facilities are already well established because of their relevance in waste-water treatment. As a consequence, PAMs provision costs are similar to the ones of a well-established commodity, rather than ones of a new technology. Scenario 1 and 2 require Research and development on nozzle, water and PAM ratios, and on spraying speed. Scenario 3 potentially can be implemented in a short time by upgrading the pumps and the hydraulic system, as well as welding a longer boom. However, nozzle development (including PAM:water ratio and PAM broadcast homogeneity), and spraying speed remain two key areas to be improved, regardless of costs.

6.5 References

Alastair, B. (2021) *The farm management handbook 2020/2021*. 2021st edn. Edited by A. Beattie. Penicuik: SAC Consulting. Available at: www.sruc.ac.uk/fmh.

DEFRA (2020) *Food Statistics in your pocket: Food Chain* - GOV.UK, Food

Statistics in your pocket: Food Chain. Available at: <https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-food-chain>.

DEFRA (2022) *Wholesale fruit and vegetable prices series 2015 to 2022*. London. Available at: <https://www.gov.uk/government/statistical-data-sets/wholesale-fruit-and-vegetable-prices-weekly-average>.

FAO (2017) *The future of food and agriculture: trends and challenges, The future of food and agriculture: trends and challenges*. Rome. Available at: www.fao.org/publications%0Ahttp://www.fao.org/3/a-i6583e.pdf%0Ahttp://siteresources.worldbank.org/INTARD/825826-1111044795683/20424536/Ag_ed_Africa.pdf%0Awww.fao.org/cfs%0Ahttp://www.jstor.org/stable/4356839%0Ahttps://ediss.uni-goettingen.de/bitstream/han.

Graham, R. (2021) *John Nix Pocketbook for Farm Management*. Edited by The anderson Centre. Melton Mowbray.

Nicholson, C. (2012) *The relationship between supermarkets and suppliers: What are the implications for consumers ?, Consumers International*. Available at: [https://www.farminguk.com/content/knowledge/consumers and supermarkets.pdf](https://www.farminguk.com/content/knowledge/consumers%0Ahttps://www.farminguk.com/content/knowledge/consumers-and-supermarkets.pdf).

7 Synthesis, Conclusions and Recommendations

Abstract

According to the Sustainable Crop Production Intensification (SCPI) a Food System can be defined sustainable firstly if it meets the dietary requirements to feed humanity (FAO, 2009). Field-grown leafy greens are providing fresh produce at affordable prices (DEFRA, 2020b). However, to achieve an increased provision of food can be costly in terms of non-traded ecosystem services. These are benefits for the community that are not monetarily recognised to the farmer. This chapter will firstly recap how this research has addressed key knowledge gaps. Secondly, it will consider PAM application in the leafy green and field grown herb sector in relation to the ecosystem services delivered by the land and within the Sustainable Development Goals (SDG) in the wider agronomic trends. Lastly, it will make recommendations for future research.

7.1 Intensification of Leafy Greens Affects Soil Health

Conventional intensive agriculture tends towards privileging one single provisional Ecosystem Service (ES) (Reid *et al.*, 2005), and often comes with a trade-off of other provisional, supporting or regulating ESs (Stoate *et al.*, 2001). Food Production negatively affects ES such as Water Availability and Quality, Carbon Sequestration, and soil formation (Reid *et al.*, 2005; Lal, 2009; Al-Kaisi and Lal, 2020). Particularly, in Intensive Leafy green horticulture, the intensive soil management regime affects acutely soil-related ESs, that results in on-field long term effects, such as Soil organic matter (SOM) oxidation and loss, depletion of the organic matter pools on the soil (Lal, 2016) that evolve in poor soil structure, leading to soil capping and sealing. In natural and rangeland ecosystems soil crusting is a desertification precursor (Fox, Bryan and Price, 2004), whereas in agricultural ecosystem, especially in temperate areas, the effects consists of uneven emergence, splash contamination of stems and misused water resources. As shown in literature (Stoate *et al.*, 2001; Bronick and Lal, 2005; Pagliai and Stoops, 2010) and in previous chapters (2, 3, 4 and 5), intensively-grown leafy greens can be disruptive to soil, but this high-input management

system is somewhat justified by the end product: an affordable (DEFRA, 2022), micronutrient-rich (Subhasree *et al.*, 2009; Mirdehghan, 2010; Khair *et al.*, 2012) produce that is ready for the distribution market. The diet shift from a calorie to a nutrient-dense calorie is necessary in the populations that are benefitting from increased mechanisation and tend not to consume as many calories as their pre-industrialisation ancestors fits with the human wellbeing in relation with the ecosystem services (Reid *et al.*, 2005).

As a consequence, any loss of yield due to subpar emergence or due to soil borne diseases, as well as the cost of any operation that the farmer has to do in order to remediate the effects of soil degradation, have a cost, and that cost reflects on the final product, and therefore on the final citizen. Any increase on the final cost of produce, offsets the primary ecosystem service that justifies such an intensive agriculture practice: provision of affordable, nutrient-dense food.

The key knowledge gaps were addressed in this research where:

- Delivery dynamics of PAM and Water sprayed using a dual-fluid nozzle
- Determination of the PAM formula to be applied with the dual-fluid nozzle
- If PAM applied with the dual-fluid nozzle withstands multiple simulated rainfall events
- If spraying PAM is an implementable operation in commercial context
- If PAMs are effective in mitigating the agronomic effects of soil capping and sealing on-field
- If the yield increments correlated to a single PAM application in commercial context are cost-effective

The aim of this research was to critically evaluate the efficacy of a novel Dual-Fluid PAM sprayer to deliver PAM to the immediate soil surface to minimise the agronomic impact of soil crusting on high value horticultural crops.

Chapter 1 laid the foundation for this research and identified key knowledge gaps. The literature review evaluated the performance of a range of soil conditioners, and focused on Polyacrylamides (PAMs), with particular attention on

mechanisms of PAM sorption, delivery options explored in the past, and current practices. This review highlighted how PAMs have been investigated for >40 yrs, yet have been primarily and successfully applied in furrow-irrigated arable crops. The number of publications investigating the effect of their application in other contexts, such as sprinkle-irrigated systems, or sowed in a granular form to soil with or prior to drilling seeds to facilitate emergence of fine-seeded crops, suggests an interest in the topic. The efficacy of PAMs to prevent and/or reduce crusting and promote emergence has largely been confirmed in laboratory studies. The scarcity of publications investigating field-based PAM application in a commercial and practical context despite multitude delivery options, suggests that the real limit to the effective use of PAMs is in practical and affordable delivery. No laboratory or field-based research had previously been undertaken to investigate PAM application using Dual-Fluid nozzles and no research had investigated the use of PAMs in intensive high value baby leaf or field grown herb productions systems.

Chapter 2 and 3 investigated in the laboratory an innovative Dual-Fluid PAM-spraying technology. In Chapter 2, this explored a set of metrics to be used effectively in lab and on-field. methodological approaches to evaluate the effect of PAM application on rainfall/irrigation-induced soil crusting were critically investigated. Chapter 2 also identified the most crust susceptible soil that would be taken forwards into further laboratory (Chapter 3) and 2020 and 2021 field trials (Chapters 4 and 5). Key findings were:

Instron Penetrometer (T-5001 manufactured by J.J. Lloyd Instruments Ltd) and 3D scanner (Creaform EXAScan) where the most effective tools in measuring soil crust.

Soil 2, a Clay loam with 67.4% quartz in its ashes was found the most crust-susceptible.

Chapter 3 built on the research outcomes from Chapter 2, and evaluated the efficacy of three contrasting PAM formulations to mitigate soil crusting when subjected to two simulated irrigation events typically applied to baby leaf and field

grown herbs to promote germination and prevent dehydration of structural seals and crust formation. This included the identification of appropriate application rates to carry forward into field trials. The crust susceptible soil investigated in Chapter 3 combined with the KE associated with the simulated irrigation events indicated that the PAM applications rates investigated were able to mitigate but not prevent crust formation. Consequently, high PAM application rates were investigated in the 2020 and 2021 field trials. The key findings were:

PAM is more homogeneously broadcasted at lower (1-2 atm) water pressures.

One PAM formula (anionic concentrated suspension) performed better than the other two.

Chapter 4 and 5 focused on PAM application during the 2020 and 2021 replicated field trials.

Chapter 4 had a broader, explorative aim. The hypotheses included:

- If Sprayed PAM is effective in protecting the surface of the seedbeds against sealing and splash detachment.
- If Sprayed PAM is effective in regulating the soil moisture loss after irrigation.
- If sprayed PAM has a positive effect in emergence homogeneity and in yield.

These research hypotheses were investigated using a suite of crust susceptibility metrics initially adopted in Chapter 2 and 3. The instruments that were so precise and accurate under laboratory conditions namely, the Instron tensiometer (Instron 5542) and the hand-held laser scanner (Creaform EXAScan 3D hand-held laser scanner), were not transferable to the field. The field-based instrument (Pocket GeoTester), although confirmed in literature (Callebaut *et al.*, 1985; Jester and Klik, 2005; Lehrs, Lentz and Kincaid, 2005) was not effective in capturing the strength of the soil crust. The 3D scanning on field using the hand held EXAScan from Chapters 2 and 3, similarly could not work on the field because of the strong solar radiation interfering with the laser. In the 2020 field

trials (Chapter 4) the efficacy of sprayed PAM was evaluated with the following metrics: splash detachment, Hydraulic Conductivity, Soil moisture (10 cm depth) and surface temperature, emergence count, and yield quantity. Key research outcomes from Chapter 4 include:

Spraying PAM using the dual-fluid nozzle fits in the timing and logistics of intensive leafy green horticulture.

Sprayed PAM is associated with higher soil moisture after up to two irrigations.

In some metrics (emergence, yield) spatial variability created by slope position and heterogeneous irrigation outweighed the effect of PAM on the performance metrics investigated. However, the 2020 field trials demonstrated that PAM (SFA 30) can be successfully applied to the soil surface using Dual-Fluid nozzles. This has the potential to reduce the quantity of irrigation water required to successfully grow commercial crops of coriander.

Chapter 5 focused on the 2021 field trials. The experiment design and setup was improved to minimise topographic and irrigation heterogeneity that impacted the 2020 field trials. Chapter 5 re-visited several research hypotheses from Chapter 4 and also investigated additional application rates as well as co-application of di-valent cations to promote PAM sorption. In addition, the potential to omit one of the pre-emergence irrigations conventionally adopted to prevent crust formation was investigated in order to improve water use efficiency.

The 2021 field trials provided further validation that PAM (SFA 30) can be successfully applied to the soil surface using Dual-Fluid nozzles. Key research outcomes from Chapter 5 include:

If Sprayer PAM can mitigate the agronomic effects of soil capping and sealing by layering a polymeric film on the soil surface.

If adding a divalent cation, anionic PAM is more effective at mitigation the agronomic effects of soil capping and sealing.

If PAMs characteristics as soil moisture regulator have an effect on soil structure, emergence and yield when the crop receives 33% less water-

the key conclusions are:

The polymeric mesh created on the soil surface protects it against splash erosion, also at lower (40 kg ha^{-1}) application rates.

Earlier emergence was observed in coriander, higher overall stand establishment was observed in Spinach.

Better emergence resulted in higher yields.

Chapter 6 investigated and quantified the potential financial benefits of a single post-drilling, pre-emergence application of PAM (SFA 30) on both spinach and coriander. Recommendations to further improve the cost-effectiveness of PAM application are discussed.

The cost benefit analysis identified the costs connected with PAM application that cannot be reduced, (PAM product cost, the hourly cost of manpower, the cost of water) from the variable costs (working capacity, sprayer speed) and quantified the savings associated with different evolutions of the sprayer. Key research outcomes from Chapter 6 include:

Yield uplift associated with PAM application offsets PAM application costs under the current agronomic practices adopted by Watts Farms.

Increasing the size of the sprayer would be the quickest short-term cost improvement, however, research and development on the nozzle is still strongly advised.

7.2 PAMs application in the context of providing of ecosystem services

The earth's resources are finite and the human population is growing (Zafar *et al.*, 2005). Considering climate change, a 30-62% increase in food production

from the existing global landbank is required to meet the needs of a growing world population by 2050 (Dijk *et al.*, 2021). Most of the yield growth will be needed in developing countries to sustain the evolution of their economies and will need to be coupled with optimisation of transport and storage. However, annual increases of grain yields are projected to drop from 5, to 3, to 1% by 2050 (FAO, 2009).

The first three Goals of the United Nations' Sustainable Development Goals (SDG), are No Poverty, Zero hunger and Good Health and Wellbeing. This research has demonstrated how PAM application can increase yields and reducing costs for the farmer, allowing a nutrient rich product to be available at an affordable price. However, the addition of synthetic polymers, likely coming from non-renewable resources, does not really fit in the model of sustainable agriculture (Hill, 1985; Pretty, 2020) that advocates for a reduction of external inputs. The three non-linear principles of sustainable intensification are based on (i) Efficiency - optimisation of existing inputs, e.g. GPS-guided precision agriculture - (ii) substitution - switching one input for a more productive one, e.g. mechanisation, or the advent of hybrid maize clones in the 60s - and (iii) redesign - radical change of the production system, where efforts are spent in maintaining and/or improving existing balances and natural capital, rather than exploiting them (Hill, 1985). The PAM application explored in this research is designed to fit in the current agronomic practices for baby leaf and field herbs, increasing emergence, yields and improving water use efficiency. It therefore fits between Efficiency and Substitution. According to Hill and Pretty (1985, 2020) PAMs should be considered a weaker tool towards achieving sustainable intensification goals, as it is not a radical change - redesign.

The two first principles are the easiest to implement, however they rarely achieve the optimal co-existence of different ecosystem services that could be achieved with redesigning a production system (Sandhu *et al.*, 2015). Pretty (2018, 2020) argues that redesigning is a radical change that must be achieved by groups of farmers, rather than singular players and potentially requires elevated social capital to be effectively implemented.

The stigma around the use of synthetic soil conditioners is tangible across several publications comparing PAM with alternative biopolymers, such as cellulose, guar gum, xanthate (Orts, Sojka and Glenn, 2000; Maghchiche, Haouam and Immirzi, 2009, 2010, 2013; Lentz, 2015a). Even where biopolymers have shown a comparable efficacy, they are still not yet economically unviable as compared with PAMs (Orts, Sojka and Glenn, 2002). Polyacrylamides are a widely used flocculant in waste water treatments (SNF, 2021), therefore the production facilities, the synthesis processes and their logistics are a mature technology that already has offset most of the research and development costs that would be required for biopolymer development. Sustainability is also a concern in wastewater science, which is now investigating the use of renewably-sourced flocculants. However, due to their reduced efficacy at the same dosage and reduced shelf life, biopolymers are not as cost effective as their synthetic counterpart. The solution currently explored is to graft biopolymers onto synthetic flocculants, (e.g. to PAMs), to obtain alternatives that are more environmentally-friendly whilst keeping the efficacy of conventional molecules (Siah, Robinson and Fong, 2014).

