ABSTRACT

SHUR, BRANDAN ALEXANDER. The Characterization and Development of Soilless Substrate Systems for Enhanced Mother Plant Production of Strawberries in a Precision Indoor Propagation (PIP) Environment (Under the direction of Brian Eugene Jackson).

As the demand for local produce, particularly fresh fruits like strawberries, continues to rise, the imperative for year-round production becomes increasingly evident. Controlled environment soilless substrate systems, offers a potential solution to bridge this gap and fulfill consumer demand throughout the year. Despite advancements in controlled environment systems, both traditional field and CEA growers encounter challenges in ensuring a consistent supply of high-quality plants to meet the rapidly escalating demand. Given that strawberry propagation is predominantly vegetative, the global strawberry industry requires a substantial number of cloned plants, including bare roots and plugs, to fulfill geographical and seasonal demand. However, the current field propagation system faces various issues, including decreased plant quality after long storage, limited availability of planting material, and a high risk of pathogen transmission from nurseries to production fields. Additional factors such as escalating land and labor costs, environmental challenges, and the declining availability of soil fumigants exacerbate these hurdles. In response, an alternative approach gaining momentum is the transition to Precision Indoor Propagation (PIP) soilless substrate-based systems, offering a solution that mitigates soil-borne pathogen pressures and potentially enhances overall productivity. However, the development of soilless substrate systems for strawberry mother plant production remains largely unexplored. This thesis investigates the influence of various wood fiber products, aged pine bark, and perlite as potential amendments compared to a commercial industry standard (50% perlite: 25% peat: 25% coconut coir) to reduce the reliance on peat moss and coconut coir for strawberry mother plant production. Findings suggest that materials with higher container capacity and lower air space levels increase daughter plant numbers. Wood products emerge as suitable alternative. Additionally, the thesis examines the influence of container geometry (height and volume) and substrate air space by constructing containers out of PVC pipe and evaluating two substrates (high and low air space). Results indicate that shorter containers with a high air space substrate yield more daughter plants, while taller containers perform best with a low air space substrate. Increasing substrate volume from 2 to 3L in shorter containers increases daughter plant numbers, whereas tall containers show no effect. Lastly, the study evaluates various commercially used containers and grow bags for the fruit industry and models the hydro-physical properties of these with different substrates. Results underscore the effect of container geometry on substrate air-water profiles, necessitating different management approaches for the same substrate in different containers. This research contributes to the improvement of soilless substrate systems to enhance production and deepen our understanding of these systems.

The Characterization and Development of Soilless Substrate Systems for Enhanced Mother Plant Production of Strawberries in a Precision Indoor Propagation (PIP) Production System

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Horticultural Science

Raleigh, North Carolina
2024

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DEDICATION

I would like to dedicate this to those whose unwavering support, encouragement, and belief in my potential have been the cornerstone of my journey. Your collective guidance, perseverance, and encouragement have fueled my pursuit of passion and knowledge, shaping my appreciation for nature, horticulture, and the invaluable importance of higher education. Your presence in my life has been a constant source of inspiration and motivation, for which I am proudly grateful.

BIOGRAPHY

In the year 2000, Angela and Randy Shur welcomed their first son, Brandan Alexander Shur, in the small coastal community of Mattituck, New York. His parents operated an agricultural irrigation and rare plant nursery business on a 10-acre land neighboring the Long Island Sound. Brandan's fascination with horticulture began at his first steps; he explored his father's greenhouses, assisted in potting plants, and sneaked mouthfuls of tomatoes and peppers in the garden. His childhood was rooted in this love for the outdoors and plants.

Following two tragic incidents—an injury that nearly paralyzed Randy and a near fatal incident for Brandan—the family sold the business, relocating to Mount Airy, North Carolina, near the Blue Ridge Mountains. Amidst peacocks, ducks, chickens, cats, and dogs, they built a vibrant pink Victorian home on a 65-acre pastureland property. Here, a forgotten 'Belle of Georgia' peach tree on the property became pivotal. Randy, using it as a means of recuperation, tended to the tree while Brandan shadowed closely behind him. This tree sparked Randy's passion for fruit cultivation, leading to the expansion of an orchard housing nearly 2,000 peach trees. Angela soon left retirement as well with her innovation that turned excess fruit into a successful pie-making venture, establishing thriving businesses in downtown Mount Airy.

The orchard became Brandan's classroom as he learned about cultivation, management, and sales within a fruit-focused business. A coming-of-age moment arrived when Randy suffered a severe heart attack during harvest season, prompting a 10-year-old Brandan to increase his involvement in the orchard. He worked long hours, earning the nickname as 'The Peach Kid' at local farmers markets.

Graduating from Surry Early College School of Design in 2018 with a transferable associate degree, Brandan, still unsure of his future endeavors, entered Surry Community

College's Viticulture and Enology program. While exploring vineyard management and winemaking, his interest in research and fruit production grew. Knowing that becoming a winemaker was not the path for Brandan, he was advised by several instructors to continue with his education and love for horticulture. This led him to North Carolina State University, pursuing his bachelor's degree in Horticultural Production Systems and receiving a full ride scholarship through the Goodnight Scholars Transfer Program scholarship. This program allowed him to travel to several states across the country, islands, and several countries, all while learning more about horticulture along the way.

Despite pandemic disruptions, Brandan chose to seize opportunities and attempt to stand out in a newfound virtual education, reaching out to professors and finding mentorship with Dr. Brian Jackson when he was the only one to email him back and offer him a chance to move to Raleigh. Joining Dr. Jackson's Horticultural Substrates Lab, Brandan discovered a burgeoning passion for soilless substrates. This paved the way for a Graduate Research Assistantship and pursuit of a Master of Science in Horticultural Science, focusing on soilless substrate production for small fruit crops.

With numerous projects, presentations, affiliations, scholarships, and awards—including the HortScholars award and the American Floral Endowment Richard T. Meister scholarship—Brandan's academic journey has been busy and rewarding. His imminent graduation in May 2024 is a steppingstone to a PhD position at Virginia Tech University's School of Plant and Environmental Sciences under the mentorship of Dr. Michael Evans. Brandan aspires to drive innovation in soilless food crop production, aspiring to become a pioneering horticultural scientist.

ACKNOWLEDGEMENTS

I extend my deepest gratitude to the individuals who have been instrumental in my academic and personal growth throughout this journey. First and foremost, I am indebted to my parents, Angela and Randy, for their unwavering support, encouragement, and belief in my abilities. Their guidance has been invaluable in shaping my path.

To my sisters, Melanie and Jamie, your constant companionship and humor have been a source of strength. Whether through a smile, a listening ear, or an adventurous journey, you have always been there for me. My nephew, Logan, whose presence brings joy and curiosity reminds me of mine at his age.

To my partner, Suzannah, whose unwavering support has been a cornerstone of my success. From many late-night trips to the greenhouse or lab and always offering a comforting shoulder during any challenging times, your belief in me has propelled me forward. Your motivation to continue working leaves me forever grateful.

Dr. Jim Clark, thank you for your support and welcoming me into your home with open arms. You’ve taught me to always help others, appreciate the little things around us, and sometimes a few words are more meaningful then a full conversation.

I extend my sincere thanks to Dr. Brian Jackson for recognizing my potential and offering me so many opportunities that have transformed my life. Your mentorship has taught me to strive for something more than average, but to continue to work towards excellence and reach beyond any perceived limitations. You’ve supported me professionally and personally since the first day we met, so I will always give you the credit for me being the researcher I am becoming today.

I am thankful to Dr. Bill Fonteno for his guidance and patience, despite the distance. Your insights and encouragement have been invaluable in shaping my research endeavors and has taught me how to become a better scientist. The biggest lesson I've learned through you is to always ask myself what questions we need to be asking before any project. To Dr. Ricardo Hernandez, your expertise in plant physiology has been instrumental in my understanding of greenhouse practices. I am grateful to Dr. Mike Parker for his counsel and support, both academically and personally. Your wisdom has been a guiding light during challenging times. To Dr. Melinda Knuth, thank you for your mentorship and allowing me to improve my teaching abilities through your class. Your impact extends far beyond academia. Special thanks to Chancellor Randy Woodson for his mentorship and guidance on academia and future career paths.

I would like to acknowledge Diane Mays for acting as my "plant mom" for the last four years and Alisha Ray for always being happy to help with any concerns. To my lab mates, past and present, including Jack Bobo, Bret Timmons, Brian Schulker, and Logan Hooks, thank you for your camaraderie and support. Your friendship has made the journey memorable. I am forever grateful to the Goodnight Scholars program for providing me with opportunities for growth and development. To Ethan Jenkins, and Sammie Graff, your friendship and support have made my life here entertaining. You both always stay in touch with me no matter how busy we may become. I am grateful for your companionship. Lastly, to all those who have been part of my journey, whether through shared classes, research projects, or simply lending an ear, thank you for your presence and support. Each of you has played a vital role in my journey, and I am deeply grateful for your contributions.

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CHAPTER 1

Literature Review

1. Strawberry Biology

The cultivated strawberry plant (*Fragaria x ananassa*), originating in 18th-century France, is one of the most widely consumed fruit in the world (Simpson, 2018). Alongside economically important crops such as apples, blackberries, and roses, strawberries are part of the Rosaceae family (Galletta and Himelrick, 1989). The introduction to this economically significant fruit is owed to Amedee-Francois Frezier. Frezier, a French engineer and explorer, discovered *Fragaria chiloensis* on a reconnaissance mission to Chile. Several of these plants were brought back to France and were cross bred with another species from the new world, *Fragaria virginiana* (Frezier, 1716). The modern day commercialized strawberry is this hybrid between *Fragaria chiloensis* and *Fragaria virginiana* (Darrow, 1966), which has become the predominant commercially grown strawberry.

The strawberry plant's intricate structure includes a central crown, shallow roots, trifoliate leaves, stolons, and inflorescences (Darrow, 1966). The crown, supporting flower development, gives rise to stolons that contribute to the growth of daughter plants. The root system, characterized by primary and secondary roots, presents a fibrous appearance. Strawberry fruit development is intricately tied to the plant's inflorescences, featuring perfect flowers with pistils and stamens. The resulting fruit is an aggregate and accessory fruit, with achenes carrying an average of about 200 seeds. Contrary to common perception, the strawberry is not a true berry; it matures on the receptacle, accompanied by a leafy cap. The ripening process takes 20 to 50 days post-pollination (Darrow, 1966).

Categorization of strawberry cultivars is based on photoperiod requirements, being short-day, long-day, and day-neutral cultivars (Honjo et al., 2016). Traditionally, short-day cultivars thrive in cold regions, budding with less than 14 hours of daylight and are typically harvested in late spring (Padmanabhan et al., 2016). Long-day cultivars exhibit less sensitivity to photoperiod, producing fruit throughout summer and into autumn (Castro et al., 2015; Darrow, 1966; Hancock, 1999). Day-neutral cultivars show minimal influence from photoperiod variations (Castro et al., 2015).

2. Strawberry Industry and Challenges

2.a. Overview

In 2021, China was the world's largest strawberry producer, followed by the United States and Mexico (FAOSTAT, 2018). The United States strawberry industry was valued at $3.42 billion in 2021 (USDA-NASS, 2022). Among North American contributors, California took the lead in strawberry production, outpacing others growth such as Mexico (California Strawberry Commission, 2022; USDA-NASS, 2022). This increase in crop production compared to other states are due to the variations in acreage, climate, and harvest season, such as year round strawberry production. Although year round production is achievable in California, production yields are much higher in the spring and summer months. Florida and Mexico target the off season strawberry market to take advantage of reduced California yields (Samtani et al., 2019). Following California, Florida ranked third in total strawberry production, contributing approximately 8% to the overall U.S. production. Notable contributors included New York, North Carolina, Oregon, and Washington.

2.b. Strawberry fruit production

Traditional fruit production systems include the annual hill plasticulture system, established as the primary outdoor strawberry production system in 1950's in California (Poling et al., 2005). This involves planting plug or bare-root plants into raised, plastic covered beds for easy and swift harvesting. Different plastic mulch types, including black, clear, and white are used, each influencing weed control, soil temperature, and fruit quality. In contrast, the matted row production system, once predominant in the U.S., is now less common and mainly used in cooler climates like the Northeast U.S., offering low establishment costs and multi-year harvesting from the same plants (Black et al., 2002). While the annual hill system incurs higher upfront costs, it reduces labor between establishment and harvest, leading to higher yields and income (Black et al., 2002; Fernandez et al., 2002; Garwood, 1998).

2.c. Strawberry nursery production

Another sector of the strawberry industry is the nursery trade, which supplies strawberry growers with bare-root or rooted plug plants. Initially, nurseries will propagate virus-free mother plants through tissue culture, yielding daughter plants from the mother plant's stolon. These daughter plants are harvested, rooted, and then sold to strawberry producers for fruit production. This entire process, from tissue culture to strawberry production, spans approximately five years (Kadir et al., 2006). Given the multi-location, multi-year process, disease management is crucial for heathy, high yielding plants. Methyl Bromide, which is an effective soil borne disease control chemical, was phased in in 2005 due to several environmental concerns. Despite this, nurseries can still use methyl bromide through exemptions granted by the U.S. Environmental Protection Agency, contingent on specific criteria (US EPA, 2022).