Whilst being self-sufficient in several categories, such as grains, eggs and poultry, in 2021, the UK imported 50% of its fresh vegetables (DEFRA, 2021b). In 2020, most of the horticulture products imported came from the EU (DEFRA, 2021b). Trade is usually a driver for efficient use of natural resources and is actively promoted in the pursuit of a more efficient global food system (FAO, 2022). However, two recent geopolitical changes in the asset of food marked are increasing stress on the UK food supply chain. Firstly, the recent change in trading norms between the EU and the UK has drastically increased transportation costs (paperwork, time at the border, customs) associated with produce. This has direct impacts on shelf-life and is a key driver for self-sufficient production systems. Secondly, the recent fragmentation of global trade is going to affect the provision of agriculture commodities, such as fertilisers and fuel from Russia, and grains, from Ukraine, a net food exporter (FAO, 2022). As market fragmentation is likely to limit the availability of commodities and fresh produce

from overseas, the ability to produce high nutrient density crops efficiently becomes key to ensuring adequate food provision to the community.

7.3 Conclusions

This research found most effective dose to be an 80 kg ha⁻¹ application in pre-emergence. Technical improvements on the sprayer can furtherly decrease costs associated with sprayer's speed and cleaning operations afterwards. Central to the concept of all types of sustainable systems is an acceptance that there will be no perfect end point due to the multi-objective nature of sustainability (Pretty, 2018). The main ecosystem service, the provision of nutrient-dense food is an important contributor to the wellbeing of humanity, a key objective in the millennium assessment and in the sustainable development goals (Reid *et al.*, 2005; FAO, 2021b). The concept of sustainable intensification should be open, emphasising values and outcomes rather than means, applying to any size of enterprise, and not predetermining technologies, production type, or particular design components (Pretty, 2020). No solution is fit for every ecosystem. PAM application is no different. However, this research has demonstrated that PAM has great potential, especially in terms of food security and soil erosion control. Refusing to use an available and effective technology in agriculture because it is not organically sourced, whilst leaning on the same very molecules in wastewater treatment, is incongruous. Finally, the innovative Dual-Fluid spray technology tested and validated in this research can theoretically be used to deliver PAMs, biopolymers or a combination of the two when challenges of high viscosity prohibit conventional approaches.

7.4 Recommendations

The evidence produced in this research highlights the potential benefits of Polyacrylamide (PAM) spray application both in terms of ecosystem services, sustainable development goals and profitability for the farmer. Further time and effort must be spent perfecting the sprayer, improving practicality and delivery speed. In particular, a study on PAM drop size distribution and coverage assessment would allow the optimal ratio between water and PAM application to

be isolated. Although 80 kg PAM ha⁻¹ has been proven to be the most effective application rate, little is known about the performance of different PAM:water ratios and different PAM:carrier ratios in the formula to be used on the field.

Secondly, PAMs' effect has been explored only in two relatively fast-growing species high value crops namely spinach and coriander. However, parsley and other fine seeded crops such as onions, leeks, carrots, and lettuce have a longer emergence time. These seeds require intensive cultivations to create a fine seedbed typically on crust susceptible soils. The application of PAM pre-emergence is likely to have benefits to emergence, stand establishment and yield.

Thirdly, the potential soil moisture regulation benefits associated with PAM application that were only partially explored in the current research need to be systematically trialled both in the UK and under semiarid environments. Although not directly suffering from drought, UK relies on fresh produce from the Mediterranean region, that are increasingly prone to water scarcity (DEFRA, 2021b). Therefore, PAM application to improve water use efficiency could also indirectly benefit UK food security.

7.5 References

Al-Kaisi, M. M. and Lal, R. (2020) 'Aligning science and policy of regenerative agriculture', *Soil Science Society of America Journal*, 84(6), pp. 1808–1820. doi: 10.1002/saj2.20162.

Bronick, C. J. and Lal, R. (2005) 'Soil structure and management: A review', *Geoderma*, 124(1–2), pp. 3–22. doi: 10.1016/j.geoderma.2004.03.005.

Callebaut, F. *et al.* (1985) 'Determination of soil surface strength with a needle-type penetrometer', *Soil and Tillage Research*, 5(3), pp. 227–245.

DEFRA (2020) *Food Statistics in your pocket: Food Chain* - GOV.UK, *Food Statistics in your pocket: Food Chain*. Available at: <https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-food-chain>.

DEFRA (2021) *United Kingdom Food Security Report 2021 Theme 2 UK Food Supply Sources*. Available at: <https://www.gov.uk/government/statistics/united->

kingdom-food-security-report-2021/united-kingdom-food-security-report-2021-theme-2-uk-food-supply-sources#united-kingdom-food-security-report-2021-theme2-indicator-2-1-3 (Accessed: 4 July 2022).

DEFRA (2022) *Wholesale fruit and vegetable prices series 2015 to 2022*. London. Available at: <https://www.gov.uk/government/statistical-data-sets/wholesale-fruit-and-vegetable-prices-weekly-average>.

Dijk, M. *et al.* (2021) 'A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050', *Nature Food*. Springer US, 2(July). doi: 10.1038/s43016-021-00322-9.

FAO (2009) 'Conference STRATEGIC FRAMEWORK 2010–2019, C 2009/3.', Rome, (August 2009), pp. 18–23. Available at: www.fao.org/W/K5864/e.

FAO (2021) *Strategic Framework 2022 -31*.

FAO (2022) *The State of Agricultural Commodity Markets*. Rome.

Fox, D. M., Bryan, R. B. and Price, A. G. (2004) 'The Role of Soil Surface Crusting in Desertification and Strategies To Reduce Crusting', *Environmental Monitoring and Assessment*, 99, pp. 149–159. Available at: <http://www.archive.org/details/plantrelationsfi00coul>.

Hill, S. (1985) 'Redesigning the Food System for Sustainability', *Alternatives: Global, Local, Political*, (January 1985).

Jester, W. and Klik, A. (2005) 'Soil surface roughness measurement - Methods, applicability, and surface representation', *Catena*, 64(2–3), pp. 174–192. doi: 10.1016/j.catena.2005.08.005.

Khair, U. *et al.* (2012) 'Phenolic acids, flavonoids and total antioxidant capacity of selected leafy vegetables', *Journal of Functional Foods*. Elsevier Ltd, 4(4), pp. 979–987. doi: 10.1016/j.jff.2012.07.006.

Lal, R. (2009) 'Soil Carbon Sequestration: Land and water use options for climate change adaptation and mitigation in agriculture', *SOLAW Background Thematic Report – TRO4B*, p. 37. doi: 10.1016/j.geoderma.2004.01.032.

Lal, R. (2016) 'Soil health and carbon management', *Food and Energy Security*, 5(4), pp. 212–222. doi: 10.1002/fes3.96.

Lehrsch, G. A., Lentz, R. D. and Kincaid, D. C. (2005) 'Polymer and sprinkler droplet energy effects on sugar beet emergence, soil penetration resistance, and aggregate stability', *Plant and Soil*, 273(1–2), pp. 1–13. doi: 10.1007/s11104-004-7614-6.

- Lentz, R. D. (2015) 'Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam', *Geoderma*. Elsevier B.V., 241–242, pp. 289–294. doi: 10.1016/j.geoderma.2014.11.019.
- Maghchiche, A., Haouam, A. and Immirzi, B. (2009) 'Characterization of blend and composites for agricultural use at arid and semiarid soils', *Oriental Journal of Chemistry*, 25(1), pp. 15–26.
- Maghchiche, A., Haouam, A. and Immirzi, B. (2010) 'Use of polymers and biopolymers for water retaining and soil stabilization in arid and semiarid regions', *Journal of Taibah University for Science*. Taibah University, 4(1), pp. 9–16. doi: 10.1016/s1658-3655(12)60022-3.
- Maghchiche, A., Haouam, A. and Immirzi, B. (2013) 'Use of polymers and biopolymers for water retaining and soil stabilization in arid and semiarid regions', *Journal of Taibah University for Science*. Taibah University, 4(1), pp. 9–16. doi: 10.1016/s1658-3655(12)60022-3.
- Mirdehghan, S. H. (2010) 'Determination of Mineral Nutrients in Some Leafy Vegetables', pp. 279–282.
- Orts, W. J., Sojka, R. E. and Glenn, G. M. (2000) 'Biopolymer additives to reduce erosion-induced soil losses during irrigation', *Industrial Crops and Products*, 11(1), pp. 19–29. doi: 10.1016/S0926-6690(99)00030-8.
- Orts, W. J., Sojka, R. E. and Glenn, G. M. (2002) 'Polymer additives in irrigation water to reduce erosion and better manage water infiltration', *Agro Food Industry Hi-Tech*, 13(4), pp. 37–41.
- Pagliai, M. and Stoops, G. (2010) *Physical and Biological Surface Crusts and Seals, Interpretation of Micromorphological Features of Soils and Regoliths*. Elsevier B.V. doi: 10.1016/B978-0-444-53156-8.00019-2.
- Pretty, J. (2018) 'Intensification for redesigned and sustainable agricultural systems', *Science*, 362(6417). doi: 10.1126/science.aav0294.
- Pretty, J. (2020) 'The agroecology of redesign', 70, pp. 25–30. doi: 10.3220/LBF1605102089000.
- Reid, W. V. et al. (2005) *Millennium Ecosystem Assessment, Ecosystems and Human Well-being*. Washington, DC.
- Sandhu, H. et al. (2015) 'Significance and value of non-traded ecosystem services on farmland', pp. 1–22. doi: 10.7717/peerj.762.
- Siah, C., Robinson, J. and Fong, M. (2014) *A review on application of flocculants*

in wastewater treatment, Process Safety and Environmental Protection. Institution of Chemical Engineers. doi: 10.1016/j.psep.2014.04.010.

SNF (2021) *Industrial Water Treatment*, SNF. Available at: <https://www.snf.com/markets/industrial/> (Accessed: 27 June 2022).

Stoate, C. *et al.* (2001) 'Ecological impacts of arable intensification in Europe', *Journal of Environmental Management*, 63(4), pp. 337–365. doi: 10.1006/jema.2001.0473.

Subhasree, B. *et al.* (2009) 'Evaluation of antioxidant potential in selected green leafy vegetables', *Food Chemistry*. Elsevier Ltd, 115(4), pp. 1213–1220. doi: 10.1016/j.foodchem.2009.01.029.

Zafar, A. *et al.* (2005) *Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Desertification Synthesis*, World Resources Institute.

APPENDICES

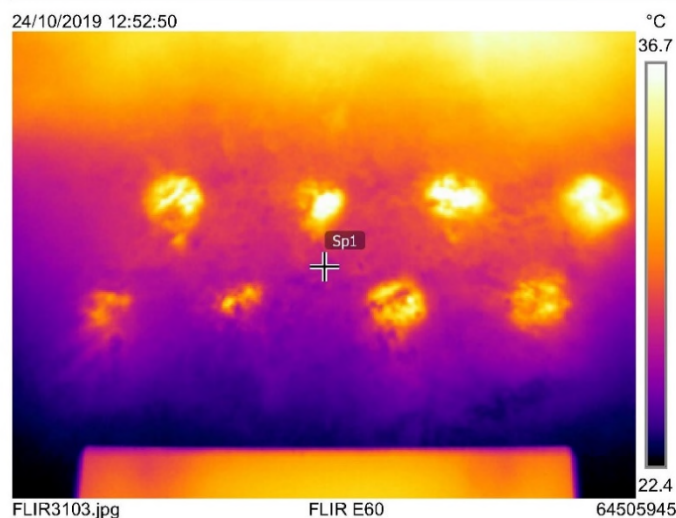
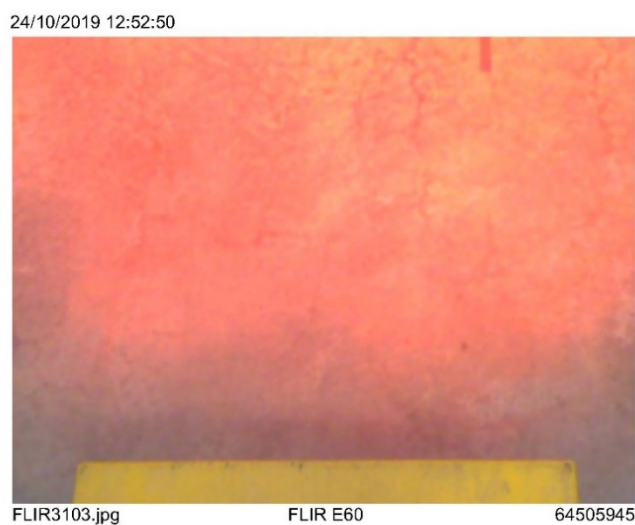
Appendix A Infrared Lights Homogeneity Test Report

A 2*1 m tray was filled up with a 40 ± 5 mm deep layer of soil and placed under a set of 8 thermic lamps., suspended at 1m height. Scoring the soil every 10 cm provided a grid with the same unitary dimension as the soil microcosms used in the lab and served as guide to identify characterise by homogenous heat. Pictures with a FLIR thermal camera were taken at regular intervals.



Homogeneity Test of Infrared Lights

Measurements	
Sp1	27.1 °C
Parameters	
Emissivity	0.95
Refl. temp.	20 °C
Note	
two minutes exposition: the heat produced by the lamps project an uneven thermic footprint onto the ground.	





Homogeneity Test of Infrared Lights

Measurements

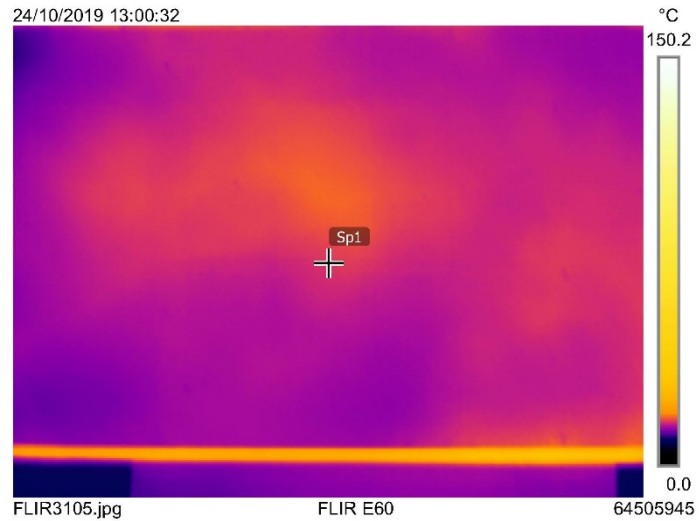
Sp1	25.7 °C
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Parameters

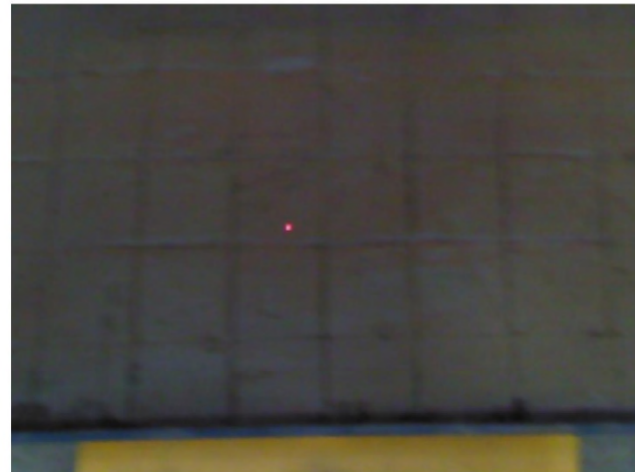
Emissivity	0.95
Refl. temp.	20 °C

10' exposition

A tray filled up with humidified soil was positioned under the bench: on the surface, 100 mm squares were marked to imitate the potential position of a 100 mm radius microcosm



24/10/2019 13:00:32



FLIR3105.jpg FLIR E60 64505945



Homogeneity Test of Infrared Lights

Measurements

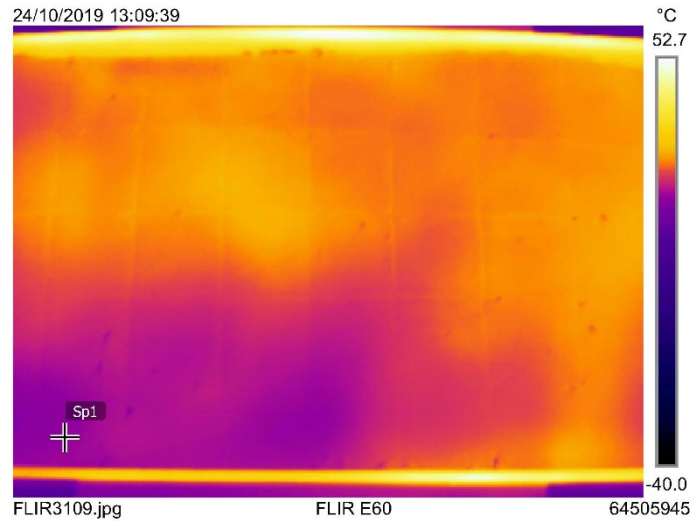
Sp1		29.5 °C
Dt1	Sp1 - Ref. temp.	29.5 °C
Dt2	Sp1 - Ref. temp.	29.5 °C
Dt3	Sp1 - Ref. temp.	29.5 °C
Dt4	Sp1 - Ref. temp.	29.5 °C

Parameters

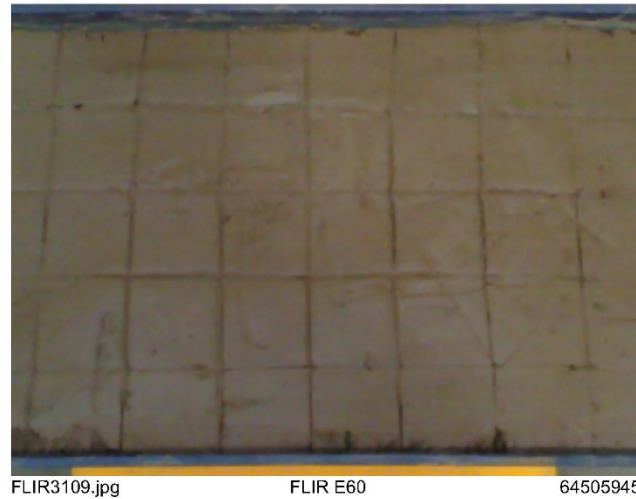
Emissivity	0.95
Ref. temp.	20 °C

Note

20' exposition



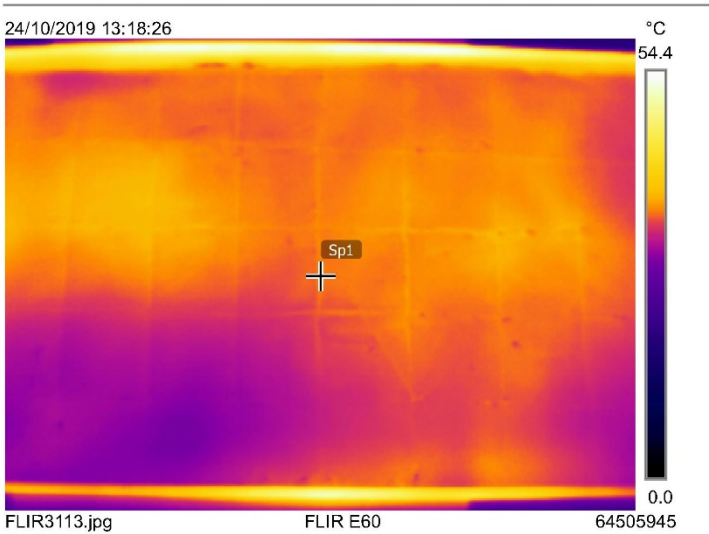
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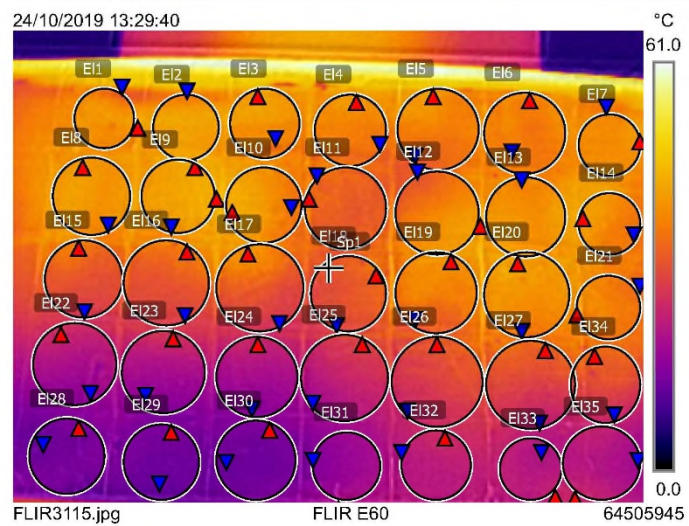
Homogeneity Test of Infrared Lights

Measurements	
Sp1	38.5 °C
Parameters	
Emissivity	0.95
Refl. temp.	20 °C
Note	
30' exposition	



EI33	Max	37.5 °C
	Min	36.1 °C
	Average	36.6 °C
EI34	Max	40.8 °C
	Min	37.2 °C
	Average	39.1 °C
EI35	Max	37.4 °C
	Min	35.1 °C
	Average	36.4 °C
Sp1		39.8 °C
Parameters		
Emissivity		0.95
Refl. temp.		20 °C
Note		
40' exposition		

Homogeneity Test of Infrared Lights



24/10/2019 13:29:40

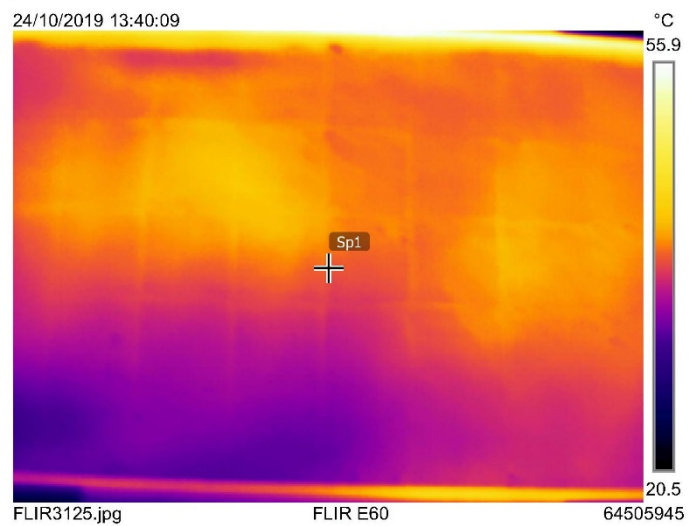


FLIR3115.jpg FLIR E60 64505945



Homogeneity Test of Infrared Lights

Measurements	
Sp1	40.4 °C
Parameters	
Emissivity	0.95
Refl. temp.	20 °C
Note	
50' exposition	

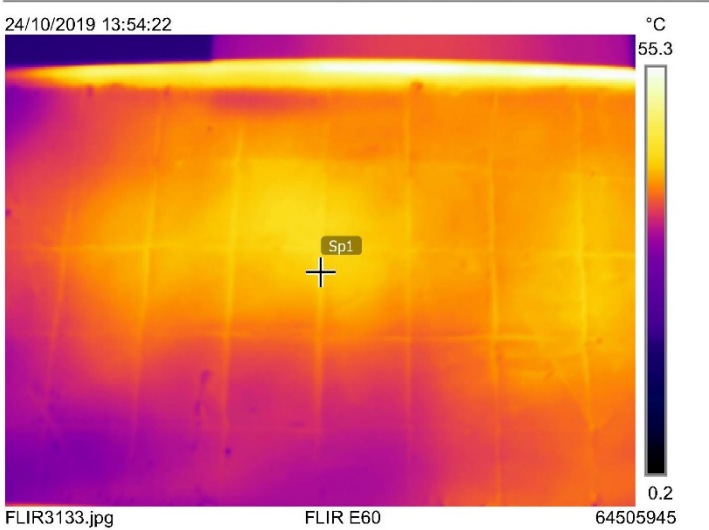




Homogeneity Test of Infrared Lights

Measurements	
Sp1	45.3 °C
Parameters	
Emissivity	0.95
Refl. temp.	20 °C

1h exposition



Appendix B Pedestrian Sprayer SOP

B.1.1 1. Source

This SOP is based on guidance and instruction provided by Charles Lecointe of SNF SAS. Safe storage, handling, exposure control/personal protection and disposal are based on product specific Material Safety Data Sheets (MSDS) and COSHH forms located in the Rainfall Laboratory in Building 54.

B.2 2. Scope

This SOP specifies a method for the application of Polyacrylamide (PAMs) to the soil surface (either in the field or to soil in microcosms or erosion trays), using the Pedestrian operated Spray Application Device (SAD) developed by SNF.

B.3 3. Principle and caution of use

The PAMs are applied to the soil surface via pressure operated nozzles which are mounted on a boom attached to the front of the pedestrian operated SAD.

The SAD enables dispersion of PAM at a constant pressure using an on board compressor and pressure vessel. Application rate is influenced by:

- Pressure supplied
- Number of nozzles in operation
- Nozzle specifications
- Boom nozzle spacing and height of on boom from soil surface
- Operator walking speed

B.4 4. Main components of the SAD

B.4.1 4.1. Frame

1. Compressor and battery housing.
2. Detachable boom bar
3. PAM and Water Bottle connectors. See section 4.3 for details
4. Pressure chamber to PAM/water bottle and PAM/water bottle to nozzle flow control valves
5. Compressor on/off switch
6. Handle bars with water and PAM on/off switches
7. Speedometer display
8. Top of main housing with bottle pressure valves and barometers (Figure B.2 for details)



Figure B.1 SAD frame with main components

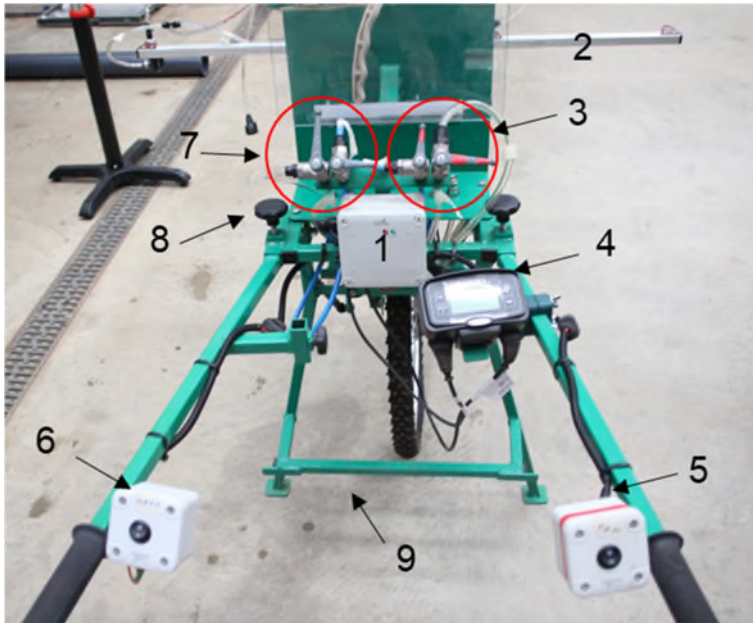


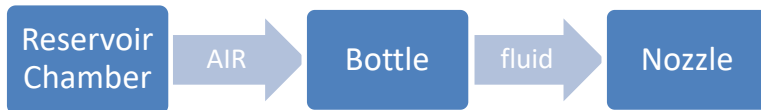
Figure B.2 SAD frame with main components

1. Compressor and main on/off switch
2. Detachable boom bar
3. Pressure chamber to PAM bottle and PAM bottle to nozzle flow control valves
4. Speedometer
5. PAM flow on/off switch
6. Water flow on/off switch
7. Pressure chamber to water bottle and water bottle to nozzle flow control valves
8. Handle retaining knob
9. Retractable stand

B.4.2 4.2. Hydraulic and tubing systems:

The Pedestrian sprayer has two independent tubing circuits: One for water and one for PAM (Figure B2 and B3). This allows greater flexibility in PAM/water application rates as each system can be pressurised and operated separately. Each circuit is identical in its components and is controlled by an on/off switch on each of the handle bars.

When the compressor is switched on pressure builds up from the pressure vessel (Figure B2) and is transferred to the water and PAM bottles in the form of compressed air. The higher density of the liquid content of the bottle allows PAM and water to flow to the nozzle.