2.d. Challenges of traditional production

While soil traditionally provides essential support for plant growth, strawberry fruit and nursery production in soil encounter persistent challenges. Traditional open-field strawberry production in the U.S. is confronted with a multitude of challenges that are reshaping the landscape of the industry. Escalating land and labor costs are eroding the profitability of production operations, with a visible impact on cultivated acreage due to the scarcity of migrant labor (Samtani et al., 2019). Concurrently, environmental challenges, encompassing variable weather conditions, rising irrigation costs, and a reduction in available soil fumigants, are posing significant threats to both productivity and profitability (Samtani et al., 2019). The complete phase-out of methyl bromide and the imposition of stricter regulation on other fumigants have intensified concerns among farmers regarding the long-term control of soil pathogens in traditional production locations. As these and more challenges persist, including water efficiency, space utilization, unpredictable weather patterns, transportation distance (cost and perishability of the fruit), and geographical harvest season constraints, the need for transformative approaches become increasingly apparent.

2.e. Soilless strawberry production introduced as an alternative to soil

One promising strategy to alleviate soilborne pathogen pressure and revolutionize traditional strawberry production is the transition to soilless substrate-based systems. Soilless substrates, composed of organic and inorganic components like peat moss, coconut coir, and perlite, coupled with drip-line nutrient solution irrigation, create a hydroponic production environment. The combination of the substrate composition, container geometry, and nutrient solution collectively form a soilless growing system. Together, this influences the rootzone's physical, chemical, and biological properties, enhancing plant growth and productivity (Gruda et al., 2013; Raviv et al., 2008; Savvas and Gruda, 2018).

Apart from pathogen control, soilless substrate systems offer various advantages. Plants grown in containers, bags, or troughs provide ergonomic working conditions and higher planting density, contributing to greater harvests per unit area compared to open-field cultivation (Lieten, 2013). Soilless strawberry cultivation is more prevalent in Europe, where innovative practices have been developed, often in conjunction with greenhouses, plastic tunnels, or indoor cultivation, to extend growing seasons (Lieten et al., 2004). These controlled environment systems optimize microclimate conditions, resulting in increased strawberry fruit yield and quality, and potentially enable year-round localized production. This contrasts with the traditional North American winter market, where production shifts to more southern climates, resulting in long transportation distances from production regions to high-population areas (Taghavi et al., 2019).

While greenhouse soilless production systems demand significant capital inputs, their potential benefits include high planting density, season extension, and environmental optimization (Lieten et al., 2004). However, challenges such as high annual production costs and energy expenditures underscore the need for continuous efforts to enhance economic viability. Efforts to improve fruit quality and maintain or improve yield are crucial, especially during the wintertime controlled environment strawberry production in the U.S., aiming to create a sustainable and economically viable industry (Lieten, 2013).

3. Introduction to Soilless Production of Strawberries

3.a. Origins of container grown strawberries

While the utilization of soilless container methods for strawberry production is gaining momentum, its historical roots trace back to the 18th century. Early references mentioned the practice of forcing strawberries to yield earlier by rooting runners into soil-filled pots and introducing them to heated forcing houses in winter. The first departure from generic soil occurred in 1812, as Thomas Haynes introduced "soft bog earth" (peat moss) combined with rich manure for improved growth in pots (Haynes, 1812). In the 1800s, the horticultural market saw the advent of "Jadoo Fibre," a substrate created by fermenting harvested peat moss with soot, gypsum, and nutrients (American Gardenings, 1898). This marked a shift towards cleaner, lightweight alternatives with enhanced moisture retention.

Throughout the 19th century, various materials, including loam, decayed manure, sand, and ashes, were explored for growing strawberries in containers. The term "pot culture" emerged to describe this out-of-season containerized cultivation, primarily adopted by average gardeners and lacking commercial importance (Fuller, 1862). Towards the late 19th century, Liberty Hyde Bailey and Charles Ellas Hunn conducted research on commercial strawberry production in containers under glass. Their "pot method" employed fibrous loam, sand, bone flour, and dissolved rock, demonstrating increased profitability through premium-priced off-season fruit and higher overall yields (Hunn and Bailey, 1897).

By the 1920s, France and Belgium pioneered soilless production in stone containers, transitioning to wooden boxes in the 1930s (Lieten, 2013). Despite initial hesitations in the early 20th century due to higher investments, interest in soilless container methods persisted. In the 1960s, Italy introduced vertical systems with white plastic containers filled with peat moss, and in the 1980s, the focus shifted to "bag culture," utilizing peat-filled bags (Lieten, 2013). Challenges were evident, but success emerged by the mid-1980s. Concurrently, the ability to cold store strawberries for up to eight months and the release of the high producing cultivar 'Elsanta' in 1981 fueled interest in year-round production.

During this time, there was an increased interested in closed hydroponic systems, such as the nutrient film technique (NFT), which recirculates a nutrient solution onto the plants root systems. However, with strawberries being a longer cycle crop (~12 months), *Phytophthora* became a common disease issue, which led to a rapid decline in water culture usage. Growers then more commonly adopted the practice of cultivating strawberries in buckets filled with 5-6 liters of peat moss, fertilized by dripline and free-draining, preventing the spread of root pathogens and increasing commercial interest in substrate culture.

3.b. Modern soilless strawberry production

Controlled environment strawberry production has witnessed a rich history spanning nearly a century across Asia and Europe, showcasing remarkable milestones in cultivation techniques (Lieten and Misotten, 1992; Oda and Kawata, 1993). As of 2013, Japan boasted over 6,000 hectares of greenhouse strawberry production, primarily soil-based, with a rising trend in substrate culture occupying around 500 hectares (Yoshida, 2013). China follows suit, with approximately 80% of its extensive 55,000-hectare strawberry production occurring under plastic-covered greenhouses (Carter et al., 2005).

In Europe, low-tech methods, dating back to the 1930s, paved the way for protected strawberry cultivation (Lieten and Misotten, 1992). By 2004, Europe had around 9,000 hectares of greenhouse and tunnel production, constituting about 20% of the total strawberry cultivation area (Lieten et al., 2004). Italy, France, and Spain emerged as key players in protected strawberry cultivation, with soil-based systems dominating, and limited prevalence of soilless production in Belgium and the Netherlands (Hancock and Simpson, 1995; Lieten, 2006).

In North America, protected strawberry culture is rapidly expanding, with notable research on tunnel-based soil cultivation (Samtani et al., 2019). Soilless tabletop cultivation, an emerging method in Canada and the United States, reflects a growing paradigm shift. Despite minimal soilless greenhouse production in North America, commercial operations or planned ventures in Canada, Mexico, and the United States indicate a changing landscape (Cantliffe et al., 2007; Kempler, 2004; Paranjpe et al., 2003). The absence of an established greenhouse production industry in the United States, driven by year-round supply from open-field producers, is gradually giving way to increased consumer interest in locally produced, high-quality strawberries, especially during California's off-season (Guda, 2019; Kadir et al., 2006).

Distinguishing North American greenhouse production is the prevalent use of ever bearing cultivars, a departure from short-day cultivars in Asia and Europe (Samtani et al., 2019; Lieten 2006; Yoshida 2013). Research delves into photoperiodic and photosynthetic responses, addressing physiological disorders like tip burn (Garcia and Kubota, 2017). While supplemental lighting is considered, its economic viability for greenhouse strawberry production remains a topic of debate (Kubota et al., 2016). The imperative lies in developing methods and technologies to enhance yield or quality, justifying higher prices and ensuring sustainability in North American greenhouse strawberry production. The evolving landscape promises a dynamic future for controlled environment strawberry cultivation on a global scale. Research initiatives have displayed an exponential increase in soilless strawberry research efforts (Figure 1), ranging from substrate composition, lighting, harvesting efficiency, economics, and overall system management.

3.c. Characteristics of soilless substrates

Although soilless production is commonly thought to be a modern practice, it can be dated back to nearly 4,000 years ago by the Egyptians. For modern horticulture, soilless substrates have played a pivotal role in both ornamental and edible horticultural crop production since the 1950's. This versatile category encompasses any growing media other than mineral soil, offering a diverse range of components to optimize plant growth (Gruda et al., 2013). Typical organic constituents, such as peat moss, coconut coir, and tree bark, have been staples in soilless substrates, with the incorporation of other organic materials steadily increasing. Inorganic components like rockwool, perlite, vermiculite, sand, and pumice further contribute to the variety of soilless substrate formulations (Gruda et al., 2013). The productivity of soilless substrate production systems stems from their ability to finely control rootzone water and air conditions, manage nutrient availability, and mitigate soilborne pathogens (Raviv et al., 2008).

Each substrate component introduces unique physical properties influencing water and air availability, emphasizing the importance of careful selection during the substrate creation process (Carlile et al., 2015). Metrics like water holding capacity and air porosity, contributing to total porosity, define the substrate's ability to retain water and facilitate air exchange. Optimal ranges for these metrics vary depending on container geometry and the specific crop under consideration. Rootzone oxygen requirements, which vary among horticultural crops, further emphasize the need for tailored substrate selection (Morard and Silvestre, 1996).

The interplay between substrate components and container geometry determines the total porosity and root zone water: air ratio. Pore size distribution and container height are also critical factors influencing these conditions. Fine particles creating micro-pores enhance water holding capacity, while coarse particles form macro-pores, improving drainage and air porosity. Container height influences gravitational drainage, making substrate components and container selection crucial for maintaining optimal air and water conditions (Gruda et al., 2013; Savvas and Gruda, 2018).

Rootzone chemical characteristics, including pH and electrical conductivity (EC), result from intrinsic substrate properties, nutrient solution contents, and irrigation strategies. Rootzone pH influences nutrient availability, with an optimal range of 5.5-6.5 for most plants. Factors such as substrate components and rootzone water: air ratio impact pH dynamics. Similarly, EC, influenced by nutrient solution, irrigation practices, and plant uptake, requires careful monitoring to prevent salt stress. Additional considerations include cation exchange capacity and nutrient concentrations in the rootzone (Carlile et al., 2015; Gruda et al., 2013; Savvas and Gruda, 2018).

A significant advantage of soilless substrate cultivation is the absence of natural soilborne pathogens, promoting a healthier growing environment (Raviv et al,, 2008). However, managing the potential decomposition of substrate components over extended production periods is crucial. Woody materials not properly composted can lead to nitrogen immobilization, negatively impacting plant and microbial growth. Understanding and addressing these factors during the substrate selection process are vital for ensuring optimal plant performance in soilless substrate cultivation (Barrett et al., 2016; Gruda et al., 2013).

4. Substrate Components for Strawberry Production

4.a. Overview of components and data from previous experiments

In European soilless strawberry cultivation, peat or a coconut coir-peat mixture stands out as the dominant substrate, with rockwool and perlite making lesser appearances (Lieten et al., 2004). Substrates, characterized by distinct physical and chemical properties, form the backbone of the cultivation process. Recent studies on alternative growing media for strawberries have garnered significant attention, emphasizing the need for well-defined water holding capacities and air porosities to optimize production (Depardieu et al., 2016; Diel et al., 2018; Kuisma et al., 2014).

Strawberries exhibit a higher root oxygen requirement compared to common greenhouse crops, making high air porosity a crucial characteristic for ideal substrates. Studies, such as Evans and Gonzalez-Fuentes (2011), suggest that 'Albion' root growth is optimal at air-filled porosities ranging from 13-25%, aligning with general recommendations for soilless substrates (Yeager et al., 2007). However, further research is needed to conclusively determine the optimal air porosity range for strawberry production, considering factors like yield.

Chemically, strawberries thrive in the standard soilless substrate production pH range of 5.5-6.5 (Lucas and Davis, 1991), with an EC range typically reported as 1-1.45 dS m-1 (Gallace et al., 2017). The effectiveness of a broader EC range of 1.1-2.1 dS m-1 has also been demonstrated, providing comparable growth and production (Sun et al., 2015).

Extensive studies have delved into the impact of substrates on strawberry yield, vegetative vigor, and fruit quality. Yield comparisons reveal variations influenced by cultivar and environmental conditions. Peat-based mixtures, owing to their favorable physical and chemical characteristics, emerge as popular choices, although environmental and economic factors warrant ongoing exploration into alternative substrate components and mixtures. The shift towards sustainable and renewable resources becomes paramount, considering the environmental, social, economic factors with resources like peat (Barrett et al., 2016; Savvas and Gruda, 2018). Continuous research into new substrate components is essential for informed and sustainable choices in European soilless strawberry production.

Coconut coir, wood fiber, tree barks, compost, and biochar are becoming more widely used alternatives to peat moss for strawberry production. A study investigating the effect of wood fiber and compost as growing media components for the cultivar 'Malling Centenary' in wood fiber and peat and 'Murano' is wood fiber and compost showed that yield was maintained in all substrate treatments compared to a coconut coir control (Aurdal et al., 2022). However, a 75% wood fiber and 25% compost mixture produced the highest yield, suggesting that components of nutritious materials with wood fiber may improve the strawberry plant performance (Aurdal et al., 2022). Another study that also investigated 'Malling Centenary' investigated a 80% peat and 20% perlite mixture, with 100% coconut coir, and three particle textures of 100% Norway spruce wood fibers (coarse and fine textured fiber treatments). This study discovered that plants grown in 100% wood fiber showed earlier berry maturation and had less unripe berries (Woznicki et al., 2023). Similar to these findings, Depardieu et al. (2015) found that a peat and sawdust mixture and a 100% aged bark substrate had comparable yields to coconut coir dust. A study by Vandecasteele et al. (2023) displayed that a wood-based biochar amended with peat showed no effect on the nutrient retention or nutrient balance.

4.b. Peat

Peat, a heterogeneous mixture of decomposed plant material, is a vital component in horticultural substrates widely utilized in container crop production (IPS, 2018). It is crucial to note that the extraction of peat is an environmentally degradative process, prompting bans and extraction regulations in peat-producing various regions globally. The major distribution of peatlands in North America lies in the boreal zone of Canada and Alaska, and the northeastern and north-central United States (Gajewski et al., 2001).