The assemble of the Front layout is explained in Figure B3 and B4, The grey squares (2) correspond to solenoid valves, controlled by the system's pressure:

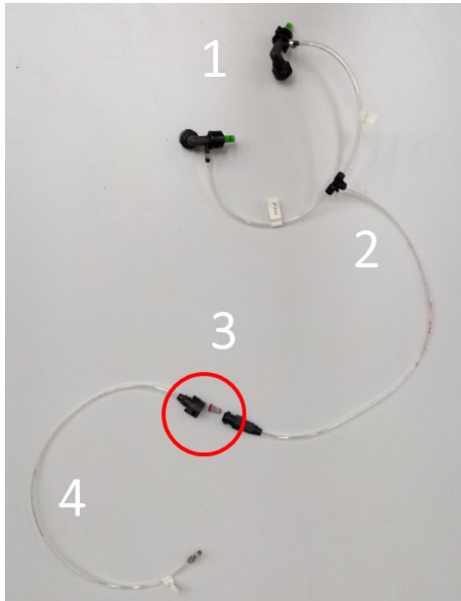


Figure B.3 Schematic display of the hydraulic system.

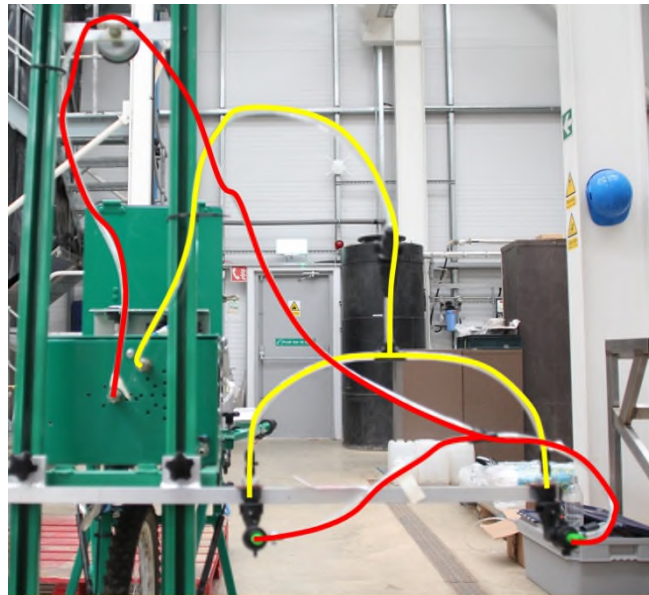


Figure B.4 Single tube assembly, it does not vary between PAM and water

1. Twin-Fluid Nozzles
2. Tubing from nozzle to filter
3. In-line Filter (<1.5mm metal mesh)
4. Tubing from in-line filter to main body

The components of the hydraulic circuit with on/off valves and taps is schematically represented in Figure B 5.

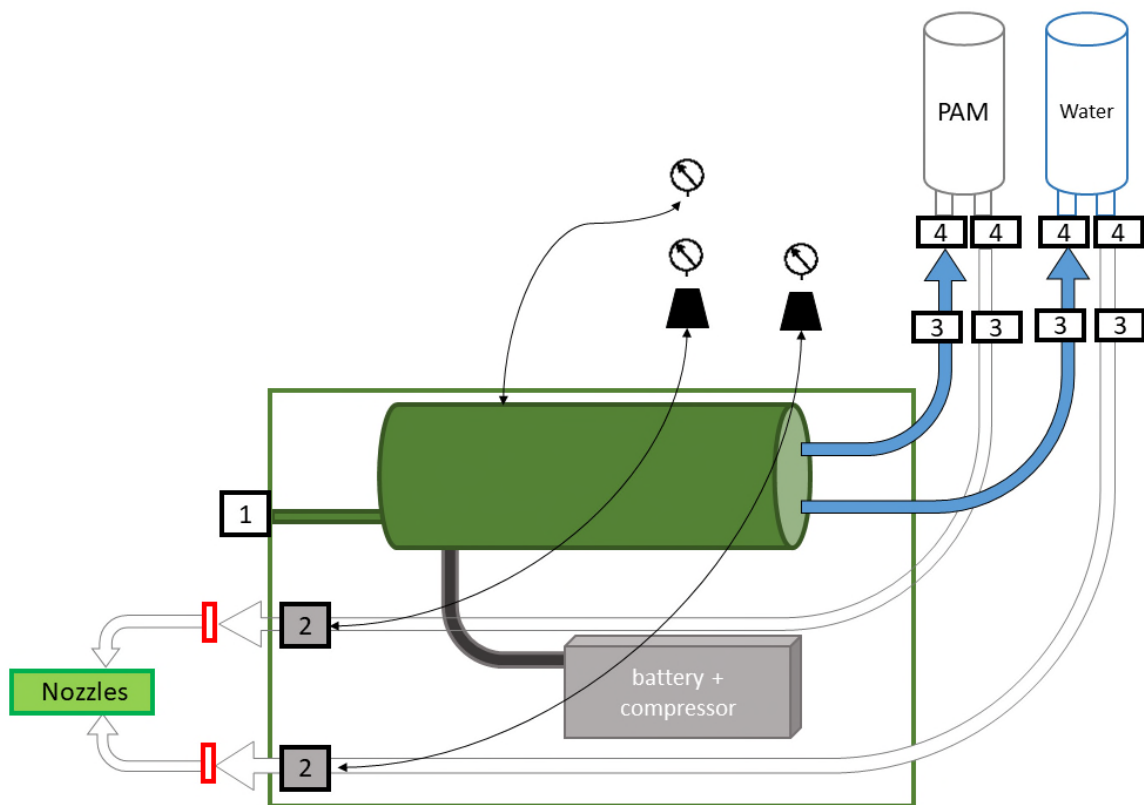


Figure B.5 Pressure control values and associated barometers on top of main housing.

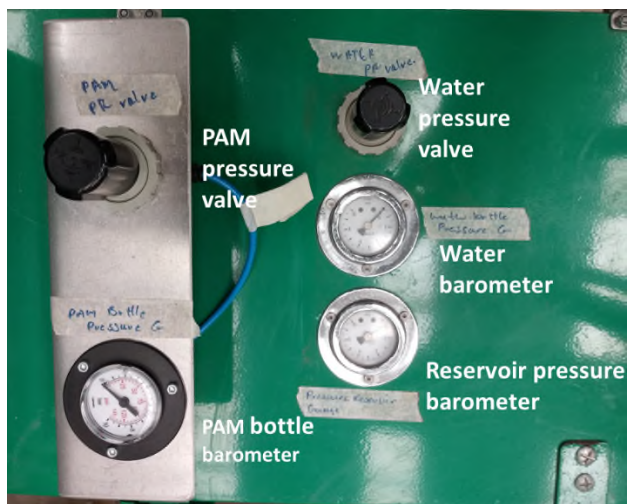


Figure B.6 Pressure Control Panel of the sprayer

B.4.3 Bottle set up



Figure B.7 Bespoke bottle connectors

A specially designed screw on bottle connector (SBC Figure B 6) is fitted to the neck of each bottle (Figure B 7).

Separate SBC's must be used for the water bottles and those containing PAM. The valves on the SBC need to be closed before connecting the bottle to the SAD.

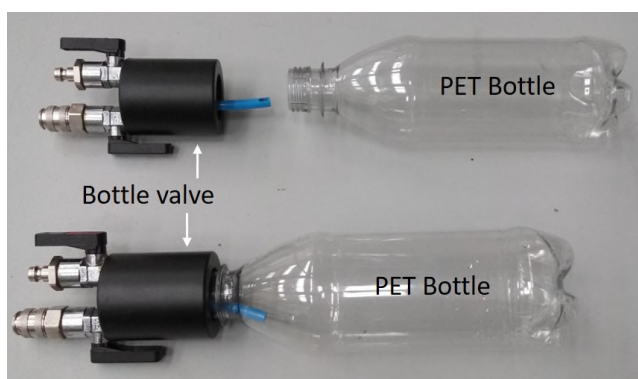


Figure B.8 SBCs with bottle valves in closed position.

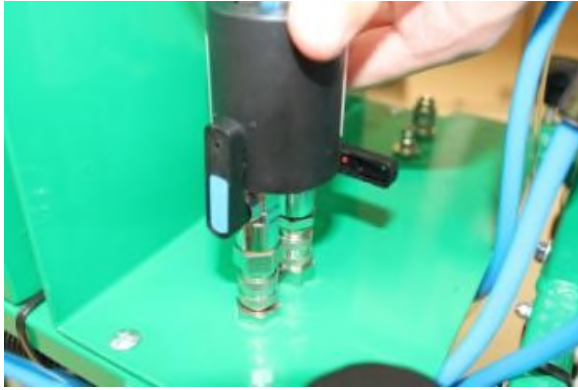
The SBCs are compatible with most commercially available PET bottle necks. Typically a 500ml PET bottle is used for the PAM and a 2.0 l PET bottle used for water. While SNF will send over PET bottles on request, it is convenient to have spare disposable clear plastic PET bottles.

Each SBC has two colour coded valves. The **red valve** is to allow water or PAM out from the bottle to the nozzle and the **blue valve** is to allow compressed air to enter the bottle from the compressor.

B.5 System Operation

B.5.1 Bottle value operation

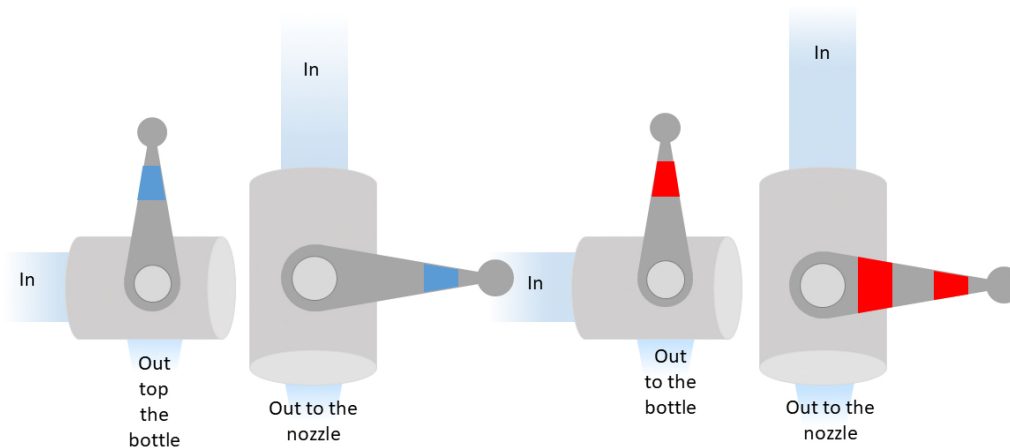
Important information: If the valve is perpendicular to the bottle (e.g. in a horizontal position, like in figure B 9) the valve is closed.



Figure_APX B.9 The blue valve is in line with the bottle and in a vertical position. It is open. The valve at the back is perpendicular to the bottle and in a horizontal position. It is closed.



Figure B.10 shows the water (blue) and PAM (red) control valves mounted on the front of the pedestrian sprayer. These control the flow of water and PAM from and to the bottles to the nozzles.



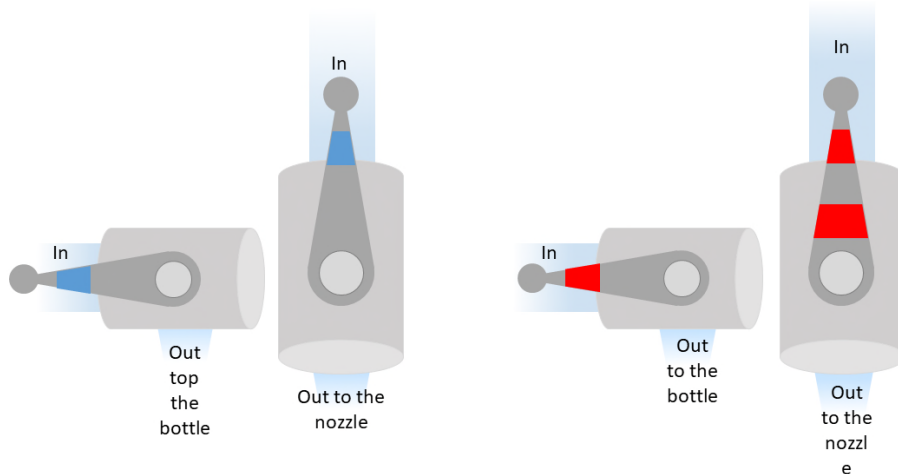


Figure B.11a and 11b are a schematic representation of their respective on/off positions. When the valves are perpendicular to the flow they are closed (Figure 8a). When the valves are in-line (parallel) with the flow, they are open (Figure 8b).

Operating the Pedestrian Sprayer



Figure B.12 Air discharge valve located in the front of the SAD

B.5.2 SAD construction:

- Unscrew the SAD from wood support
- Connect nozzle bar and the two handles
- Check the pressure of the tyre
- Open the discharge valve (Figure B 9) to bring the pressure chamber pressure to 1 atm and close it.
- Ensure that the power supply (main switch) is turned off and the two black valves (figure B 5) are set to minimum.

- Ensure all the taps (1,2,3 and 4, in figure B 4) are closed
- Ensure the SBCs and bottle valves are not clogged. Check if the ring around them moves back and forth freely and there is no corrosion or dried PAM. If damaged, replace.
- Tubing: Check tubing for damage or presence of dried PAM. If either is observed, replace. Connect water and PAM nozzles to the respective valves on the front of the main body as shown in Figure B 8. Ensure that the red filters fitted (Figure B 2).
- Connect battery and close the housing lid
- Connect PAM and water on/off switches to handles

B.5.3 Starting the SAD



Figure B.13 setting the pressure

Before starting the test, the compressor needs to be turned on. The compressor is started by pressing the green button, located on the right side of the grey box labelled “Pressure on/off ” (Figure B 13). A short ‘beep’ will be heard. The compressor delivers air to a pressure vessel (PV) and will cut off automatically when the pressure in the PV reaches approximately 8.5 bar. If the pressure is not building up make sure that the air discharge valve (Figure B 9) is closed.

The SAD has two pressure valves and three pressure gauges (Figure B 6). Depending on the desired PAM and water application rates, adjust the respective pressure valve. The pressure can be increased by pulling the respective pressure valve and turning it clockwise and pushing it back into position when the required pressure is obtained. The pressure can be decreased by pulling the respective pressure valve and turning it anti-clockwise and pushing it back into position when the required pressure is obtained.