Despite its significance in horticulture, the processes involved in obtaining peat necessitate reconsideration due to environmental degradation concerns associated with extraction. In 1998, peat production for horticultural use was estimated at 25,000,000 m^3/yr, with the United States consuming the largest share at 5,800,000 m^3/year (Caron et al., 2003). The particles in peat, ~75% of which are less than 2.0 mm in diameter, contribute to its high variability based on the source, allowing for diverse pore sizes and properties (Fields et al., 2014). This variability, however, can lead to a lack of uniformity in horticultural-grade peat.

The long-term harvest and supply of peat present potential detrimental future issues, primarily environmental concerns. Peat bogs, natural environments abundant with life, play a significant role in carbon sequestration, similar to wetlands. Unfortunately, harvesting peat from these bogs reopens carbon storage, releasing greenhouse gases into the atmosphere. This has led to the gradual ban of peat from horticultural use in many European countries.

Peat has been a major soilless substrate for decades in the greenhouse and nursery industry (Raviv and Lieth, 2008). Derived from peat bogs in Canada or Europe, peat is expensive and not produced locally in the southern United States, resulting in high initial shipping costs for nurseries in these regions (Fields et al., 2014). Sphagnum peat, the primary type used in the industry, is acidic with a pH ranging from 3.5 to 4.5, exhibiting high cation exchange capacity (CEC) and nutrient content relative to other soilless substrates like bark (Raviv and Lieth, 2008).

Despite its widespread use, challenges arise due to peat's characteristics, such as its ability to retain water, holding nearly 20 times its weight, making it suitable for horticultural use. However, this characteristic becomes problematic in open-air nursery production in the southern U.S., where heavy rain events can lead to over-hydrated containers, increased runoff, and nutrient loss (Fields et al., 2018). Additionally, peat's inefficiency in retaining water during dry conditions, coupled with its potential to develop hydrophobic conditions, can impede plant development and decrease production efficiency (Argo and Biernbaum, 1996).

4.c. Coconut coir

Coconut coir, known by various trade names such as coco dust, coco peat, and coco fiber, is a versatile horticultural substrate derived from the fibers of the mesocarp of the coconut palm *(Cocos nucifera L.)* (Abad et al., 2005). Produced as a byproduct of coconut processing in tropical countries like Sri Lanka, India, the Philippines, Indonesia, Mexico, Costa Rica, and Guyana, coir has gained prominence in the horticulture industry as an alternative to peat due to peat usage restrictions (Evans et al., 1996).

Primarily grown in tropical coastal areas, coconut palms have been shown to absorb salts that can occasionally result in high salinity in coir, affecting its electrical conductivity values (Fields et al., 2014). This characteristic, combined with the shipping costs associated with tropical regions, adds to the considerations when choosing coir over peat.

Traditional coconut coir comprises approximately 75% fiber and 25% fine material, derived from coconut husks during the production of oils and fruit (Raviv and Lieth, 2008; Adeniyi et al., 2019). However, coir husk chips are also available and are utilized to increase aeration due to their larger particle sizes. Coir's water holding capacity, similar to peat, allows it to hold up to nine times its weight in water due to its finer particles (Criscione et al., 2022). However, coir's hydrophilic nature and inverse ratio of unavailable water to available water mean that it holds water to a greater degree than peat in dry conditions, reducing plant stress or death (Fields et al., 2018). Notably, the lower bulk density of coir, in contrast to peat, allows for a compression rate nearly 8-10 times when formulated into bricks, while peat achieves only 2-3 times. Coir's distinctive advantage lies in its ability to be rewet after drying, overcoming the hydrophobicity often observed in peat under similar conditions (Fields et al., 2014).

The physical properties of coir dust, shaped by its particle size distribution, contribute to elevated air-filled porosity, facilitating exceptional water and gas exchange in containers (Fields et al., 2014). Studies have shown that coir fibers, when amended with pine bark, can enhance hydraulic conductivity, allowing for efficient water flow through the substrate (Fields et al., 2018). In terms of pH and nutrient content, coir generally falls between 4.8-6.9 and exhibits higher levels of pH, phosphorus, potassium, and sodium, as well as lower levels of calcium and nitrogen compared to peat (Rose and Haase, 2000).

4.d. Bark

The University of California's study on peat and bark, initiated in the late 1950s (Baker, 1957), marked a pivotal moment in the industry's experimentation with various substrates. Today, these substrates, particularly peat and bark, are widely adopted in the nursery industry. Before the 1970s, bark, mostly considered a waste product in the forestry industry, was often burned for energy production in sawmills (Raviv and Lieth, 2008). Despite this, an estimated 3.5 million tons of bark are produced annually in Quebec alone, with much of it buried or burned (Naasz et al., 2009).

Bark, constituting up to 10% volume of a tree, is composed of the tree's phloem and rhytidome and undergoes an aging or composting process. The aging process stabilizes the bark, reducing the release of nitrogen, while un-composted bark can release high levels of nitrogen (Joshi et al., 1997). The properties of bark, such as pH, water retention, and drainage, are influenced by factors like the tree species, growth conditions, age, and time of year harvested (Solbraa, 1979).

In the southeastern U.S., pine bark is predominantly utilized, while in the western U.S., bark from trees like *Pseudotsuga menziesii* (Douglas fir) is common. Pine bark, particularly from *Pinus taeda* (loblolly pine) trees, is favored for its cost-effectiveness and suitability for outdoor container production (Pokorny et al., 1986). Hydrophysical studies on pine bark by Fields et al. (2014) revealed its quick water release and high air-filled porosity, allowing for efficient drainage and making it suitable for container production throughout the U.S.

Comparisons between peat and pine bark in terms of water retention and drainage have shown that peat retains more water, but plants in peat wilt quicker than those in pine bark. Beardsell et al. (1979) found that crops in pine bark lasted 80% longer than those in peat before wilting. However, challenges arise as organic substrates, including pine bark, can become hydrophobic and challenging to rewet after drying (Airhart et al., 1978; Beardsell and Nichols, 1982). The pH of pine bark, generally acidic, is often amended with dolomitic lime to influence nutrient availability (Altland and Jeong, 2016).

The aging process of pine bark is critical for its stability and performance. As pine bark ages, microbial decomposition occurs, reducing particle size and increasing water retention. Despite becoming stabilized for plant production after approximately six months of aging, pine bark remains susceptible to shrinkage and degradation in the container. Microbial activities can lead to nitrogen release during decomposition, requiring supplemental nutrients (Jackson et al., 2009). Composting has been shown to reduce nitrogen immobilization rates (Guster et al., 1983).

Predictions indicate a steady decline in the availability of pine bark as a soilless substrate (Lu et al., 2006). To address this, alternative components like peat, coir, wood fiber, and sugarcane bagasse are suggested to enhance crop vigor through increased water retention and nutrient availability (Hoskins et al., 2014). Pine bark, remains the most common substrate in the Southeastern United States nursery industry, offering excellent aeration and moderate water-holding capacity (Owen et al., 2008). The industry acknowledges the declining availability of pine bark due to reduced timber and paper industry activities, urging exploration into alternative components for sustainability (Jackson, 2009). Studies have shown that aging processes improve wettability, making aged pine bark more suitable for container production compared to its hydrophobic fresh counterpart (Kaderabek et al., 2017). The physical characteristics of pine bark substrates, including low water-holding capacity and higher availability of water, make them distinct from peat moss and coir (Pokorny, 1984).

4.e. Wood products and fibers

The decline in the use of pine bark has prompted research into wood alternatives, offering new possibilities for horticultural substrates. Processed tree substrates (PTS) present an innovative approach, which three various forms of this product including WholeTree, Clean Chips, and Clean Chip Residual (CCR), which can all be milled in different mesh screens for diverse shapes and sizes (Boyer et al., 2012). WholeTree includes the bark, limbs, and needles of the tree and is milled all together. Clean Chips are trees that have had the limbs and needles removed, leaving behind the bark and wood. CCR is a material that is derived as a byproduct of forest thinning operations, typically being left in the pine plantations or sold to pulp mills for fuel. Research results show interchangeability between WholeTree, Clean Chips, and CCR, all with minimal growth differences, indicating the potential for cost-effective production without the need for complete de-limbing before grinding (Gaches et al., 2010).

The idea of using wood in substrates originated in Europe in the late 80s and early 90s, gaining popularity in the U.S. in the early 2000s. Research focused on species like *Pinus taeda* (loblolly pine), *Pinus strobus* (white pine), *Platanus occidentalis* (sycamore), *Acer rubrum* (red maple), and *Quercus alba* (white oak) to identify the most effective species for the industry. *Pinus taeda* amended with peat emerged as the most commonly used wood substrate in the industry due to its abundance in the southeastern U.S, with an estimated 29 million acres planted (Perdue et al., 2017). The trend extends to alternatives like coconut coir and bio-char, all aiming to replace perlite while being environmentally conscious and cost-effective.

PTS provides economic advantages by allowing local production, reducing transportation costs associated with traditional peat-perlite mixtures (Jackson et al., 2009). However, using alternative substrates like PTS requires adjustments in container capacity, liming rates, and fertilizer requirements. Plant production in wood-based substrates, compared to peat and pine bark, tends to face nitrogen deficiencies due to high rates of nitrogen immobilization (Handreck et al., 1993). Nutrient issues in wood substrates are attributed to the larger amounts of usable carbon but limited available nutrients to microorganisms (Jackson et al., 2009). Composting wood materials is one method employed to alleviate nitrogen immobilization by lowering the carbon-to-nitrogen ratio and facilitating initial breakdown. Little to no composting of any wood substrate materials is done however. Altering fertigation practices to compensate for the N-draw is the most common solution.

Wood fiber substrate products like HortiFiber, GreenFiber, HydraFiber, and ForestGold are gaining prominence globally, aiming to replace perlite and reduce peat usage as a horticultural substrate component. The wood fiber industry is rapidly evolving, with companies contributing to the quest for sustainable and environmentally friendly alternatives in horticulture (Gruda, 2019).

4.f. Spent growing media

The disposal of spent substrates after cultivation poses an environmental threat, prompting a shift towards the circular economy's "3R" principles – Reduce, Reuse, and Recycle. With strawberry production cycles typically lasting for less than a year, many soilless growers dispose of large quantities of substrates annually. While some spent growing media can be recycled as soil improvers or solid fuel, the risk of containing harmful chemicals remains. Although mineral wool has been demonstrated to be suitable for strawberry production, its derivation from non-renewable sources and involvement in costly and energy-intensive production and recycling processes pose environmental concerns (Bussel and Mckennie, 2004; Pluimers et al., 2000). If not appropriately recycled, mineral wool may persist in landfills for thousands of years (Bussel and Mckennie, 2004).

The reuse of growing substrates, though economically and environmentally beneficial, raises concerns about nutrient accumulation impacting subsequent plant growth, emphasizing the need for careful consideration of physio-chemical properties and crop-specific tolerances during reuse (Recchia et al., 2013; Incrocci et al., 2010). Wonznicki et al. (2024) investigated the reuse of coconut coir, peat, and wood fiber, and results show that yields slightly decreased in peat and wood fiber in the second and third year of reuse; however, the yield was comparable to the yield in the new and reused coir. Mineral wool slabs have been shown to be reused at the end of the growing period by grinding the slab into fine particles to be amended into new substrate blends (Donners et al., 2017).

5. Container Geometry and Container Types for Strawberry Production

5.a. Container geometry

The interaction between substrate and container dimensions is crucial, impacting plant support, aeration, and moisture levels. Long (1933) identified an "ideal" growth medium as pathogen-free, aerated, with high water-holding capacity, and efficient drainage. Container dimensions significantly influence media characteristics, affecting aeration and water-holding capacity. The same substrate exhibits distinct properties in containers of varying sizes; larger containers yield different results than smaller ones. While total porosity may remain consistent, air space increases with container height, impacting container capacity. Challenges in shorter containers include poor aeration and a "perched water table" after irrigation, affecting plant growth. Container height influences gravitational drainage, reducing water holding capacity due to decreased capillary action and adhesion with increasing column height (Gruda et al., 2013). Careful selection of substrate components and containers is essential to ensure favorable air and water conditions (Barret et al., 2016). Inadequate drainage may cause root asphyxia, while low water availability can induce drought stress, both adversely impacting plant performance (Barrett et al. 2016; Gruda et al. 2013). The regions within a container vary in air and water conditions, with hypoxic conditions at the container base and higher gas exchange in the upper regions (Evans and Gonzalez-Fuentes 2011; Morad and Silvestre, 1996).

The container volume plays a pivotal role in shaping the trajectory of plant growth within a pot, wielding influence over various critical facets. Its impact is profound on root development, as larger pots provide ample space for the cultivation of extensive and robust root systems, thereby fostering healthier above-ground growth. Additionally, container volume serves as a determinant for water retention, with larger pots acting as a buffer against dehydration, maintaining consistent soil moisture levels and preventing water stress. The facilitation of adequate aeration is another hallmark of larger containers, ensuring optimal oxygen exchange for roots and mitigating issues such as suffocation. Moreover, the size of the container influences nutrient availability, with larger pots boasting a more substantial reservoir of nutrients, consequently reducing the necessity for frequent fertilization and fostering sustained and balanced growth. Beyond its direct impact on plant development, the volume of containers also resonates in the realm of production costs, influencing the economic considerations associated with soilless media.

Notable reports, including studies by Cantliffe et al. (2001) and Dufault and Waters (1985), underscore the multifaceted implications of container volume. While Takeda and Hokanson (2000) observed comparable yields from 'Chandler' and 'Camarosa' strawberry plants in greenhouses using different-sized pots, Dijkstra et al. (1993) emphasized a minimum peat volume requirement for optimum yields from 'Elsanta' strawberry growth in specific pot sizes, illuminating the nuanced relationship between container volume, plant growth, and production outcomes. Container size alters substrate properties, highlighting the importance of optimizing the substrate system (combination of container and substrates).

5.b. Container types

A variety of container types are utilized in strawberry cultivation, each with its unique set of advantages and challenges. One commonly used system is the pot/container setup, involving either pots, troughs, or buckets that one or multiple strawberry plants are planted into. Initially praised for its open surface that creates a favorable microclimate after planting. However, this system can also lead to potential issues such as increased humidity levels which can lead to fruit rot from the fruit being exposed to the substrate. This leads to growers having to be careful with excessively wide containers (more than 18 cm) to minimize fruit contact (Jones and Lee, 2020). While these containers provide an accessible planting surface, the risk of fruit spoilage necessitates strategic management practices to ensure optimal conditions for fruit development and quality preservation.

In contrast, layflat growbags offer an alternative system that eliminates fruit-to-substrate contact and employs wider pots (typically 20-26 cm), allowing more space for root development and growth (Nguyen et al., 2019). Despite this advantage, since these come pre-filled with substrate, there is typically a higher costs, and limits the growing media formulation options a grower can use. These growbags are discarded after each growing cycle, so this can also contribute to plastic waste, raising sustainability concerns (Nguyen et al., 2019). The trade-off between enhanced plant growth and the environmental impact of plastic waste requires careful evaluation when considering the adoption of such systems.

6. Growing Systems Utilized for Soilless Substrate Strawberry Production

Various growing systems are utilized in soilless substrate strawberry production, each with distinctive setups, advantages, and challenges (Smith et al., 2021). Solid growing media, such as pot and bag cultures, involve systems where the bags or containers rest directly on the ground or on ridges and elevated beds filled with substrate. These systems benefit from soil contact, enabling earlier growth due to the warmth retained by the substrate. However, the ground-level positioning poses challenges similar to traditional soil planting, affecting picking efficiency and labor conditions (Jones and Lee, 2020).

The table-top or high-bed system, elevated above ground level on poles, provides economic advantages by reducing labor costs. The varying heights of these systems, ranging from 80 cm to 1.4 meters, cater to different picking techniques, accommodating seated or stand-up picking practices (Brown et al., 2019).

The "Rakuchin" Japanese system introduces innovative hanging structures, facilitating easy mobility within the production area for transporting substrate, plants, fruit, and conducting spraying operations. However, constructing these systems requires robust designs to support the substantial weight of the hanging infrastructure (Johnson, 2018). Hanging systems offer mobility advantages but demand sturdy construction due to the considerable weight borne by the hanging structure. On the other hand, liquid growing media systems, like nutrient film technique (NFT) or aeroponics, embrace both recirculating (closed loop) and water-to-waste (open loop) systems, providing distinct nutrient solution control methodologies (Garcia and Perez, 2021).

These systems are often associated with different structures like glasshouses, high/low tunnels, and indoor vertical farming setups. Each structure offers unique advantages in terms of climate control, light exposure, and space utilization, contributing to the diversity of soilless strawberry growing systems (Perez and Garcia, 2020).

7. Potential Limitations of Soilless Substrate Strawberry Production

Soilless substrate culture for strawberries is not without its challenges, prominently centered on the significant upfront investment and ongoing operational costs. The establishment of soilless systems demands a substantial initial investment, notably higher when compared to conventional field-grown systems. The infrastructure required for soilless cultivation, encompassing specialized equipment, climate control, and irrigation systems, incurs substantial expenses, posing a challenge for smaller-scale or financially constrained growers to embrace this technology (Li et al., 2020). Additionally, the recurring costs associated with maintaining these systems can be substantial, impacting the overall economic feasibility of soilless cultivation.

The management of water quality stands out as another critical challenge in soilless strawberry production. Precise control of pH and electrical conductivity (EC) levels in the nutrient solutions is paramount. Deviations in these parameters can adversely affect plant health and growth, necessitating meticulous monitoring and adjustment (Rorabaugh et al., 2019). Equally crucial is the maintenance of optimal micronutrient levels in the nutrient solutions. Deficiencies or imbalances in micronutrients, such as iron, manganese, or zinc, can impede plant development, influencing yields and quality (Zaller, 2019). This requires continuous monitoring and adjustments in the nutrient solution, adding complexity and costs to the production process.

Ongoing expenses related to substrate materials and pots also contribute significantly to the overall financial burden. The price of these materials can notably impact annual operational costs. Depending on the chosen substrate components—such as peat moss, coconut coir, or other organic and inorganic elements—the annual expenses for replenishing or replacing substrates and containers can pose a financial challenge. The need for regular substrate replacement to maintain optimal conditions for plant growth further adds to the operational costs (Li et al., 2020).

In summary, while soilless substrate culture offers numerous advantages in strawberry production, the substantial initial investment, ongoing operational costs, water quality management, and expenses related to substrates and containers present notable limitations that growers must carefully consider before adopting this cultivation method.

8. Future Trends

One significant advancement on the horizon involves the integration of automation and robotics into strawberry production processes. Tasks conventionally performed by human labor, such as fruit picking, are increasingly being automated. Robots equipped with advanced sensors and manipulators are being developed to delicately pluck ripe strawberries, reducing reliance on manual labor and optimizing efficiency (Kong et al., 2020). This transition toward mechanization not only addresses labor shortages but also improves precision and productivity in harvesting operations.

Lighting research stands as another pivotal area in soilless strawberry cultivation. As the industry moves toward year-round production, optimizing light conditions becomes paramount. Advancements in LED technology and tailored light spectrums are being explored to enhance plant growth, flowering, and fruit quality, ensuring consistent and optimal yields irrespective of seasonal variations (Palmitessa et al., 2021). These innovations in lighting technologies aim to mimic and optimize natural sunlight, fostering improved photosynthesis and fruit development throughout the year.

Additionally, strategies to decrease row spacing are gaining attention. A significant hurdle in traditional strawberry harvesting is the need for adequate spacing between rows, allowing room for harvesters to maneuver. Research is focusing on compacting row layouts without compromising harvesting efficiency. Innovations in cultivation techniques, such as modified plant architecture or container-based systems, aim to optimize space utilization while maintaining accessibility for harvesting equipment (Fernandez et al., 2019).

Enhancing flavor characteristics remains a crucial frontier. Despite advancements in production methods, ensuring strawberries retain their distinct taste and aroma is a priority. Researchers are exploring breeding techniques and cultivation practices that prioritize flavor over other attributes, aiming to preserve and even enhance the natural sweetness and tanginess of strawberries (Sønsteby et al., 2020).

Moreover, there is a growing interest in sustainability, including the reuse of spent substrate materials. Efforts are underway to develop innovative ways to recycle and repurpose substrates used in soilless cultivation. Strategies to rejuvenate spent substrates through composting or processing aim to minimize waste and production costs while maintaining or even enhancing substrate quality for subsequent crop cycles (Martinez et al., 2021).

As the agricultural landscape continues to evolve, these futuristic trends in soilless strawberry research promise to revolutionize cultivation methods, productivity, and sustainability, paving the way for a more efficient, technologically advanced, and flavorful strawberry industry in the years to come

Figures:

Figure 1.1. Field of annual hill plasticulture grown strawberries in North Carolina.

Figure 1.2. Field grown strawberries with runners growing off of them and rooting into the soil.

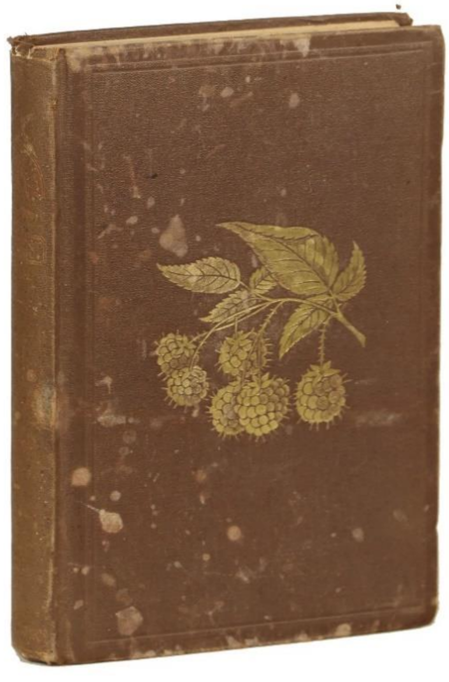

Figure 1.3. *The Small Fruit Culturist* by Andrew Fuller (1867) is one of the earliest references of "pot culture" of strawberries.

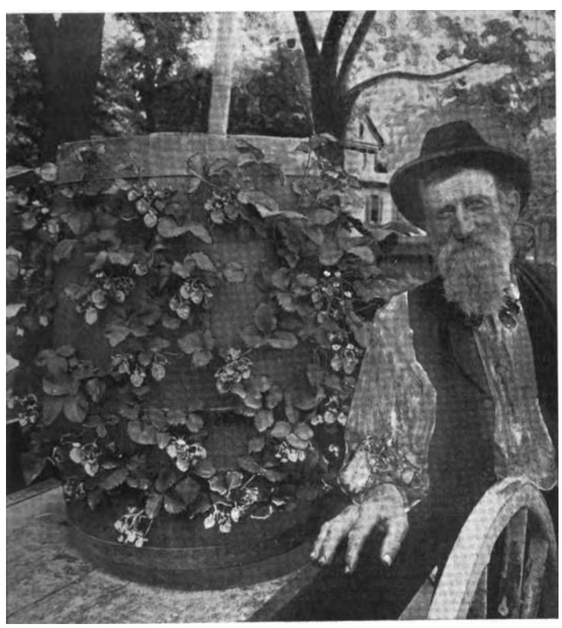

Figure 1.4. Historical image from *American Gardening* magazine from 5 February, 1898, showing the method of "barrel culture" to grow strawberries out of the soil.

Figure 1.5. Soilless substrate production of strawberries inside a plastic greenhouse structure located in Zebulon, NC.

Figure 1.6. Advanced raised soilless substrate system for strawberry production in Spain.

Figure 1.7. Canadian peat bogs before peat extraction.

Figure 1.8. Close-up view of peat moss, which is the most commonly used soilless substrate.

Figure 1.9. Truckload awaiting shipment of coconut coir in India. Coconut coir is produced from the husk and shell of the coconut.

Figure 1.10. Close-up view of coconut coir, a commonly used substrate for soilless fruit production.

Figure 1.11. Loblolly pine (*Pinus taeda*) trees, which are typically grown for pulpwood and the saw timber industry. However, research is investigating its use for producing wood fiber substrates for the horticulture industry.

Figure 1.12. Loblolly pine wood chips that were hammer-milled into a wood fiber substrate.

Figure 1.13. Substrate lay flat coconut coir growbags that had strawberries growing in them for 10 months. This material is typically sent to the landfill or composted after each crop cycle since it is not reused.

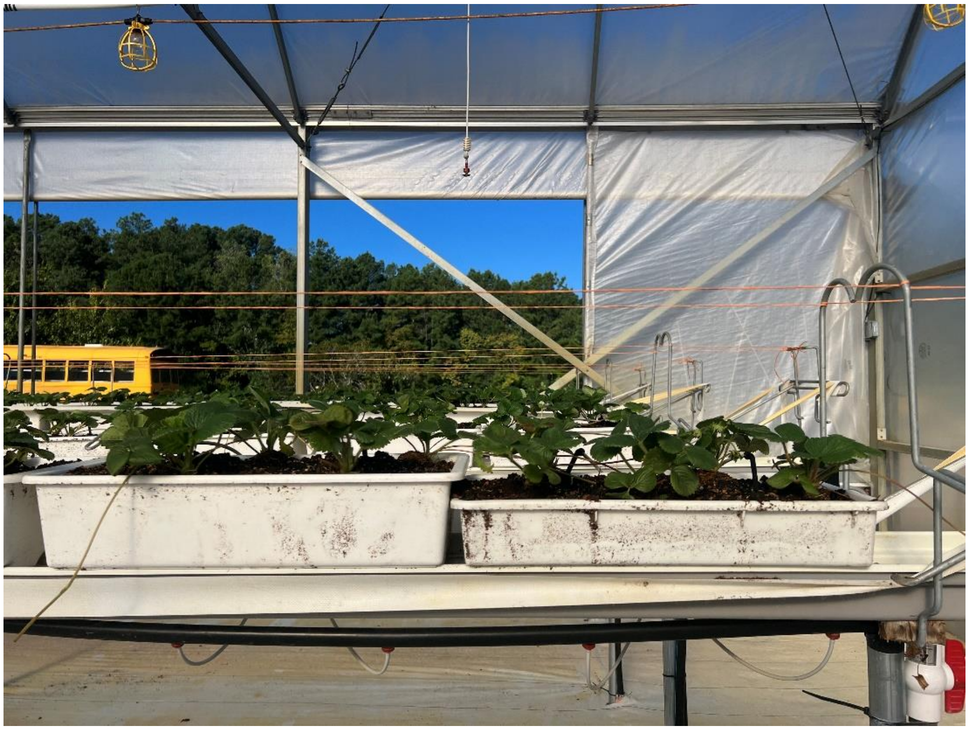

Figure 1.14. Example of two different container heights of troughs used for strawberries.