B.5.4 Connecting the PAM and water bottles.

B.5.5 Valve opening order

The principle to follow is: the pressure builds up from the pressure reservoir to the bottles, referring to hydraulic scheme (fig 6), to start spraying, the opening order of the valves (Figure B 4) is 2, 3 and 4. When dismantling or changing the bottle, the closing order is reversed: 4, 3 and 2.

Always ensure that bottle valves 3 and 4 on the SBC's are closed when connecting the PAM and water bottles to the SAD.

B.5.6 Procedure:

While the pressure is rising, is possible to connect the bottles, ensure all the valves closed.

Set the desired pressure of liquid using the two black valves (2) on top of the main body. Note that when set to minimum, the valves require a good amount of twisting before the barometer to start recording the desired pressure.

Open valve 3 and 4

Is now possible to operate the machine by controlling the switching on the handles.

B.5.7 Calibration

Calibration takes place by measuring the weight of substance sprayed at a given time. A spraying time of 20-30 seconds has proven to be accurate for this pedestrian sprayer.

20" water flows can be easily collected with 1L Beckers, while sample bags have proven to perform better with PAMs. The expected pam discharge goes from 15 to 120 g for a 30" measurement at 0.5 and 4 atm respectively. The 2019 calibration yielded a linear curve for water and all the three polymers tested.

B.5.8 Spraying tips:

- DO NOT SPRAY OVER NAKED TARMAC OR OTHER NON-SOIL SURFACES. Use a nylon sheet or work on sand/ soil. If a spill occurs, please see the Troubleshooting section
- Allow plenty of buffer distance to ensure homogenous product dispersion on the substrate both before and after the samples
- See separate section for velocity control and calibration

B.5.9 Flushing

Flushing the machine is required every time to change the polymer or to dismantle the sprayer after use. The procedures are similar for PAMs and water:

- lock valve 4 and 3 respectively

- Unload the bottle and depressurise it by opening the red valve gently. Make sure to point the bottle away from any possible target to prevent any unwanted contamination (e.g. toward grass or in a plastic bag)
- Load an empty bottle –small is better- and run the sprayer far from any unwanted surface.
- Replace bottle with one containing either water, either a brine of NH_4SNO_4 , using the same bottle tap.
- Load the bottle and open taps 3 and 4
- Switch on the PAM sprayer and let the solution or water flow. Make sure to gently bend the tubes to ensure the complete detachment of the polymers from the tubes' surface.
- Repeat from 1 to 6 three four times with a 2L bottle of water, or until there is no more trace of PAM in the tube circuit
- Repeat from 1 to 6 without adding water, and flush with air until the tubes are dry and clean

B.5.10 Tip:

PAM's volume and viscosity increases when water is added during the flushing: fist try to remove as much product as possible with high pressure dry flushing, then proceed with water. Rather than flushing with one whole bottle of water at the time, is more effective to alternate small quantities of water and air. This allows the polymer to adsorb water and increase its volume, making it faster and easier to slush away.

B.5.11 5.5. Dismantle

At the end of daily use:

Flush as described in 5.4

Set the valves 2 to minimum and unload the pressure from the system by opening valves 3 and 1

Turn off the centraline

B.6 Nozzle maintenance

Although the system might appear well flushed, the PAM is likely to sit in the inner parts of the nozzle, and clog it use after use. Before or after every use, is good practice to dismantle the nozzles and clean it.

- Dry-wipe off excess PAM from the nozzle.
- Dismantle and inspect the joint tubes, after dry-wiping the inside, insert a long crew in the tube and twist it gently. The polymer should stick to the metal and the twisting movement should guide it outside the tube, allowing a deep cleaning.
- Repeat the same step with the nozzle main body

B.6.1 PPE

Anyone operating, or in the immediate vicinity of the SAD, when it is being used for PAM application, must wear a complete disposable suit, disposable overshoes, disposable gloves and a face shield.

Once used, all disposable items should be bagged, labelled as PAM contaminated waste and disposed of according to the COSHH assessment.

B.6.2 Troubleshooting:

Symptom	Possible cause	Solution
Red light and long beep on the centreline	Compressor overheating	Allow cooling time
	Low battery charge	Charge battery (12 V)
Pressure in the bottle is too high		If the adjustment is small, it is possible to lower the pressure slightly, if not, it is necessary to unload the bottle and release the excess pressure manually via the valves on the bottle. OR spray out some of the bottle content from the nozzles.
Black eye	You didn't close the valve in the right order	Wipe off excess polymer with dry paper and then wash with high quantity of water or of Apply ice on the eye and curse in Italian
Polymer spill	N/A	Dry wipe off excess and then wash with plenty of water. If safe, use $(\text{NH}_4)_2\text{SO}_4$ MARK THE AREA OF SPILLAGE: PAMs ARE SLIPPERY

<p>PAMs tubes are not coming clean, the tubes are clogged</p>	<p>Not enough polymers were sprayed off from the tubes during the preliminary drying cycle.</p> <p>A mixture might be more viscous.</p>	<p>Increase the pressure in the PAM bottle up to 4 atm.</p> <p>Switch between air and water and make sure not to finish all the water in the bottle before unload and change it.</p> <p>The first portion of the circuit to come clean is the one near the nozzle, if that portion is PAM free dismantle it and run the sprayer to clean the inner portions of the circuit.</p> <p>If necessary leave the circuit full of water for a brief time to let the PAMs adsorb water and become bulkier and lighter.</p> <p>Patience is key.</p>
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Appendix C Seed drill mounted PAM sprayer Standard Operating Procedure (SOP)

C.1 Source

This SOP is based on guidance and instruction provided by Charles Lecointe and Romain Garez of SNF. Safe storage, handling, exposure control/personal protection and disposal are based on product specific Material Safety Data Sheets (MSDS) and COSHH forms (Appendix 1).

C.2 Scope

This SOP specifies the correct methodology to prepare, use and flush the Seed drill mounted PAM sprayer which is fitted on the back of a seed driller (Figure C 1). As the technology and the applications of this sprayer are in constant development, this document is likely to be updated and revised.

C.3 Principle

The PAM is applied to the soil surface via pressure operated twin-fluid nozzles which are mounted on a boom attached to the back of the Seed drill mounted PAM sprayer.

The Seed drill mounted PAM sprayer allows the dual application of PAM and water. This facilitates uniform application of PAM to the soil surface with minimal drift. Application rate is influenced by:

- Flow (l/min) of PAM and water
- Number of nozzles in operation
- Nozzle specifications
- Height of boom above soil surface and spacing of nozzles on boom
- Tractor speed



Figure C.1 Seed drill mounted PAM sprayer fitted to the back of a seed driller

C.4 Water Circuit

The Seed driller mounted PAM sprayer has two independent hydraulic circuits. One for water and one for PAM. The main components of the water circuit are shown in Figure C 2a and 2b. The water circuit has two outputs: one to the nozzle on the spray boom and one to the PAM tank washer head. The direction of flow is controlled by the 'water flow direction valve' (Figure C2a and C 2b – Component Number 8).

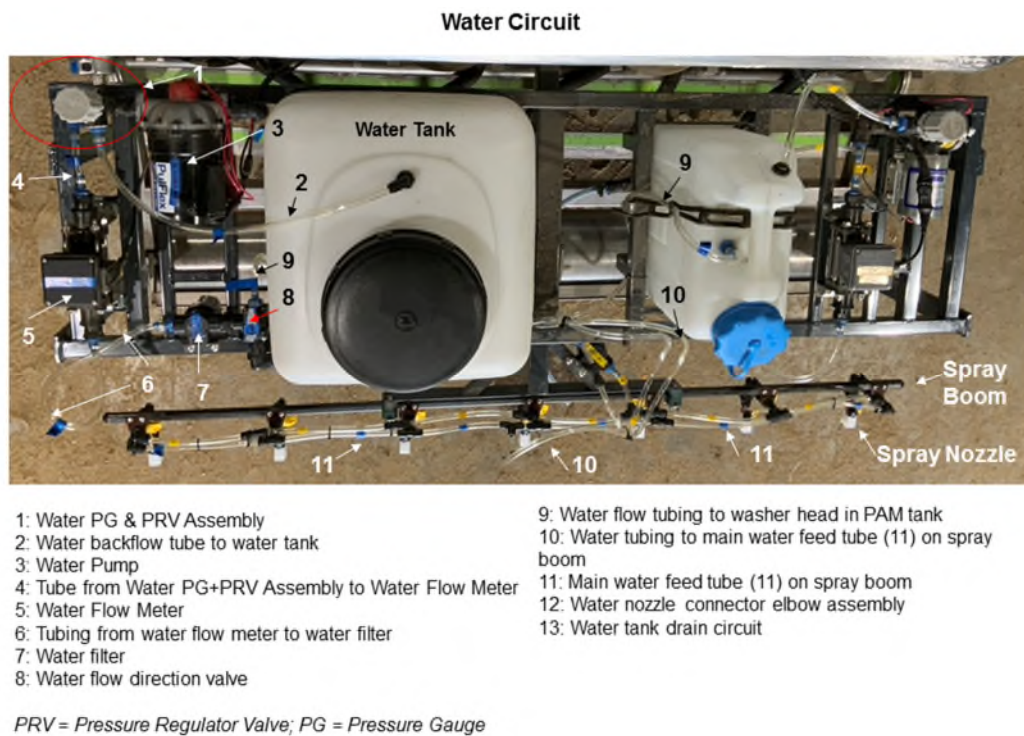


Figure C.2a Main components of the water circuit (Plan view).

Water Circuit

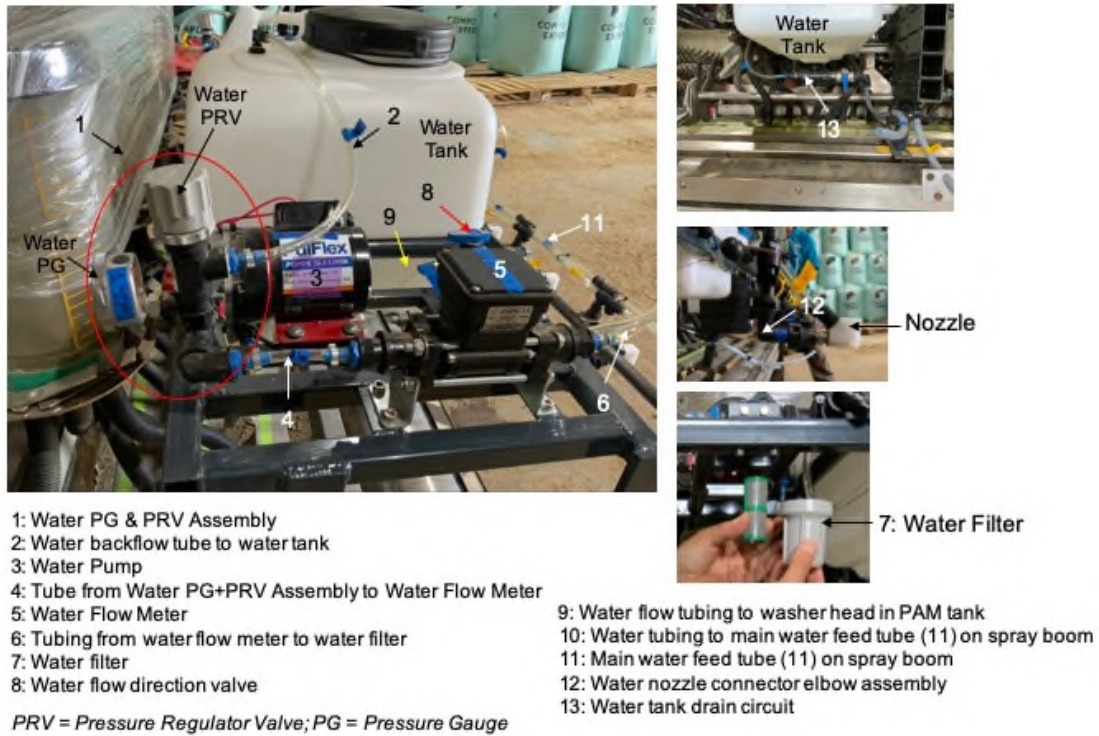


Figure C.3b Main components of the water circuit.

C.5 .2. PAM Circuit

The main components of the PAM circuit are shown in Figure C 3a and 3b.

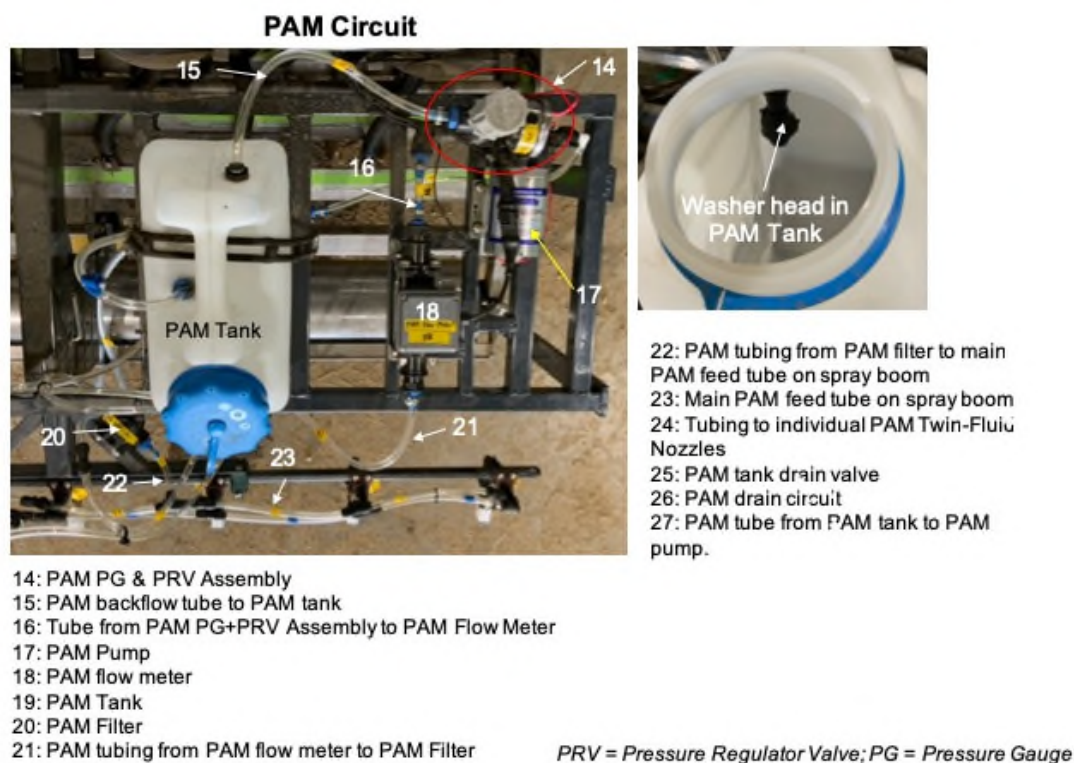


Figure C.4a Main components of the PAM circuit (Plan view).