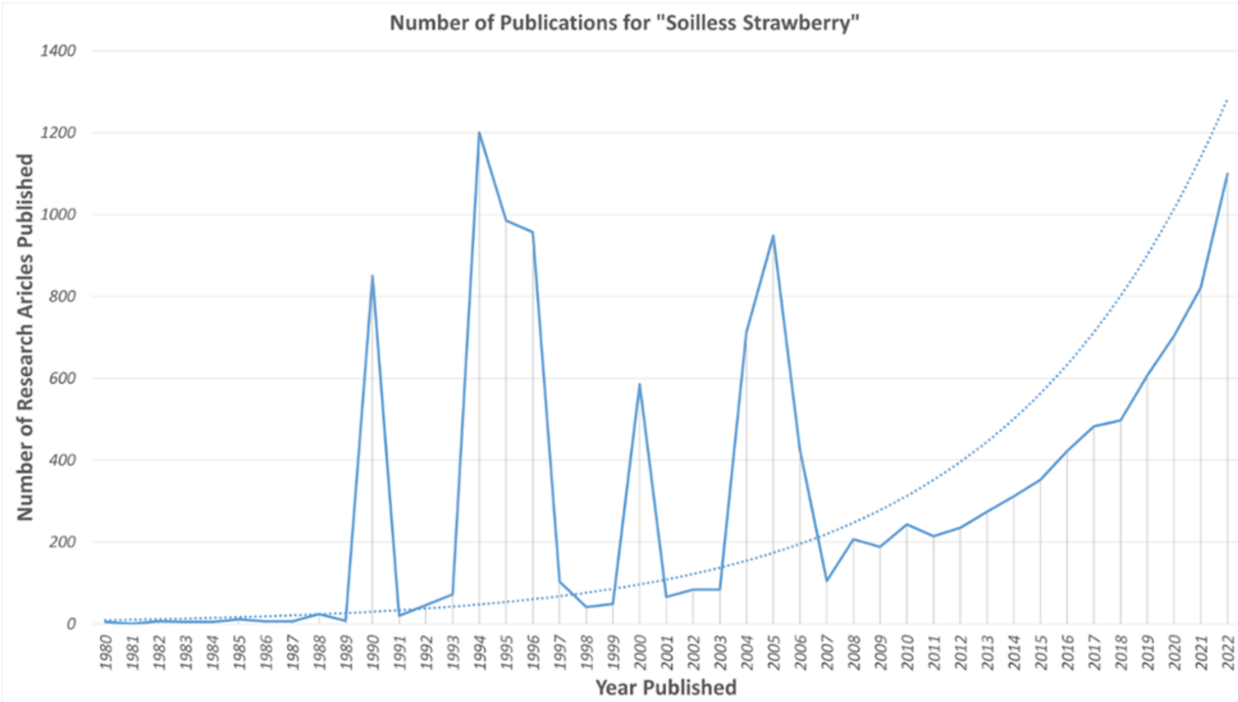

Figure 1.15. Google scholar search result for “soilless strawberry” from the years 1980-2022.

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CHAPTER 2

Evaluation of Peat and Coconut Coir Blended with Pine Wood Products, Aged Pine Bark, and Perlite: Impacts on Substrate Physical Properties and Mother Plant Productivity of 'Albion' Strawberry (*Fragaria* × *ananassa*)

Abstract:

As the demand for locally grown produce, especially fresh fruits like strawberries, continues to escalate, the necessity for year-round production becomes increasingly apparent. Given that strawberry propagation primarily relies on vegetative methods, the international industry requires a large number of cloned plants, such as bare roots and plugs, to fulfill geographical and seasonal demands. While 'Albion' strawberry plants have gained popularity in the United States for their extended-season production capabilities, the nuanced environmental factors influencing daughter plant production remain incompletely understood, including the impact of soilless substrates. Given the increasing concern for availability of peat resources and the heightened governmental restrictions on its usage, there is a projected growth in the market for peat-reduced alternatives. Coconut coir also may present drawbacks such as a significant CO_2 footprint due to transportation and concerns regarding ecosystem quality and human health. Therefore, this study aims to evaluate the influence of various wood fiber products, aged pine bark (APB), and perlite as potential 20% and 40% amendments compared to a commercial industry standard (50% perlite: 25% peat: 25% coconut coir) to reduce reliance on components such as peat and coir, for enhancing strawberry mother plant production. During the peat-based experiment, plants grown in a 20% APB amended substrate exhibited an increase in daughter plant yield. Similarly, 20% and 40% amendments of various wood fiber products showed no significant decrease in daughter plant yield compared to the industry standard. In the coir-based experiment, various wood fiber components showed a slight reduction in daughter plant numbers. These findings suggest that utilizing wood-based products may be suitable for mother plant production of strawberries with minimal adverse effects on growth and production.

Introduction:

As the demand for local produce continues to rise, particularly for fresh fruits like strawberries, the need for year-round production becomes evident (Zacharaki et al., 2024). While California, Florida, Oregon, and Washington dominate strawberry production in the United States, accounting for 96% of the production area, access to high-quality, local produce remains a challenge for those residing outside these states, especially during winter months (USDA-NASS, 2017; Banerjee et al., 2022). Controlled Environmental Agriculture (CEA), utilizing heated greenhouse structures and soilless substrates, presents a potential solution to bridge this gap and meet consumer demand throughout the year (Bradford et al., 2010; Hamano et al., 2014). Despite the advancement in CEA systems, both traditional field and CEA growers face the challenge of ensuring a consistent supply of high-quality plants to meet the rapidly escalating demand.

Since the propagation of strawberries is mainly vegetative, primarily via aerial stolons that yield daughter plants for large-scale propagation (Heide et al., 2013), the international industry requires a vast number of cloned plants, such as bare roots and plugs, to meet the geographical and seasonal demand (Hoffmann, 2020). In order to have enough planting material (daughter plants) to supply fruit growers, propagators have to carefully coordinate the reproduction of strawberry stock plants for several years and in multiple geographical locations [USA and Canada (Samtani et al., 2019)].

'Albion' strawberry plants have become popular in the United States for extended-season production. Albion is commonly classified as a "day-neutral," ever-bearing (EB) flowering plant since it is capable of flowering under both long-day and short-day light conditions (Garcia and Kubota, 2017). Albion and other EB cultivars often produce low numbers of daughter plants in open-field propagation systems (Durner et al., 1984). The intricate environmental factors influencing daughter plant production, especially in EB cultivars designed for extended production windows, are not fully understood (Guttridge, 1955). These EB cultivars, propagated in North American nurseries, contribute over two billion strawberry plants annually, highlighting their economic importance (Hoffmann, 2020).

The current field propagation system is vulnerable to several problems including a decrease in plant quality after long storage, limited availability of planting material, and high risk of pathogen transmission from the nursery to the production field (Hoffmann, 2020; Samtani et al., 2019; Pritts and Sjulin, 2019). Additional factors such as rising land and labor costs, environmental challenges, and the declining availability of soil fumigants pose significant hurdles (Samtani et al., 2019; Gutherman, 2017). In response, an alternative approach gaining traction is the transition to soilless substrate-based systems, providing a controlled environment that mitigates soil-borne pathogen pressures and enhances overall productivity (Ameri et al., 2012; Martinez et al., 2013; Samtani et al., 2019). Utilizing strategies such as precision indoor propagation [PIP (Xu and Hernandez, 2020)], to produce strawberry mother plants and asexually propagate them in a controlled environment utilizing soilless substrates may offer solutions to certain challenges encountered in open-field strawberry propagation. A gap exists in the current literature regarding available data on the impact of substrate composition on the growth and productivity of strawberry mother plants.

Considering the diminishing availability of peat resources and the heightened governmental restrictions on its usage in some countries, there is an anticipated growth in the market for alternatives that are peat-reduce/free (Caron et al., 2013; Blok et al., 2019; Altieri et al., 2014). Despite coconut coir and mineral wool being existing options available in the market, they are not devoid of sustainability concerns. Coir, a commonly used substrate, exhibits potential drawbacks such as a substantial CO_2 footprint due to extended transportation and concerns related to ecosystem quality and human health (Chauhan et al., 2020). While mineral wool has been demonstrated to be suitable for strawberry production, its involvement in costly and energy-intensive production and recycling processes pose some environmental concerns (Flury et al., 2012; Bussel and Mckennie, 2004; Pluimers et al., 2000). If not appropriately recycled, mineral wool may persist in landfills for thousands of years (Bussel and Mckennie, 2004).

In recent years, various research teams have investigated alternative substrates like composts, rice hulls, and biochar for soilless strawberry production (Altieri et al., 2014; Signorini et al., 2023; Vandecasteele et al., 2023; Depardieu et al., 2016). However, several factors such as availability, consistency, and unstable physical/chemical properties may pose issues with these components. Forestry products, including wood fiber, have emerged as promising components for sustainable growing media (Drotleff, 2018; Harris et al., 2020). The global market for wood fiber has witnessed steady growth for nearly 15 years, with its initial development dating back to the 1970's (Jackson, 2019). There is a growing interest in incorporating wood fiber in soilless strawberry production (Woznicki et al., 2023; Aurdal et al., 2022; Kusnierek et al., 2021). These substrates are attracting attention due to their lower cost and renewability (Harris et al., 2020). Nevertheless, they present challenges, including nitrogen immobilization, particularly shown when used at 40% amendment rates or more by volume (Gruda et al., 2000; Handreck, 1993; Harris et al., 2020; Jackson et al., 2008), and the possible leaching of toxic compounds (Gruda et al., 2000; Bugbee and Heins, 2018).

Existing research has demonstrated the viability of various wood fiber types as effective alternatives to reduce the reliance on peat or coir in soilless strawberry production (Woznicki et al., 2023; Aurdal et al., 2022; Kusnierek et al., 2021). Notably, success has been achieved even at 100% wood fiber usage rates through careful engineering of the physical and chemical properties to create a suitable root environment (Woznicki et al., 2023). Despite these promising findings, the commercial adoption of wood fiber as a substrate necessitates thorough evaluations of the properties of different wood fiber products and their effectiveness as growing media. While prior studies have showcased encouraging outcomes, comprehensive assessments are imperative for successful implementation in commercial settings.

This research aims to address the gaps in understanding the influence of wood fiber products utilized as soilless substrates, specifically their impact on substrate physical properties and mother and daughter plant production of strawberries. By comparing major wood fiber sources with traditional substrate materials like peat, coir, perlite, and aged pine bark (APB), a more thorough evaluation of incorporating wood components in soilless substrates for strawberry mother plant production can take place.

The first objective was to evaluate the physical properties of peat and coir amended with various wood fiber products, aged pine bark, and perlite. The second objective was to evaluate peat or coir-based substrates blended with three wood products, APB, and perlite for effects on strawberry mother and daughter plant growth and substrate chemical properties over time. This second objective was separated into two trials, the coir and the peat-based trials, so the data will not be cross analyzed between the two. It is hypothesized that the amount of peat and coir can be reduced without a reduction in plant growth.

Materials and Methods:

Substrate preparation and blending. Sphagnum peat (Premier Pro-Moss, Quakertown, PA) was used as one of the primary substrate components. The compressed bale of peat was unpacked and placed into a large tub. Water was incrementally added in 2-liter increments, and the peat was manually agitated to facilitate proper water absorption, reaching an initial moisture content (IMC) of 50%. Similarly, compressed 5kg blocks of coconut coir (Jiffy Group International, Zwijndrecht, the Netherlands) were hydrated by adding 14 liters of water in 1-liter increments. The blocks were fluffed by hand until hydrated to an IMC of 50%.

The blending process involved combining each of these substrates with ForestGold [FG (Pindstrup, Midtjylland, Denmark)], a disc-refined wood fiber sourced from *Pinus sylvestris*, GreenFibre [GF (Klasmann-Deilmann, Niedersachsen, Germany)], an extruded fiber from *P. sylvestris*, processed tree substrate [PTS (NCSU, Raleigh, NC)], a hammer-milled product made using *P. taeda*, aged pine bark [APB (Pacific Organics, Henderson, NC)] aged for six months in outdoor windrows and specifically engineered, and coarse-grade perlite (Supreme Perlite, Portland, OR).

The experimental substrates for the peat-based trial were formulated by combining peat with each of the five components at two volumetric blend percentages (20% and 40%) along with a 100% peat treatment. For the coir-based trial, coir was combined with each of the five components at two volumetric blend percentages (20% and 40%) along with a 100% coir treatment. As an strawberry industry standard (McKean et al. 2019), an experimental substrate was made utilizing 50% perlite, 25% peat, and 25% coir (by volume) and included in each of the two trials. All blending procedures were carried out by hand. Notably, fibers in FG, the 100% peat, and the 100% coir substrates tended to aggregate during blending, forming clumps. To optimize fiber distribution and minimize clumping, these aggregates were meticulously separated by hand. It's worth noting that in commercial settings, mechanical equipment is commonly employed to blend these materials together (Drotleff, 2018; Dickson et al., 2022).

Initial substrate pH and electrical conductivity (EC) for each treatment were measured using the 2:1 saturated media extraction method [2 parts deionized water: 1 part substrate (Argo and Fisher, 2002)] using a hand-held pH and EC meter (HI 9813-61; Hanna Instruments, Woonsocket, RI). Based on the initial substrates pH values, it was determined that dolomitic limestone was needed to be incorporated during the substrate blending to raise the pH to the suggest value of 5.2-6.5 for strawberries (Akon, 2019). The incorporation rates were 84.05 g per cubic foot for the 100% peat substrate and all 20% and 40% amendments, and 33.62 g per cubic foot for the 100% coir substrate and all 20% and 40% amendments. The industry-standard substrate received dolomitic limestone at a rate of 84.05 g per cubic foot. Substrates were incubated for 2 d in seal plastic bags to allow for lime/pH equilibrium and then the pH and EC were re-tested using the same method as described previously.

Substrate physical properties. For each experimental substrate treatment (Table 1), three representative samples of each substrate were taken to determine the physical properties using the NCSU Porometer Method (Fonteno et al. 1995). Container capacity (CC), air space (AS), total porosity (TP), and bulk density were derived from this procedure.

Particle size distribution (PSD) analysis was performed only on the seven substrate components (peat, coir, perlite, GF, FG, PTS, and APB). This involved passing 150g of oven-dried samples through five U.S. Standard sieves with mesh sizes ranging from 0.106 to 6.3 mm, in addition to a bottom pan. The sieves and pan underwent shaking for 5 minutes using an RX-29 RoTap sieve shaker (278 oscillations per min, 150 taps per min; W.S. Tyler, Mentor, OH). The particle fractions retained on each sieve and pan were subsequently weighed, and their proportions were assessed as a percentage of the total sample.

Greenhouse experiment and experimental design. The experiment was conducted from 24 April 2023 to 3 July 2023 in a glasshouse at North Carolina State University in Raleigh, NC evaluating substrate compositions effect on the plant growth of 'Albion' strawberries (*Fragaria* x *ananassa*) planted in 2.9 L black containers (Hummert International, Topeka, KS).

Environmental parameters, including daily light integral [DLI (Hobo Data Logger, Cape Cod, MA)], average daily air temperature (ADT), and relative humidity (SensorPush HT, New York, NY) were measured throughout the experimental period. DLI, ADT, and relative humidity were reported as (mean ± sd) 25.2 ± 9.3 mol $m^{-2}d^{-2}$ of photosynthetically active radiation, 22.3 ± 8.1 °C, and 76 ± 4.6%, respectively.

To accommodate for the anticipated stolon growth, containers/plants were elevated by placing them on top of 5.08-cm x 15.24-cm x 304.8-cm treated lumber, supported by 38-cm tall buckets (Home Depot, Atlanta, GA), on benches. Each trial occupied its designated bench, allowing the solons to cascade down the sides of the benches (Figure 1). Each week, combing and organization of the stolons were carried out to minimize entanglement and shading, ensuring optimal plant development among treatments.

The experiment included 12 treatments for each the peat or coir trials. These treatments comprised varying proportions (0% to 40% by volume) of perlite, APB, GF, FG, or PTS, with each trial also containing the industry-standard substrate (Table 1). The substrate treatments were arranged in a randomized complete block design. Each replicate consisted of one containerized plant, with five replicates assigned to each substrate treatment. However, 10 replicates were designated for the industry-standard substrate, as it was employed as a treatment in both the peat and coir-based trials. This resulted in a total of 120 containers/plants [(12 treatments for the peat trial + 12 treatments for the coir trial) x 5 single-plant replications].

Vegetatively propagated 72-cell plugs of 'Albion' strawberries were purchased from a local nursery specializing in the cultivation of virus-free plants, rooted in a peat moss propagation blend [Fresk-Pik Produce Inc., Wilson, NC (Figure 2A)]. Following one week of acclimation in the glasshouse, plants with comparable crown diameter (1.5 cm), leaf count (4.0-5.0), and visually assessed root health were carefully chosen (Figure 2B). Subsequently, these selected plants were transplanted into 2.9 L pots, ensuring that the initial moisture content across all substrate treatments was standardized at 50% for consistency. Each container was weighed while being filled with substrate to allow for equal densities between replicates within the assigned treatment.

Each replicate container underwent individual hand-irrigation at the start of the trials and were brought to effective container capacity [ECC (maximum mass of the container, substrate, and plant after gravitational water has drained)] as described by Sammons and Struve (2008), then weighed. When substrate moisture (container weight) decreased by 25% of the maximum ECC, then that amount of water was re-applied plus an additional 30% to allow for the recommended leaching volume (Gontijo et al., 2020). Moisture content was determined through twice-daily weighing of each container, and correlations between container weight and moisture content were established through gravimetric techniques for each substrate treatment. Adjustments were made every seven days to accommodate increasing plant growth by reweighing and determining the adjusted ECC.

Plants were fertilized at each irrigation with a commercial complete fertilizer with micronutrients (Jack’s 20-nitrogen (N)-4.4 phosphorus (P)-16.6 potassium (K)-0.15 magnesium

(Mg)-0.02 boron (B)-0.01copper (Cu)-0.1iron (Fe)- 0.05 manganese (Mn)-0.01molybdenum (Mo)-0.05 zinc (Zn), JR Peters, Inc., Allentown, PA) at a rate of 100 mg L-1 N. A supplemental Calcium nitrate was separately applied once a week (Jack's 15N-0P-0K, JR Peters, Inc., Allentown, PA) at a rate of 75 mg L-1 N. Fertilizer solutions were applied by hand directly to the substrate surface and under the plant canopy to prevent foliage wetting. Beginning on day 45, all plants were irrigated automatically between 2 to 4 times daily, with all treatments receiving the same amount of water (150 mL/pot per fertigation event). This was due to the plants requiring a more frequent supply of water as the plant biomass and stolon network increased overtime.

Measured plant growth traits. Weekly assessments of substrate pH and EC were conducted on each replicate using the nondestructive pour-through method (Cavins et al., 2004), employing the same handheld pH and EC meter as previously described. Before each data collection, plants were irrigated to effective container capacity two hours in advance. Subsequently, 75 mL of deionized water was uniformly poured over the substrate surface, collecting approximately 50 mL of leachate, which was then analyzed to measure pH and EC.

Nondestructive measurement of leaf SPAD chlorophyll content (SPAD 502 Plus Index Meter from Konica Minolta, Tokyo, Japan) was undertaken for each replicate at the d 35 and d 70. Three measurements were acquired on the most recently fully expanded leaf and subsequently averaged to determine each leaf's SPAD value. Throughout the trial, the quantification of flower buds was systematically recorded, and once apparent, they were promptly removed.

At the conclusion of the trial, the number of daughter plants with at least one leaf was recorded for each replicate. Additionally, the count of primary stolons directly attached to the mother plant was determined for each replicate. Following the count, each stolon was severed at the crown of the plant, and the length of each stolon was measured individually for every replicate. The measured lengths of all stolons per replicate were aggregated to calculate the total stolon length per plant. The internode distance between each daughter plant on an individual stolon was measured for all stolons in each replicate. The entire stolon network, encompassing all stolons and daughter plants on a single plant, was subjected to a 48-hour drying process at 80 degrees Celsius, and dry weights were subsequently recorded.

Following stolon removal, each strawberry mother plant underwent evaluation. The number of crowns per mother plant replicate was documented. To determine crown diameter, a digital caliper (Fisherbrand, Fisher Scientific) was used. One measurement was taken, followed by turning the caliper 90 degrees and taking another measurement, with the average of these measurements representing the crown diameter. Once measured, the mother plant was cut at the substrate surface, and its dry weight was determined following the previously described procedure.

Statistical analysis. Each trial was grown seperately on one bench inside the NC State University greenhouse by Randomized Complete Block Design (RCBD). Each substrate mix type was defined as an independent treatment. ANOVA was use to analysis the substrate effect, and Tukey's HSD analyzed multiple comparisons used to compare the effects of each substrate. Mean separation used Tukey's honestly significant difference with $\alpha = 0.05$.

Results and Discussion:

Particle size distribution. The particle size distribution (PSD) of individual substrate components was analyzed, revealing variations in the distribution of various particle sizes (Table 2). Perlite and APB exhibited the highest percentages of particles in the coarse-sized fraction

(>2.0mm), with values of 67.3% and 54.4%, respectively (Table 2). Notably, while perlite showed minimal presence in the >6.3 mm fraction, bark contained 16.4% in this category, resulting in perlite having nearly double the amount of particles as APB in the 2.0-6.3 mm fraction. FG also demonstrated relatively high percentages of coarse-sized particles, accounting for 43.7% of its composition, primarily due to aggregated clumps of fibers that remained intact during sieving. Conversely, coir, GF, and PTS contained the least amount of coarse-sized particles, representing 7.8%, 7.2%, and 8.0%, respectively. The majority of particles for coir, GF, and PTS fell within the medium-sized fraction (0.3-2.0 mm), comprising 72.7%, 72.2%, and 76.0%, respectively. Peat and FG exhibited the highest percentages of fine-sized particles (<0.3 mm), with values of 28.4% and 23.6%, respectively. GF and coir also contained a relatively high amount of fine-sized particles, accounting for 20.6% and 19.5%, respectively.

It's worth noting that Bartley (2019) and Dickson et al. (2022) have suggested that the higher proportion of fine particles in these materials may be attributed to delicate fibers being damaged during the sieving process. In contrast, perlite and APB contained the least amount of fine-sized particles, with values of 9.8% and 14.8%, respectively. Peat and FG exhibited similar PSD within all the size fractions.

Peat-based experiment.

Physical properties. The components utilized for blending and the rate of the amendment interacted in effect on TP, AS, and CC (Table 3). The highest TP was observed in the 100% peat (90.6%), while the lowest was shown in the industry standard mix and 40% APB blend with 75.2% and 73.4%, respectively (Table 3). It was observed that as the blend percentage increased, the TP decreased for peat blended with perlite, APB, and PTS. Conversely, results from Dickson et al. (2022) indicated that TP increased with the blend percentage of peat with PTS. For GF, TP increased with the blend percentage, while it remained stable for FG. Notably, TP was most similar to peat across substrates when components were blended at 20%, but this difference grew for 40% rates. While there are no established standards or guidelines for strawberry substrate TP, various recommendations exist in the literature. Yeager et al. (2007) suggested a TP range of 50% to 85% for substrates used in the nursery industry, while Riviere (1980) recommended a TP of 75%. De Boodt and Veronck (1972) and Goh and Haynes (1977) advocated for an ideal substrate with 85% total porosity. It's worth noting that substrates can even exceed 85% TP, particularly those with high wood percentages or rockwool, as observed in studies by Fields et al. (2014) and Bougoul et al. (2005).

Air space was notably influenced by the interaction of blend component and blend percent. AS increased with an increase in blend percent for GF and FG substrates, as indicated in Table 3. Conversely, incorporating 20% and 40% perlite led to a decrease in AS, while AS remained relatively constant with the addition of 20% and 40% APB and PTS. The highest observed AS was recorded for the 40% GF and 40% FG blends, reaching 29.2% and 29.6%, respectively. In contrast, the lowest AS was observed for the 20% and 40% perlite blends, with values of 13.6% and 12.7%, respectively, similar to the AS of 100% peat (14.0%). CC also varied due to this interaction. CC decreased among the perlite, APB, FG, and PTS treatments, while CC remained relatively constant for GF blends. However, CC was significantly lower compared to 100% peat, which exhibited the highest CC at 76.6%. The lowest CC was observed for the industry standard, 20% and 40% GF blends, as well as the 40% FG blend, with values ranging between 52.3% and 54.4%.

Substrate dry bulk density increased as the blend percent increased with perlite, APB, and PTS (Table 3). This could be due to these materials having higher bulk densities then the peat, as

Dickson et al. (2022) found. In contrast, FG bulk density decreased with blend percent, while GF remained constant, suggesting that FG has a lower bulk density to peat, while GF has a similar bulk density to peat.

Chemical properties. Substrate type and blend percent interacted in effect on the substrate pH over time (Table 4). At the initiation of the trial on day 0, the industry standard exhibited a significantly higher pH compared to all other treatments (6.7), a trend which persisted throughout the 70-day duration, reaching 7.2. Conversely, the lowest initial pH was observed in the 100% peat substrate, with a pH of 5.2. Across all treatments, as the blend percent increased, so did the pH levels. However, with the exception of the industry standard, all pH values remained within the acceptable range for strawberries (5.2-6.5) as suggested by Akon (2019), until day 42. At this point, the substrates comprising 40% perlite and 40% PTS exhibited slightly elevated pH levels, measuring 6.6 and 6.7, respectively. By day 56, the substrates with 40% GF and 40% forest FG also displayed pH values exceeding this range. At the conclusion of the trial on day 70, the highest pH was recorded in the substrate with 40% PTS at 7.1, while the lowest was observed in the substrate with 20% APB at 6.2. The observed increase in pH values with higher wood fiber rates aligns with findings by Jackson et al. (2009) and Dickson et al. (2022).

The EC value was influenced by substrate composition over time (Table 5). Initially, on day 0, the EC values were relatively similar, ranging from 0.50 (40% PTS) to 0.66 (industry standard), with most substrates falling within 0.02 of the 100% peat substrate (0.53). By day 14, all substrate blend’s EC values were lower than that of the 100% peat, a trend that persisted throughout the trial, indicating a decrease in EC as the wood fiber percentage increased. Conversely, an increase in EC was observed with increasing blend percentage of APB, maintaining levels similar to the 100% peat throughout the trial. Notably, at a 40% blend rate, FG substrate exhibited an EC of 0.73 (0.10 less than peat), while other wood fiber materials displayed EC levels less than 0.70. These findings suggest a potential nitrogen immobilization effect, as blending wood fiber with peat has been shown to cause such effects (Gruda et al., 2000; Handreck, 1993; Harris et al., 2020; Jackson et al., 2008).

Strawberry mother plant growth. At trial end, all strawberry plants across the various substrate treatments exhibited robust growth with dark green foliage, substantial stolon development, and demonstrated satisfactory quality and health. The analysis revealed no statistically significant differences between substrate types concerning plant dry weights (Table 6). Additionally, measurements of leaf SPAD chlorophyll content at both day 35 and day 70, crown number, stolon number, and internode length did not exhibit significant variations between the substrates.