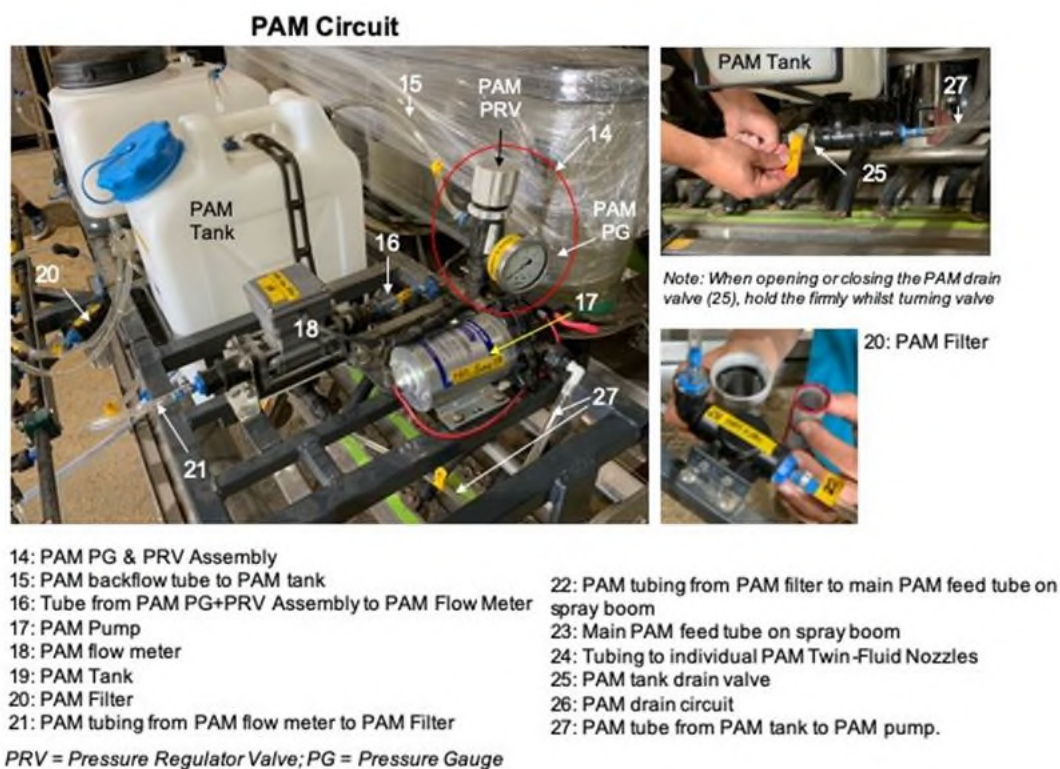


Figure C 3b. Main components of the PAM circuit.

C.6 Electrical circuit and control panel

Both the water and PAM pumps are controlled by the same control box (Figure C 4) which can be mounted on the Seed Drill Mounted Sprayer or be operated from the tractor cab. Adjusting either the PAM or Water pressure regulator valve (PRV) will alter the display on the respective displays.



- 1: Water Flow Meter Visual Display
- 2: PAM Flow Meter Visual Display
- 3: Tube from PAM PG+PRV Assembly to PAM Flow Meter
- 4: PAM Pump

Figure C.5 Control box.

The PAM and water flow meters are both connected to Visio digital displays. Both are connected to a single 12V point in the tractor. The PAM pump draws *circa* 15 amp and Water pump an additional 23 amp. Consequently the fuse in tractor needs to be capable of withstanding 43 amp maximum combined amperage. Typically tractor fuses are 30 amp. The PAM and water pumps preferably need to connect to separate 12V female connecting points on the tractor.

If this is not possible then these can be combined and connected (via appropriate battery head connectors) to a LBLiFe12-12/B1, technology LiFePo4 Battery [Charging voltage: 14.4V; Max discharge current: 25A; Max load current: 10A]

C.7 Operating Procedure

C.7.1 Before Use:

- Make sure that all fittings and tubing are in good condition. If worn or damaged replace.

- Make sure PAM and Water PRVs are set to zero.
- Check (and change if necessary) the Water and PAM filters [Reference 'Spare Parts Section' for specifications].
- Check that power supply meets the specifications, this is particularly important if connecting the sprayer directly to the tractor battery [Reference <https://www.farmersguide.co.uk/electrical-accessory-wiring-major-factor-behind-tractor-fire-surge-says-nfu-mutual/>]

Note: Steps 1-16 Should be undertaken on a suitable field margin in a clearly designated area. Make sure the designated area is visible using flags/marker tape. Do not traffic this area to AVOID getting PAM on the tractor tyres.

C.7.2 Operation

Step 1: Connect power supply to Visio displays for Water and PAM flow meters and to PAM and Water pumps

Step 2: Make sure that PAM and Water tank drain valves are closed (Figure C 2b Component Number 13 & Figure C 3b Component Number 25)

Step 3: Make sure that PAM and Water PRV are set to zero (Figure C 2b Component Number 1 & Figure C 3b Component Number 14)

Step 4: IMPORTANT: Make sure that water direction valve (Component Number 8) is pointing towards the spray boom (Figure C 2a). Using the securing bands, fix the water direction valve (Component Number 8) in this position.

*Note: It is critical that the water direction valve (Component Number 8) is not directing water flow to the washer head in the PAM tank. Adding water to the PAM tank whilst it contains PAM and before cleaning with 25% Ammonium Sulphate solution will cause the PAM to hydrate and swell. This significantly increases viscosity and makes it impossible to spray. This will necessitate prolonged cleaning of the PAM tank and may require replacement of tubing. **Before operating the sprayer make sure you mark***

on the water tank the water direction valve position that directs flow to the water washer head and the boom respectively.

Step 5: Make sure all nozzles are perpendicular to the boom

Step 6: Fill water tank (Figure C 2a)

Step 7: Carefully pour approximately 2.0l of 25% Ammonium Sulphate solution into the PAM tank [wear appropriate PPE, gloves and safety glasses].

Step 9: Close the PAM boom on/off valve (not currently in image) and switch on PAM pump (Figure C 4). Circulate 25% Ammonium Sulphate solution in the PAM tank and associated tubing for 3-5 mins to remove any moisture and clean any dried PAM from the system.

Step 10: Open the PAM boom on/off valve and switch on the PAM pump. Increase the pressure in the PAM circuit to 2.0 bar by adjusting the PAM PRV (Figure C 3b Component Number 14). Direct the 25% Ammonium Sulphate through the nozzles.

Step 11: Wearing gloves and safety glasses, carefully pour the required volume of PAM into the PAM tank, directing the flow using a funnel. Decant required volume of PAM into a suitable container (e.g. plastic jug or cut 2.5l plastic water bottle).

Note: Carefully remove any excess PAM from the funnel with soil. Wipe up any PAM spillage with disposable tissue/soil.

Step 12: Close the PAM boom on/off valve and switch on the PAM pump. Circulate for 5 mins the PAM in the PAM tank and associated tubing to homogenise the PAM before spraying. Switch off PAM pump.

Step 13: Immediately open the PAM boom on/off valve and switch on the PAM pump. Gently increase the pressure in the PAM circuit by adjusting the PAM PRV (Component Number 14) so that PAM is seen to trickle through the nozzles. Adjust the PRV to set the required flow rate on the PAM Visio display [see Table 1 for PAM application rate settings]

Step 14: Switch on the Water pump and adjust the Water PRV (Components 3 & 1 respectively) to set the required water flow rate on the Water Visio display [see Table 1 for PAM application rate settings].

Step 15: Before moving out of the designated area, cover areas sprayed with PAM with soil. This will rapidly sorb the PAM and limits the risk of transference to tyres/footwear. Once this is done, it is safe to move to the required area of the field to start spraying PAM.

Step 16: Set the boom to the required height to achieve the required bed coverage. Typically, with x7 flat fan twin-fluid nozzles on a 1.75m wide boom at 0.25 m spacing between nozzles, boom height should be set at 0.5 m. This will achieve uniform spray application to a 1.5m bed top width.

Step 17: Drive to the area of the field to be sprayed. Allow yourself adequate run-on until the tractor has achieved the required speed for the desired PAM application rate [see Table 1 for PAM application rate settings]. Once the tractor is at the required speed, switch on both the PAM and Water pumps and spray the PAM/Water.

Step 18: Top up the water and PAM as required (following the steps above) until the required area has been sprayed.

C.7.3 Flushing/Cleaning Procedure

Note: Move to a designated area of the field margin or adjacent field where flushing can take place.

Step 1: Re-fill the water tank

Step 2: Carefully pour approximately 2.0l of 25% Ammonium Sulphate solution into the PAM tank [wear appropriate PPE, gloves and safety glasses].

Step 3: Close the PAM boom on/off valve (not currently in image) and switch on PAM pump. Circulate 25% Ammonium Sulphate solution in the PAM tank and associated tubing for 5 mins to ensure that the remaining PAM is homogeneously mixed with the Ammonium Sulphate solution.

Note: To clean the PAM back-flow tube (Component Number 15 Figure C 3a) increase and decrease the PAM PRV whilst circulating 25% Ammonium Sulphate (low pressure in the PAM PRV will preferentially cause flow through the back-flow tube).

Step 4: Open the PAM boom on/off valve and switch on the PAM pump. Increase the pressure in the PAM circuit to 2.0 bar by adjusting the PAM PRV (Component Number 14, Figure C 3b). Direct the 25% Ammonium Sulphate / PAM solution through the nozzles until PAM tank is empty. This Step can be undertaken whilst the tractor is in motion to avoid ponding of 25% Ammonium Sulphate / PAM solution in the field.

Step 5: Repeat Step 3 and 4.

Step 6: Remove the water direction valve (Component Number 8) securing bands and turn so that the water direction valve is directing flow to the washer head in the PAM tank (***before operating the sprayer make sure you mark on the water tank the water direction valve position that directs flow to the water washer head and the boom respectively***).

Step 7: **Make sure that the PAM tank lid is closed:** Switch on the water pump and increase the PRV to maximum (*circa* 2.5 bar on the pressure gauge). Allow water to be sprayed via the washer head into the PAM tank until $\frac{3}{4}$ full, make sure to stop the water flow manually to not cause any overflow from the tank.

Step 8: Close the PAM boom on/off valve and switch on PAM pump. Circulate water in the PAM tank and associated tubing for 5 mins.

Step 9: Open the PAM boom on/off valve, switch on the PAM pump increase the pressure in the PAM circuit to 2.0 bar by adjusting the PAM PRV. Whilst the tractor is in motion spray the PAM tank flushing water in designated flushing area of the field or adjacent field.

Step 10: Repeat Steps 7-9.

Step 11: Whilst wearing disposable gloves, use tissues to carefully remove 'snoticles' from the nozzles. Put tissues in PAM waste bag.

Step 12: Check water and PAM filters and wash/replace as required.

Step 13: Finally, wash down sprayer with water/pressure washer.

Important: Never drive through PAM in the field. If PAM is on tyres rub off with soil.

1. 7.0 Application Rate: Table and Calculation

Table 1. Parameters to calculate application rate (l/ha) for PAM (SFA30) and water

PAM (SFA30)															
No. of nozzles on boom	4			5			6			7			8		
Spray Boom Width (m)	1			1.25			1.5			1.75			1.75		
Flow rate (l/min)	0.2			0.25			0.3			0.35			0.7		
*Flow rate (kg/min)	0.24			0.3			0.36			0.42			0.84		
Tractor Speed (km/h)	1.0	1.5	3.0	1.0	1.5	3.0	1.0	1.5	3.0	1.0	1.5	3.0	2	3	6
Application rate (l/ha)	120	80	40	120	80	40	120	80	40	120	80	40	120	80	40
Water															
No. of nozzles on boom	4			5			6			7			8		

Spray Boom Width (m)	1			1.25			1.5			1.75			1.75		
Flow rate (l/min)	4.56			5.7			6.84			7.98			15.96		
Tractor Speed (km/h)	1.0	1.5	3.0	1.0	1.5	3.0	1.0	1.5	3.0	1.0	1.5	3.0	2	3	6
Application rate (l/ha)	2736	1824	912	2736	1824	912	2736	1824	912	2736	1824	912	2736	1824	912

*Assuming a SFA30 Density of 1.2

Application rate is calculated using the following formula:

$$\text{Liquid volume } \left(\frac{l}{ha} \right) = \frac{\text{Nozzles or diffusers flow rate } \left(\frac{l}{m} \right) \times 600}{\text{Treated width (m)} \times \text{Forward speed } \left(\frac{km}{h} \right)}$$

For example (values from table above), for a 7 nozzle boom with a spray boom width of 1.75 m, flow rate of 0.35 l/min for PAM and 7.98 l/min for water, and a tractor speed of 1.5 km/h, the **PAM liquid volume** (l/ha) would be:

$$\text{Liquid volume} = \frac{0.35 \times 600}{1.75 \times 1.5}$$

$$\text{Liquid volume} = 80 \left(\frac{l}{ha} \right)$$

The **water liquid volume** (l/ha) would be:

$$\text{Liquid volume} = \frac{7.98 \times 600}{1.75 \times 1.5}$$

$$\text{Liquid volume} = 1824 \left(\frac{l}{ha} \right)$$

C.8 Spare Parts:

Component parts for the sprayer are supplied by TeeJet <https://www.teejet.com/> unless otherwise stated.