The stolon network, comprising daughter plants and stolons, did not exhibit significant differences in dry mass per plant, with an average weight of 33.91 g (Table 6). It is noteworthy that despite significant variations in daughter plant numbers, the stolon network's dry weight may not fully represent these differences due to the minute size of newly formed daughter plants, contributing minimally to the overall mass and thus influencing the dry weight measurement insignificantly. No significant differences were observed in mother plant dry weight or total plant dry weight across all treatments.

Leaf SPAD chlorophyll content displayed relatively high values across all substrate treatments at 35 d and 70 d (Table 7). Strawberry plants with sufficient amounts of N have been shown to have SPAD values > 30 unit (Guler et al., 2006). This indicates no differences in foliage greenness among the treatments overtime. SPAD readings have been shown to have a direct linear relationship to extracted leaf chlorophyll and are also related to the leaf N concentration (Bullock and Anderson, 1998). Harris et al. (2020) and Dickson et al. (2022) also found minimum substrate effects on SPAD values for petunias grown in peat amended with 30% (by volume) FG, GF, and PTS wood components.

Flower number removed per plant was highest in the industry standard treatment (Table 7). However, the 100% peat yielded a flower number of 8.0. By the addition of amendments of 20% and 40% perlite, GF, and PTS, as well as 20% APB, and 40% FG, a significant increase in flower number was observed. Conversely, the amendment of 40% APB and 20% FG led to a decrease in flower number. Furthermore, the analysis uncovered a negative correlation between flower number and daughter plant number, with several treatments exhibiting this relationship. Particularly the observation that the 40% APB treatment, which showed the highest number of daughter plants, displayed a significantly lower flower number. The highest number of daughter plants were shown in 40% APB, which displayed a significantly lower flower number. The industry standard mix had the highest flower number, but displayed a lower daughter plant number. This suggest a complex interplay between substrate composition and reproductive output.

There was no discernible difference observed in the cumulative number of stolons per mother plant across treatments, with an average of 7.6 stolons per mother plant recorded (Table 7). In a study conducted by Morrison et al. (2018), 'Albion' strawberries cultivated in a commercial blend consisting of 25% pine bark, 55% peat, and 25% vermiculite and perlite exhibited an average of less than 7.0 stolons per mother plant over a 20-week period. The inclusion of 20% GF in the substrate blend notably increased the total stolon length per mother plant to 1079.49 cm, in contrast to 100% peat, which yielded 759.46 cm (Table 7). There also were no discernible differences in internode length among treatments, with an average length of 49.98 cm. Previous studies have indicated that photoperiod and temperature exert significant influence over strawberry stolon number and internode length (Morrison et al., 2018).

No significant differences in crown number per plant were observed across all treatments. However, a trend emerged regarding mother plant crown diameter. Specifically, the 40% perlite treatment demonstrated a significantly larger crown diameter, while the smallest crown diameter was observed in the 40% FG treatment. This discrepancy could potentially be attributed to the influence of daughter plant number on mother plant development. It is conceivable that treatments with fewer daughter plants, such as the 40% perlite treatment, allow for greater resource allocation towards mother plant growth, resulting in larger crown diameters. Conversely, treatments with higher daughter plant numbers, like the 40% FG treatment, may divert resources towards stolon network and sexual reproductive organ development, thereby limiting mother plant crown diameter. This observation underscores the intricate relationship between substrate composition, daughter plant proliferation, and mother plant morphology.

Substrate composition displayed significant impact on the number of daughter plants produced per plant. The 20% APB treatment exhibited the highest average number of daughter plants per mother plant, reaching 48.0, surpassing other treatments. Following closely were the 100% peat and 20% perlite treatments, with approximately 44.0 daughter plants per mother plant. Notably, these materials also demonstrated some of the highest electrical conductivity (EC) values, ranging from 0.83 to 0.87, coupled with high substrate total porosity (ranging from 85.8% to 90.6%), reduced substrate air space (13.3% to 14.0%), and elevated substrate container capacity (72.2% to 76.6%). Similar results for soilless strawberry growth was displayed by Ameri et al. (2012), which showed the highest growth in substrates with high water holding capacity and increased total porosity. Despite the 40% APB exhibiting the highest EC (0.88), there was a decline in daughter plant number, potentially attributable to the decrease in container capacity. These treatments also deviated significantly from the industry standard, which typically yields 36.0 daughter plants per mother plant, showcasing one of the lowest container capacities among all treatments (52.3%). The 20% FG and 40% FG treatments demonstrated the least daughter plant growth, yielding 34.2 and 32.2 daughter plants per mother plant, respectively. The latter particularly displayed the highest air space among treatments (29.6%) and a relatively low container capacity (54.4%). Among the wood product treatments, the 20% GF and 20% PTS treatments performed comparably to 100% peat moss, each yielding approximately 40.0 daughter plants per mother plant, with the 40% APB also aligning with these outcomes.

Generally, the number of daughter plants produced per plant tended to decrease with increasing amendment rates, except for FG treatments. Although the 40% PTS treatment exhibited physical property trends similar to those resulting in the highest number of daughter plants, its EC was the lowest among all treatments, potentially attributed to nitrogen immobilization, which might limit the available nitrogen for plant uptake (Gruda et al., 2000; Handreck, 1993; Harris et al., 2020; Jackson et al., 2008). This aligns with findings from previous studies by Harris et al. (2020) and Jackson et al. (2008), which demonstrated similar trends with peat amended with 40% wood fiber materials.

Coir-based experiment.

Physical properties. The highest TP was observed in the 100% coir, 20% and 40% PTS, with values ranging between 92.5%-93%, while the lowest was shown to be the industry standard, with 75.2% (Table 3). As the blend percentage increased, TP decreased in perlite and APB, while it increased in GF, and remained stable in FG and PTS. TP in the 100% coir was most similar to the 20% PTS and 20% APB, while it was most different to the industry standard, with a TP of 75.2%.

AS and CC were both influenced by the interaction of blend component and blend percent (Table 3). AS increased with an increase in blend percent for perlite, APB, FG, and PTS, resulting in a decrease in CC among these materials as blend percent increased. Notably, FG exhibited the largest percent change in AS with increasing blend percent, transitioning from 15.4% to 25% with a change from 20% to 40%. In contrast, GF showed no change in AS and only a minor increase in CC with increasing blend percent, although both blend percentages were approximately 10% higher than 100% coir. The highest AS was observed in the two GF blends, 40% FG, with AS ranging from 24% to 25%, while the industry standard was close behind with an AS of 22.8%. Conversely, the lowest observed AS was in the 20% perlite blend, with an AS of 10.4%. Regarding CC, the highest values were found in the 20% perlite blend and 100% coir, with values of 78.9% and 78.3%, respectively, while the lowest CC was observed in the industry standard at 52.3%, followed by 20% GF and 40% FG at 59.8% and 60.1%, respectively.

Additionally, substrate bulk density increased as blend percent increased with perlite, APB, and PTS, consistent with observations for the peat-based mixes (Table 3). However, the bulk density of FG and GF decreased with blend percent. Among all blends, 100% coir exhibited the lowest bulk density.

Chemical properties. Substrate type and blend percentage displayed notable effects on substrate pH over the course of the experiment (Table 4). At the start of the trial, the industry standard substrate exhibited the highest pH reading at 6.8, a trend that persisted throughout the 70-day duration, eventually reaching 7.2. Conversely, the lowest initial pH was recorded in the 40% APB treatment, which aligns with expectations for tree bark substrates with pH ranges typically falling between 3.7-4.4 (Atland and Buamscha, 2008). Notably, the 20% GF treatment demonstrated no significant change in pH at the initiation of the trial. Interestingly, this observation held steady until the trial's conclusion, with the 40% GF and 20% FG treatments also exhibiting no significant difference in pH compared to the 100% coir substrate (pH 6.7). Incremental increases in perlite amendment, from 20% to 40%, did not yield discernible changes in pH values, a pattern also observed with GF across most of the trial duration. However, for APB and FG substrates, pH levels exhibited a decreasing trend with higher blend percentages, while for PTS substrates, pH levels tended to increase with greater blend percentages. Notably, throughout the duration of the trial, all pH values on the experimental mixes remained within the recommended range for optimal strawberry cultivation. It is noteworthy that exceptions to this trend were observed, with the industry standard substrate reaching a pH of 7.2 by the trial's conclusion, and the pH of the 40% APB substrate rising to 5.9 by the end of the trial period.

Initial measurements revealed the highest EC in the 100% coir substrate (0.95), with EC values decreasing as the percentage of coir decreased in the blends (Table 5). This trend persisted over the 70-day trial period, with the 100% coir substrate consistently maintaining the highest EC. Conversely, the lowest EC readings were initially observed in the 40% GF and 40% FG blends, with EC values of 0.63 and 0.61, respectively. By the conclusion of the trial, substrates composed of 40% GF, 40% FG, and 40% PTS exhibited the lowest EC values (<0.67). While EC values fluctuated over time, none of the treatments exceeded an EC of 1.02 during the course of the experiment. It is noteworthy that an EC of 1.2 is commonly recommended for soilless strawberry production (Zucchi et al., 2017).

Strawberry mother plant growth. At the conclusion of the trial, all strawberry plants cultivated in the various substrate treatments displayed vigorous growth characterized by dark green foliage, substantial stolon development, and overall satisfactory quality and health. Despite this general vigor, notable differences were observed among the substrates in terms of flower number, crown number, total stolon length, stolon network dry weight, mother plant dry weight, and total plant dry weight. However, statistical analysis revealed no significant disparities between substrate types in leaf SPAD chlorophyll content at both 35 days and 70 days, crown diameter, stolon number, and internode length.

The stolon network, comprising daughter plants and stolons, exhibited significantly higher dry weight in the industry standard treatment, followed by the 20% perlite treatment. Conversely, the 40% APB treatment, despite displaying the highest stolon length, recorded the lowest measured dry weight. This observation may be attributed to a higher number of smaller daughter plants and the minute size of newly formed daughter plants, which could lead to lower overall weight. To delve deeper into these dynamics, future studies could focus on investigating individual daughter plant weights and their quality, providing valuable insights into optimizing substrate compositions for enhanced strawberry plant growth and development.

The highest measured mother plant dry weight was observed in treatments with 20% APB, FG, and PTS amendments, indicating that the amendment of these materials led to increased mother plant size. Conversely, the lowest measured dry weight was recorded in the 100% coconut coir treatment. Although no significant difference was found in crown diameter across treatments, variations were observed in crown number per mother plant. Specifically, the 20% FG treatment exhibited a higher number of crowns, while the 40% GF treatment displayed the lowest number of crowns per mother plant. All other treatments showed an equal crown number.

Total plant dry weight, comprising both stolon network and mother plant, was significantly higher in the industry standard treatment, followed by the 20% perlite, GF, and FG treatments. Conversely, the lowest measured total plant dry weight was observed in the 40% APB treatment, likely due to its lower stolon network dry weight. These findings highlight the influence of substrate composition on various growth parameters in strawberry mother plants, emphasizing the importance of carefully selecting and amending substrates to optimize plant size and yield.

Similar to the findings in the peat-based experiment, leaf SPAD chlorophyll content remained consistently high across all substrate treatments throughout the trial. This consistent greenness indicates that the coconut-based experimental treatments provided adequate nutrition for strawberry plants, suggesting that the inclusion of these materials likely had minimal impact on overall plant health.

Highest flower number removed per plant was observed in the 20% FG treatment, totaling 17.6 flowers. In contrast, the 100% coconut coir treatment exhibited the lowest flower numbers removed, with only 6.8 flowers, followed by the 40% APB treatment with 7.6 flowers. Interestingly, several treatments, including the industry standard mix, as well as those incorporating 20% and 40% perlite, GF, FG, PTS, and 20% APB, demonstrated an increase in flower number per plant. This suggests that the inclusion of these substrates or amendments positively influenced floral productivity in the strawberry plants under study.

Similar to the findings in the peat-based experiment, the number of stolons per mother plant did not exhibit a significant difference across treatments. However, notable distinctions were observed in the total stolon length per mother plant, with the 100% coconut coir treatment displaying the lowest length at 512 cm. In contrast, all amendments at 20% and 40% levels led to an increase in total stolon length, with the 40% APB treatment yielding the highest length of 758.38 cm. Internode length did not differ significantly between substrates. The stolon network, comprising daughter plants and stolons, exhibited significantly higher dry weight in the industry standard treatment, followed by the 20% perlite treatment.

Although no significant difference was found in crown diameter across treatments, variations were observed in crown number per mother plant. Specifically, the 20% FG treatment exhibited a higher number of crowns, while the 40% GF treatment displayed the lowest number of crowns per mother plant. All other treatments showed an equal crown number.

The substrate composition displayed a significant influence on the number of daughter plants produced per mother plant. Specifically, the 20% perlite treatment displayed the highest average number of daughter plants per mother plant, with an average of 60. Additionally, this treatment exhibited the highest CC at 78.9%, coupled with the lowest AS at 10.4%. This trend mirrors findings from the peat-based experiment, where treatments with elevated CC and relatively low AS also yielded the highest daughter plant numbers (depending on the chemical properties).

Conversely, among the treatments with the lowest measured number of daughter plants were the 20% APB and 40% PTS treatments, both averaging around 41 daughter plants. Despite the 20% APB showing slightly higher AS (3.6% higher) and lower CC (2.6% lower), its lower pH at the start of the trial (5.4) and consistently low pH throughout likely contributed to this outcome. Similarly, the 40% PTS treatment exhibited the lowest electrical conductivity (EC) throughout the trial, potentially explaining the observed low daughter plant numbers.

Moreover, the amendment of 20% perlite or GF resulted in increased daughter plant numbers compared to the 100% coconut coir treatment. Furthermore, no significant differences were found between the 100% coconut coir treatment and the industry standard, 20% PTS, and FG treatments, as well as the 40% perlite, GF, APB, and FG treatments. This suggests the potential for these materials to effectively reduce the reliance on coconut coir in strawberry cultivation practices.