PAM Filter:

TeeJet AA122-PP Compact Liquid Strainer with 50 Mesh Size (TeeJet Part Number: CP45102-3-SSPP)

Water Filter:

TeeJet AA122-PP Compact Liquid Strainer with 100 Mesh Size (TeeJet Part Number: CP45102-5-SSPP)

Water Pump:

Pulflex diaphragm pump 26.5 l/min 4.1 bar

PAM Pump:

Pulflex diaphragm pump 20.8 l/min 4.1 bar

PAM Flowmeter:

Orion electromagnetic flowmeter 0.3 – 6.0 l/min

Water Flowmeter:

Orion electromagnetic flowmeter 1.0 – 20.0 l/min

Tubing:

Polyether Polyurethane tube 10 x 7.5mm

Appendix D Penetrative Resistance Example of data from Instron

flat slope

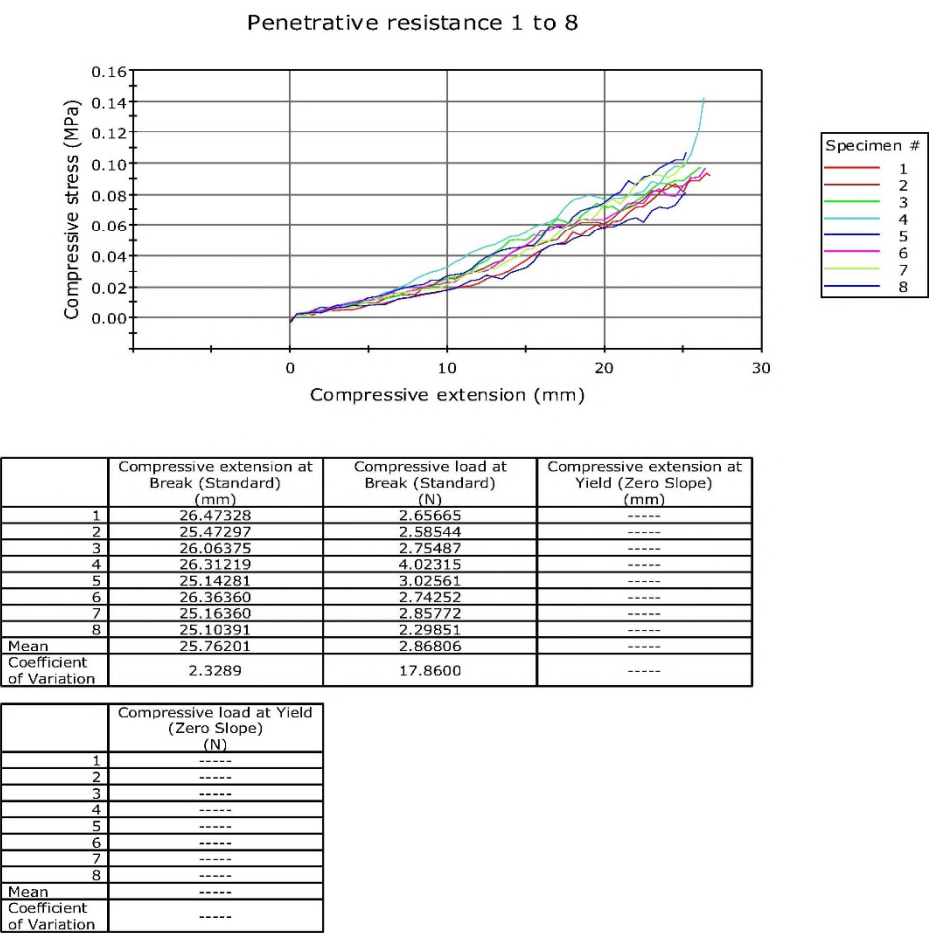


Figure D.1 Instron Exported dataset soil 1, 0 minutes of rainfall

1.10

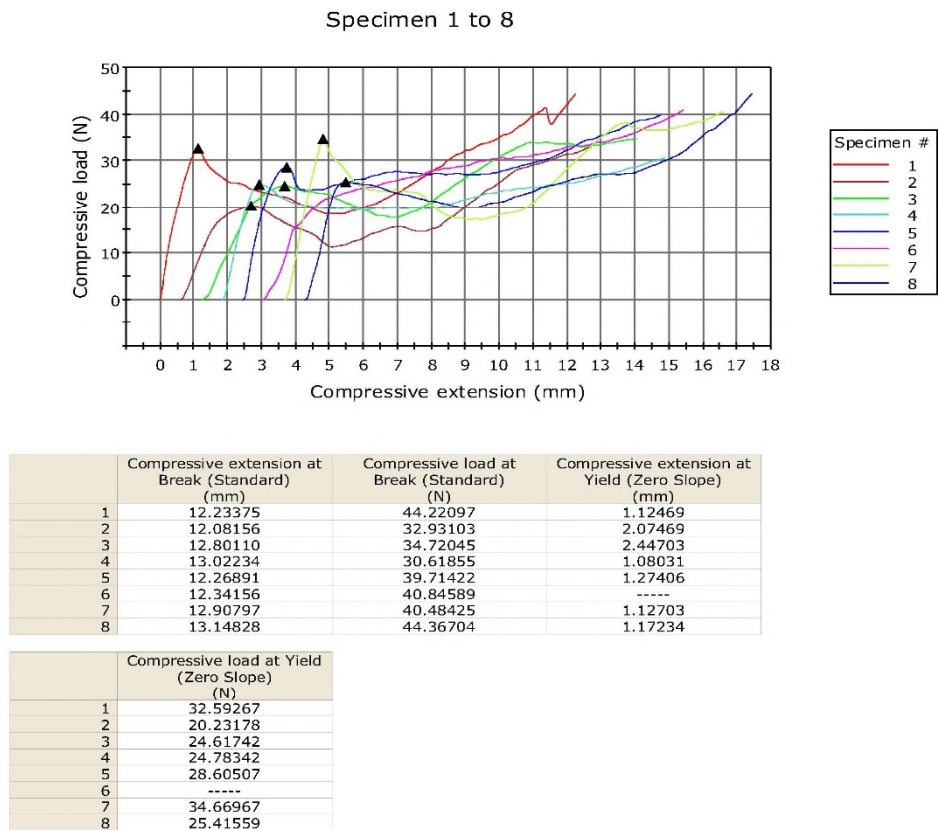


Figure D.2 Instron Exported dataset soil 1,10 minutes of Rainfall

Appendix E Mineralogy Report from James Hutton Institute

Report Number: 2020-30313



X-Ray Powder Diffraction (XRPD) and X-ray Fluorescence (XRF) Examination of Three UK Soil Samples

For:
Robert Simmons
Cranfield University
School of Energy, Environment and Agrifood
Cranfield
Bedfordshire
MK43 0AL

REPORT AUTHORS

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2020-11-18 09:23Z

Prof. Stephen Hillier

Valid report must contain authorised signature above



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Job and Sample Information:	
Client Order No/Reference:	5527168
Date Sample(s) Received:	20-October-2020
Appendix 1	XRF Results (1 Page)
Hutton ID:	Client Sample ID:
1334014	PRE-EX1-ARPANO-S
1334015	PRE-EX2-ARPANO-S
1334016	PRE-EX3-ARPANO-S

Introduction

Three samples were forwarded for whole rock mineralogical analysis by X-ray powder diffraction (XRPD) and chemistry by X-ray fluorescence (XRF).

Methods

Methods	Accreditation Reference	Date Analysis Completed
Identification and Quantification of a polycrystalline material by XRPD	GM003 and GM004	17/11/20
Chemistry by X-ray Fluorescence	Sub-contracted	10/11/20

XRPD

For bulk (whole sample) quantitative analysis samples are wet ground for 12 minutes (in ethanol or water) in a McCrone mill and spray dried to produce random powder specimens (Hillier, 1999). X-ray powder diffraction (XRPD) patterns are typically recorded over a range of $65^{\circ}2\theta$ or more using either Cu or Co radiation, the actual range being instrument dependent is given on the scans. Quantitative analysis is made by a normalised full pattern reference intensity ratio (RIR) method as described in Omotoso et al., (2006). Unless stated otherwise, expanded uncertainty using a coverage factor of 2, i.e. 95% confidence, is given by $\pm X0.35$, where X = concentration in wt.%, e.g. 30 wt.% ± 3.3 (Hillier 2003). Note also that for phases present at the trace level (<1%) there may also be uncertainty as to whether or not the phase is truly present in the sample. This is both phase and sample dependent. It arises because at trace concentrations identification is often based on the presence of a single peak and the judgement of the analyst in assigning that peak to a likely mineral or phase. XRPD patterns are identified by a Hutton ID and by names based on customer supplied identifiers, plus the suffix 'B' for bulk sample.

Hillier, S., 1999, Use of an air brush to spray dry samples for X-ray powder diffraction: Clay Minerals, v. 34, no. 1, p. 127-135.

Omotoso, O., D. K. McCarty, S. Hillier, and R. Kleeberg, 2006, Some successful approaches to quantitative mineral analysis as revealed by the 3rd Reynolds Cup contest: Clays and Clay Minerals, v. 54, no. 6, p. 748-760.

Hillier, S., 2003, Quantitative analysis of clay and other minerals in sandstones by X-ray powder diffraction (XRPD), in RH Worden and S Morad eds., Clay Mineral Cements in Sandstones: International Association of Sedimentologists Special Publication 34, p. 213-251.

Results

Bulk sample XRPD results are presented in Table 1. The XRPD patterns, with the main phases identified in the bulk samples by reference to patterns from the International Centre for Diffraction Database (ICDD), are provided for reference. XRF results are presented as Appendix 1.

Comments and opinions

The samples are dominated by quartz, with small to trace amounts of K-feldspar, plagioclase, goethite, hematite, chlorite, muscovite, undifferentiated illite plus mixed layered illite/smectite, and possible traces of calcite.

Note:

Samples will be stored for a period of eight weeks following completion of analysis and acceptance of analytical report(s) at no extra cost after which samples will be disposed of unless a specific instruction is given (with the sample analysis request/order) to store the sample beyond this period. Extended storage charges will apply.

Report Number: 2020-30313

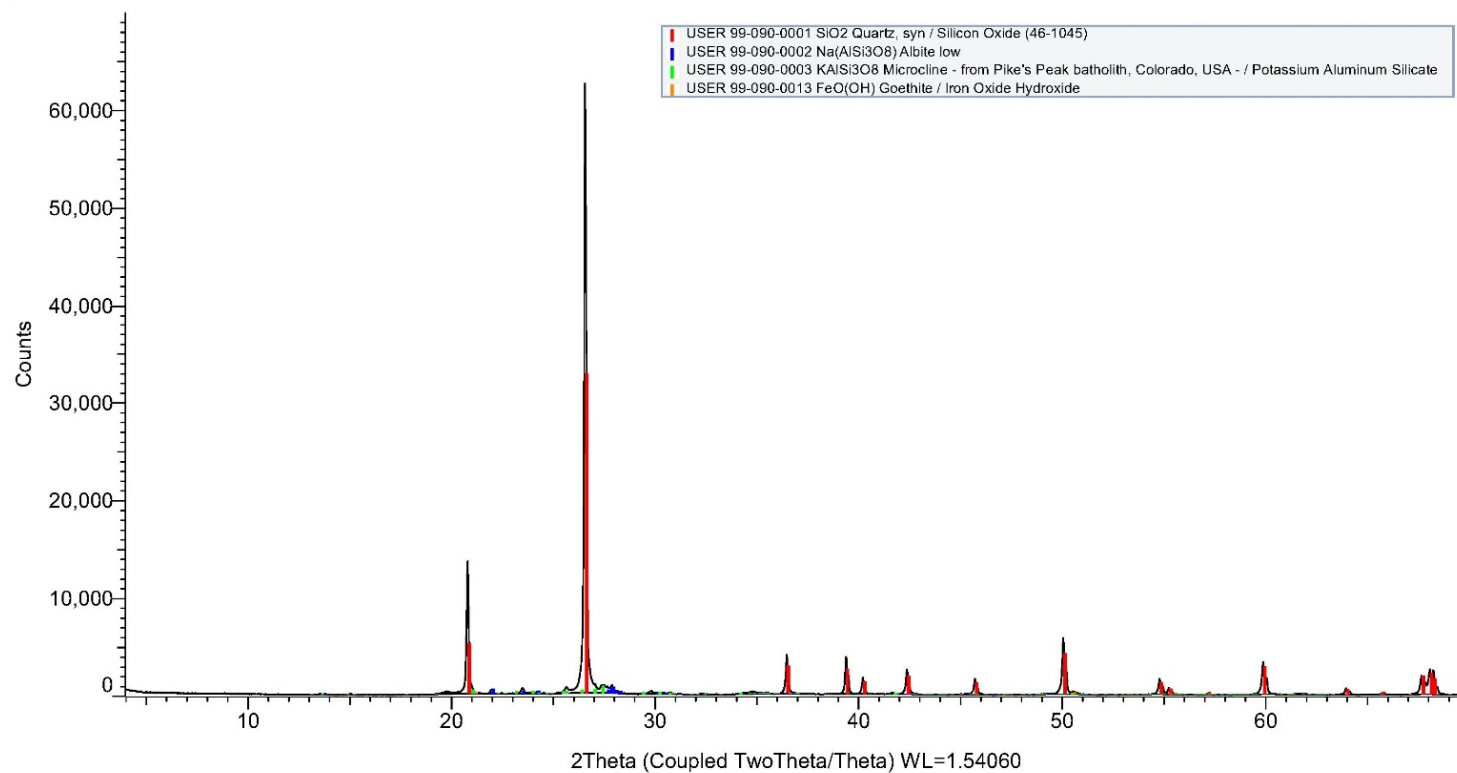
Table 1: XRPD Bulk Mineralogy (weight %) by RIR Method

Hutton ID	Sample ID	Quartz	K-feldspar	Plagioclase	Calcite	Goethite	Hematite	Chlorite(Tri)	Muscovite	I+I/S-ML	Total
1334014	PRE-EX1-ARPANO-S-B	77.9	6.4	5.1	0.3	2.1	0.3	0.1	0.2	7.6	100.0
1334015	PRE-EX2-ARPANO-S-B	67.4	6.9	6.4	0.3	3.9	0.3	0.9	0.0	13.9	100.0
1334016	PRE-EX3-ARPANO-S-B	72.3	6.6	3.4	0.2	3.6	0.2	0.3	0.0	13.4	100.0

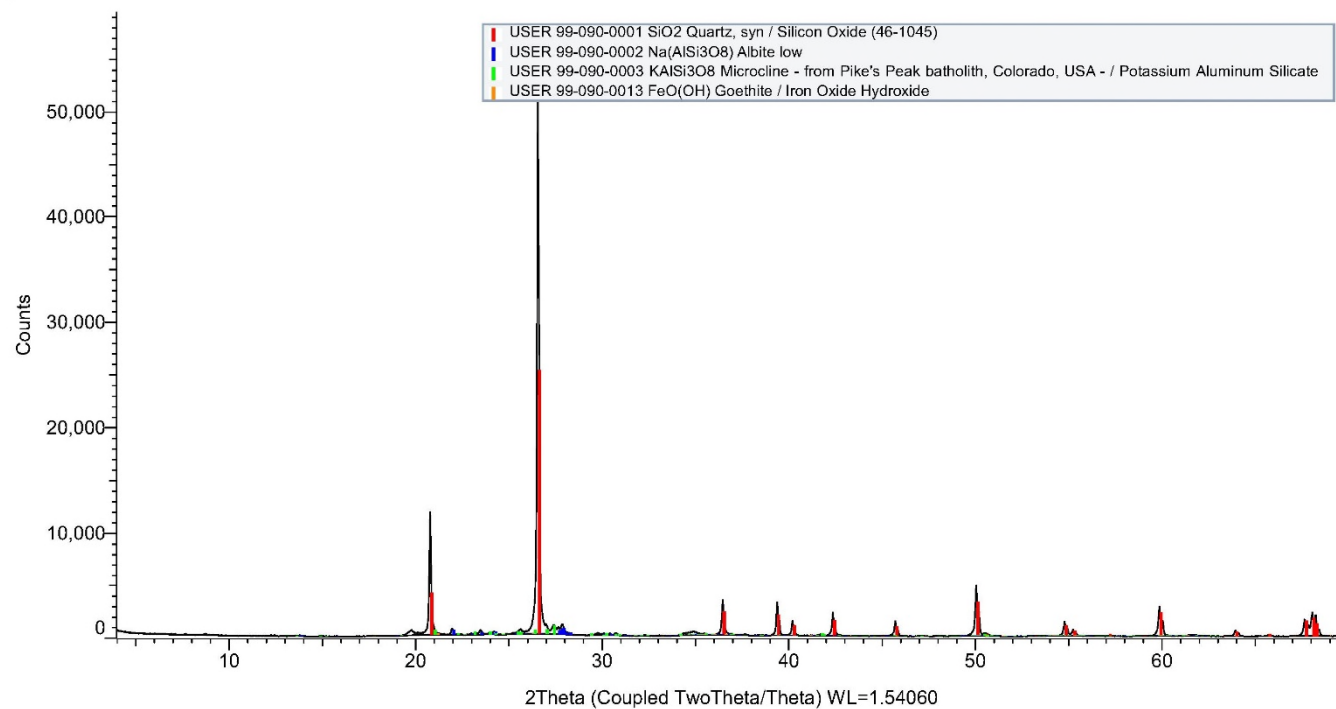
I+I/S-ML = Illite plus Illite/Smectite – Mixed Layered

Report Number: 2020-30313

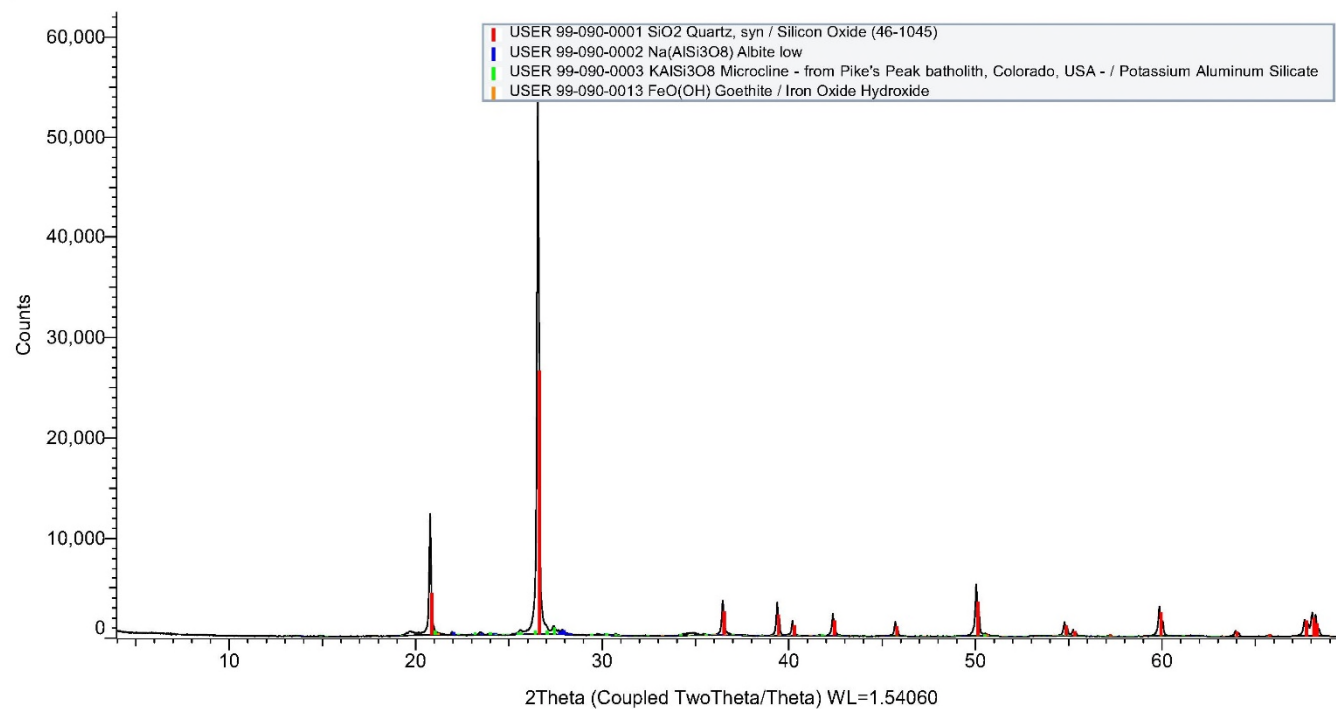
1334014-PRE-EX1-ARPANO-S-B



1334015-PRE-EX2-ARPANO-S-B



1334016-PRE-EX3-ARPANO-S-B



Report Number: 2020-30313



AMG Superalloys UK Limited

Fullerton Road, Rotherham, South Yorkshire S60 1DL, England

ANALYTICAL SERVICES

Tel. 01709-833763

Fax. 01709-830391



CERTIFICATE OF ANALYSIS

Page No. 1 of 1

Material analysed has been supplied to AMG Analytical Services for 3rd party analysis
Results only relate to items tested

To The James Hutton Institute Macaulay Drive Craigiebuckler Aberdeen AB15 8QH Scotland	Certificate Date	09/11/2020	Certificate No.	Lab Request No.																																																																																																																								
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<table border="1"> <thead> <tr> <th colspan="2">4017930</th> <th colspan="2">4017931</th> <th colspan="2">4017932</th> </tr> <tr> <th colspan="2">1334014 UK SOILS</th> <th colspan="2">1334015 UK SOILS</th> <th colspan="2">1334016 UK SOILS</th> </tr> </thead> <tbody> <tr> <td>LOD@110°C</td> <td>0.95 %</td> <td>LOD@110°C</td> <td>1.62 %</td> <td>LOD@110°C</td> <td>1.99 %</td> </tr> <tr> <td>LOI@1000°C (After LOD)</td> <td>2.46 %</td> <td>LOI@1000°C (After LOD)</td> <td>4.03 %</td> <td>LOI@1000°C (After LOD)</td> <td>4.16 %</td> </tr> <tr> <td>Na2O</td> <td>0.62 %</td> <td>Na2O</td> <td>0.69 %</td> <td>Na2O</td> <td>0.36 %</td> </tr> <tr> <td>MgO</td> <td>0.23 %</td> <td>MgO</td> <td>0.47 %</td> <td>MgO</td> <td>0.38 %</td> </tr> <tr> <td>Al2O3</td> <td>4.32 %</td> <td>Al2O3</td> <td>6.85 %</td> <td>Al2O3</td> <td>4.60 %</td> </tr> <tr> <td>SiO2</td> <td>88.81 %</td> <td>SiO2</td> <td>81.27 %</td> <td>SiO2</td> <td>85.25 %</td> </tr> <tr> <td>P2O5</td> <td>0.09 %</td> <td>P2O5</td> <td>0.15 %</td> <td>P2O5</td> <td>0.17 %</td> </tr> <tr> <td>K2O</td> <td>1.56 %</td> <td>K2O</td> <td>1.86 %</td> <td>K2O</td> <td>1.45 %</td> </tr> <tr> <td>CaO</td> <td>0.28 %</td> <td>CaO</td> <td>0.42 %</td> <td>CaO</td> <td>0.36 %</td> </tr> <tr> <td>TiO2</td> <td>0.41 %</td> <td>TiO2</td> <td>0.65 %</td> <td>TiO2</td> <td>0.46 %</td> </tr> <tr> <td>Mn3O4</td> <td><0.05 %</td> <td>Mn3O4</td> <td>0.06 %</td> <td>Mn3O4</td> <td><0.05 %</td> </tr> <tr> <td>V2O5</td> <td><0.05 %</td> <td>V2O5</td> <td><0.05 %</td> <td>V2O5</td> <td><0.05 %</td> </tr> <tr> <td>Cr2O3</td> <td><0.05 %</td> <td>Cr2O3</td> <td><0.05 %</td> <td>Cr2O3</td> <td><0.05 %</td> </tr> <tr> <td>Fe2O3</td> <td>1.62 %</td> <td>Fe2O3</td> <td>2.98 %</td> <td>Fe2O3</td> <td>2.82 %</td> </tr> <tr> <td>BaO</td> <td><0.05 %</td> <td>BaO</td> <td>0.05 %</td> <td>BaO</td> <td><0.05 %</td> </tr> <tr> <td>ZnO</td> <td><0.05 %</td> <td>ZnO</td> <td><0.05 %</td> <td>ZnO</td> <td><0.05 %</td> </tr> <tr> <td>SrO</td> <td><0.05 %</td> <td>SrO</td> <td><0.05 %</td> <td>SrO</td> <td><0.05 %</td> </tr> <tr> <td>XRF/LOI Total</td> <td>100.45 %</td> <td>XRF/LOI Total</td> <td>99.56 %</td> <td>XRF/LOI Total</td> <td>100.08 %</td> </tr> </tbody> </table>					4017930		4017931		4017932		1334014 UK SOILS		1334015 UK SOILS		1334016 UK SOILS		LOD@110°C	0.95 %	LOD@110°C	1.62 %	LOD@110°C	1.99 %	LOI@1000°C (After LOD)	2.46 %	LOI@1000°C (After LOD)	4.03 %	LOI@1000°C (After LOD)	4.16 %	Na2O	0.62 %	Na2O	0.69 %	Na2O	0.36 %	MgO	0.23 %	MgO	0.47 %	MgO	0.38 %	Al2O3	4.32 %	Al2O3	6.85 %	Al2O3	4.60 %	SiO2	88.81 %	SiO2	81.27 %	SiO2	85.25 %	P2O5	0.09 %	P2O5	0.15 %	P2O5	0.17 %	K2O	1.56 %	K2O	1.86 %	K2O	1.45 %	CaO	0.28 %	CaO	0.42 %	CaO	0.36 %	TiO2	0.41 %	TiO2	0.65 %	TiO2	0.46 %	Mn3O4	<0.05 %	Mn3O4	0.06 %	Mn3O4	<0.05 %	V2O5	<0.05 %	V2O5	<0.05 %	V2O5	<0.05 %	Cr2O3	<0.05 %	Cr2O3	<0.05 %	Cr2O3	<0.05 %	Fe2O3	1.62 %	Fe2O3	2.98 %	Fe2O3	2.82 %	BaO	<0.05 %	BaO	0.05 %	BaO	<0.05 %	ZnO	<0.05 %	ZnO	<0.05 %	ZnO	<0.05 %	SrO	<0.05 %	SrO	<0.05 %	SrO	<0.05 %	XRF/LOI Total	100.45 %	XRF/LOI Total	99.56 %	XRF/LOI Total	100.08 %
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LOD@110°C	0.95 %	LOD@110°C	1.62 %	LOD@110°C	1.99 %																																																																																																																							
LOI@1000°C (After LOD)	2.46 %	LOI@1000°C (After LOD)	4.03 %	LOI@1000°C (After LOD)	4.16 %																																																																																																																							
Na2O	0.62 %	Na2O	0.69 %	Na2O	0.36 %																																																																																																																							
MgO	0.23 %	MgO	0.47 %	MgO	0.38 %																																																																																																																							
Al2O3	4.32 %	Al2O3	6.85 %	Al2O3	4.60 %																																																																																																																							
SiO2	88.81 %	SiO2	81.27 %	SiO2	85.25 %																																																																																																																							
P2O5	0.09 %	P2O5	0.15 %	P2O5	0.17 %																																																																																																																							
K2O	1.56 %	K2O	1.86 %	K2O	1.45 %																																																																																																																							
CaO	0.28 %	CaO	0.42 %	CaO	0.36 %																																																																																																																							
TiO2	0.41 %	TiO2	0.65 %	TiO2	0.46 %																																																																																																																							
Mn3O4	<0.05 %	Mn3O4	0.06 %	Mn3O4	<0.05 %																																																																																																																							
V2O5	<0.05 %	V2O5	<0.05 %	V2O5	<0.05 %																																																																																																																							
Cr2O3	<0.05 %	Cr2O3	<0.05 %	Cr2O3	<0.05 %																																																																																																																							
Fe2O3	1.62 %	Fe2O3	2.98 %	Fe2O3	2.82 %																																																																																																																							
BaO	<0.05 %	BaO	0.05 %	BaO	<0.05 %																																																																																																																							
ZnO	<0.05 %	ZnO	<0.05 %	ZnO	<0.05 %																																																																																																																							
SrO	<0.05 %	SrO	<0.05 %	SrO	<0.05 %																																																																																																																							
XRF/LOI Total	100.45 %	XRF/LOI Total	99.56 %	XRF/LOI Total	100.08 %																																																																																																																							
END OF REPORT																																																																																																																												
<table border="1"> <thead> <tr> <th>Analysis on Dried Basis</th> <th>Analysis on Dried Basis</th> <th>Analysis on Dried Basis</th> </tr> </thead> <tbody> <tr> <td>Material: Non-Metallic</td> <td>Material: Non-Metallic</td> <td>Material: Non-Metallic</td> </tr> </tbody> </table>					Analysis on Dried Basis	Analysis on Dried Basis	Analysis on Dried Basis	Material: Non-Metallic	Material: Non-Metallic	Material: Non-Metallic																																																																																																																		
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Comments / Remarks Analysed using in - house documented procedures for technique(s) : LOD LOI XRF			Certificate Signed by ☒ P. W. Hurditch Chief Chemist ☐ S. L. Temple Office Manager ☐ I. Hyde Assistant Chief Chemist																																																																																																																									
Signed 																																																																																																																												

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