Conclusion:

Based on the findings of this study, blending peat with 40% APB emerged as a significant contributor to increasing the daughter plant number per plant. However, treatments involving 20% perlite, GF, APB, PTS, as well as 40% perlite and FG, also demonstrated promising results and require only minor adjustments to current management strategies. These amendments notably increased the daughter plant yield compared to the industry standard (50% perlite, 25% coir, and 25% peat), or 100% peat.

Blending coconut coir with 20% perlite and GF proved effective in increasing daughter plant numbers. Nevertheless, the use of 100% coconut coir did not yield results comparable to the highest-performing treatments. Hence, it could be beneficial to amend coconut coir with 20% perlite, GF, PTS, FG, as well as 40% perlite, GF, APB, and FG, with minimal impact on daughter plant yield.

This study underscores the intricate interplay between the physical and chemical properties of substrates in influencing daughter plant growth in 'Albion' strawberries. Optimal performance was observed at lower AS and higher CC levels, coupled with electrical conductivity (EC) values near 1.0. Moreover, the introduction of wood fiber at 40% generally resulted in decreased EC levels, which may necessitate compensatory adjustments through higher levels of fertilization.

In conclusion, this research provides valuable insights into substrate composition strategies for enhancing daughter plant yield in 'Albion' strawberries. These findings can inform growers and agricultural practitioners in optimizing substrate formulations to maximize plant productivity and overall crop yield.

Figures and Tables:

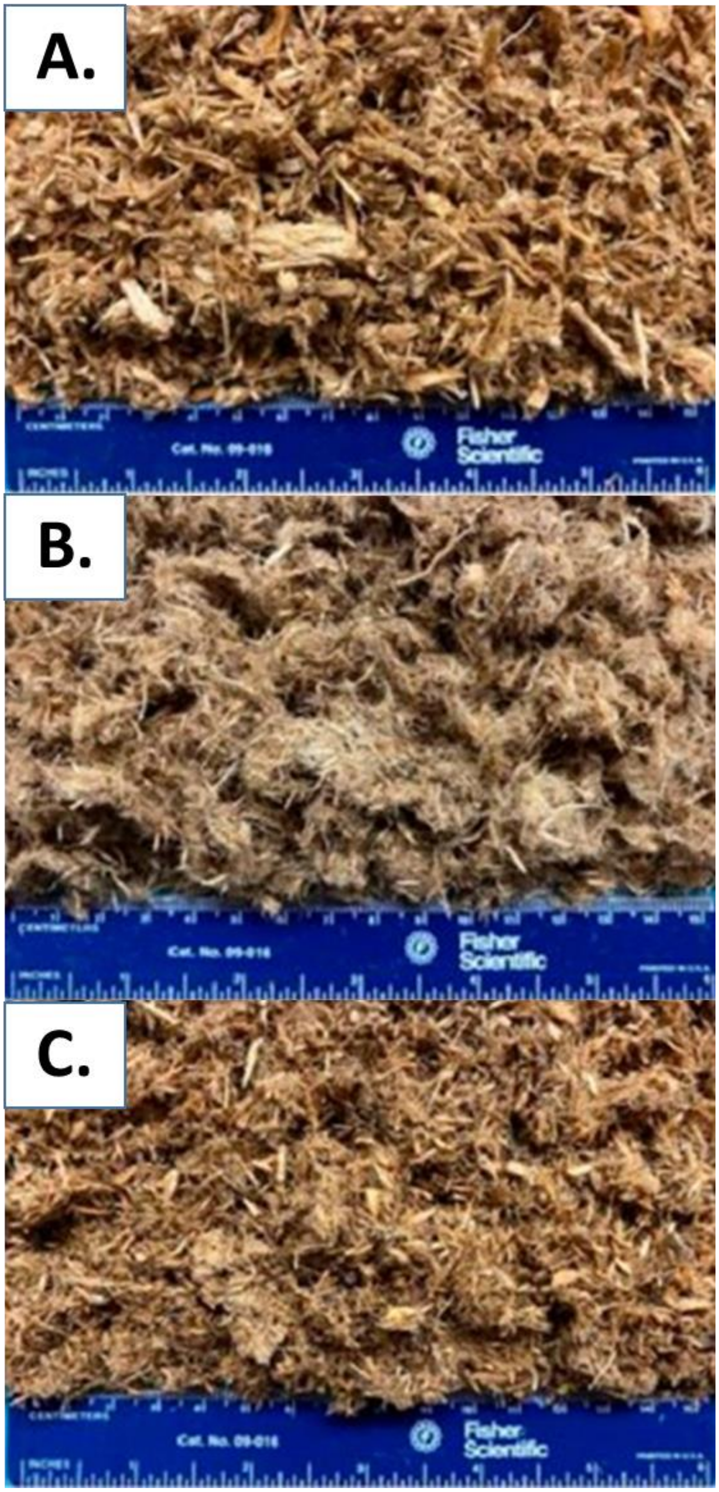

Figure 2.1. Pictures of (A) GreenFibre, (B) ForestGold, and (C) processed tree fiber components.

Figure 2.2. Pictures of (**A**) 72-cell plug flat of ‘Albion’ strawberry and (**B**) individual plug of ‘Albion’ strawberry, which were used for an evaluation trial of peat moss and coconut coir substrates amended with 20% and 40% perlite, aged pine bark, GreenFibre, ForestGold, and processed-tree-fiber.

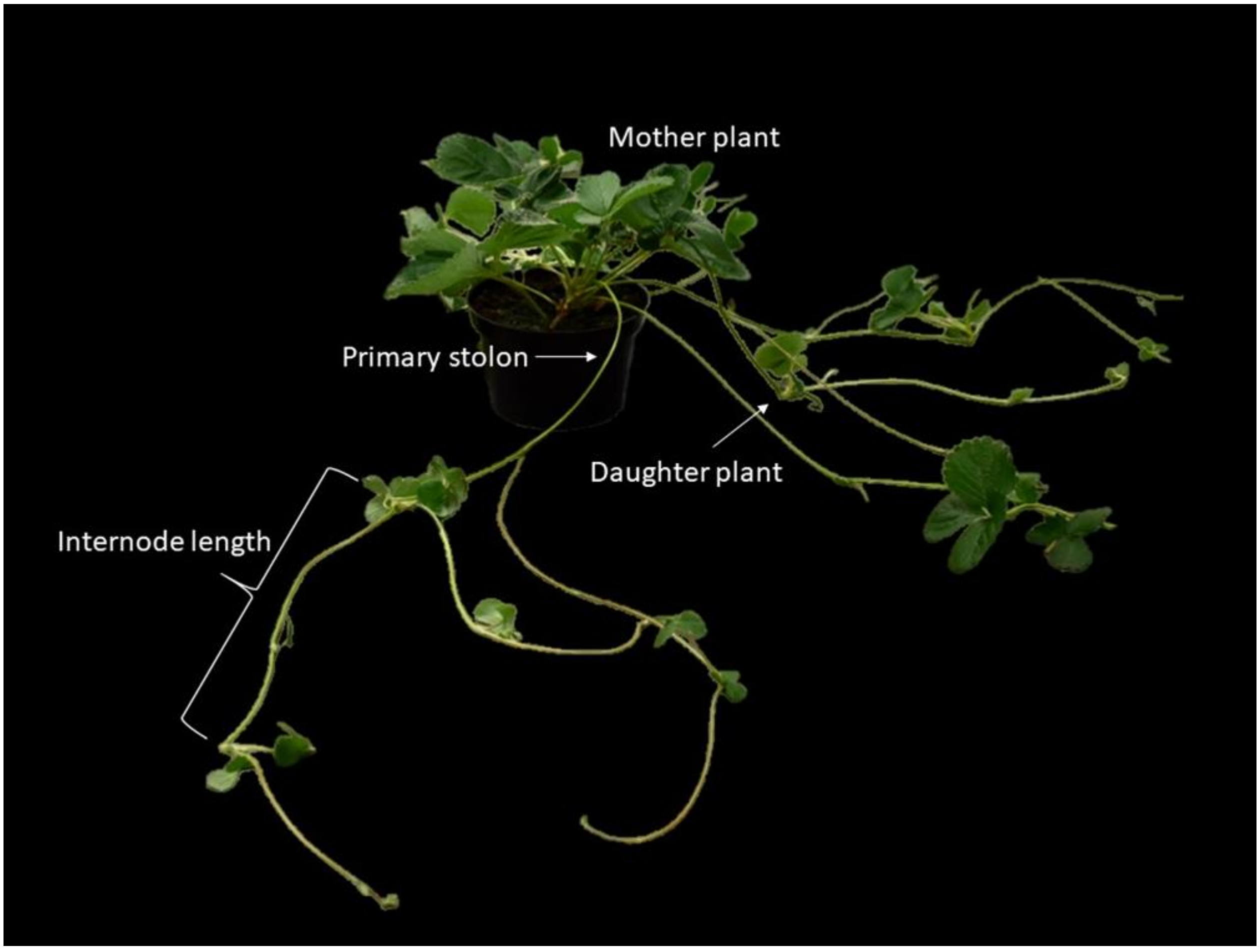

Figure 2.3. ‘Albion’ strawberry mother plant with primary stolon’s, daughter plants, and internodes displayed. These morphological features consist of several of the measurements taken for an evaluation trial of peat moss and coconut coir substrates amended with 20% and 40% perlite, aged pine bark, GreenFibre, ForestGold, and processed-tree-fiber.

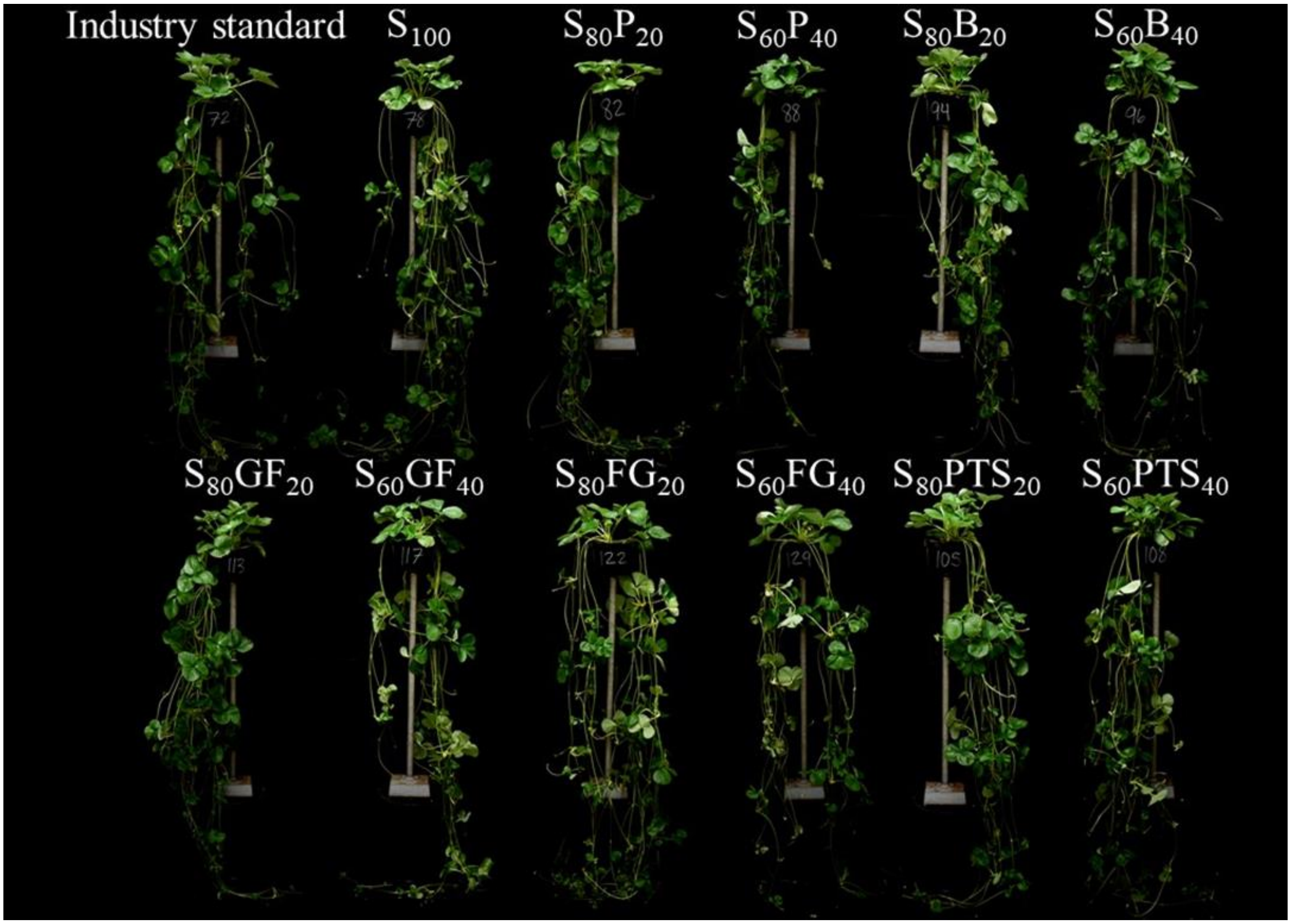

Figure 2.4. Influence of peat (S) amended 20% or 40% (by volume) with perlite (P), aged pine bark (B), GreenFibre (GF), ForestGold (FG), and processed tree substrate (PTS) on *Fragaria x anannasa* ‘Albion’ mother plant growth 10 weeks after transplantation.

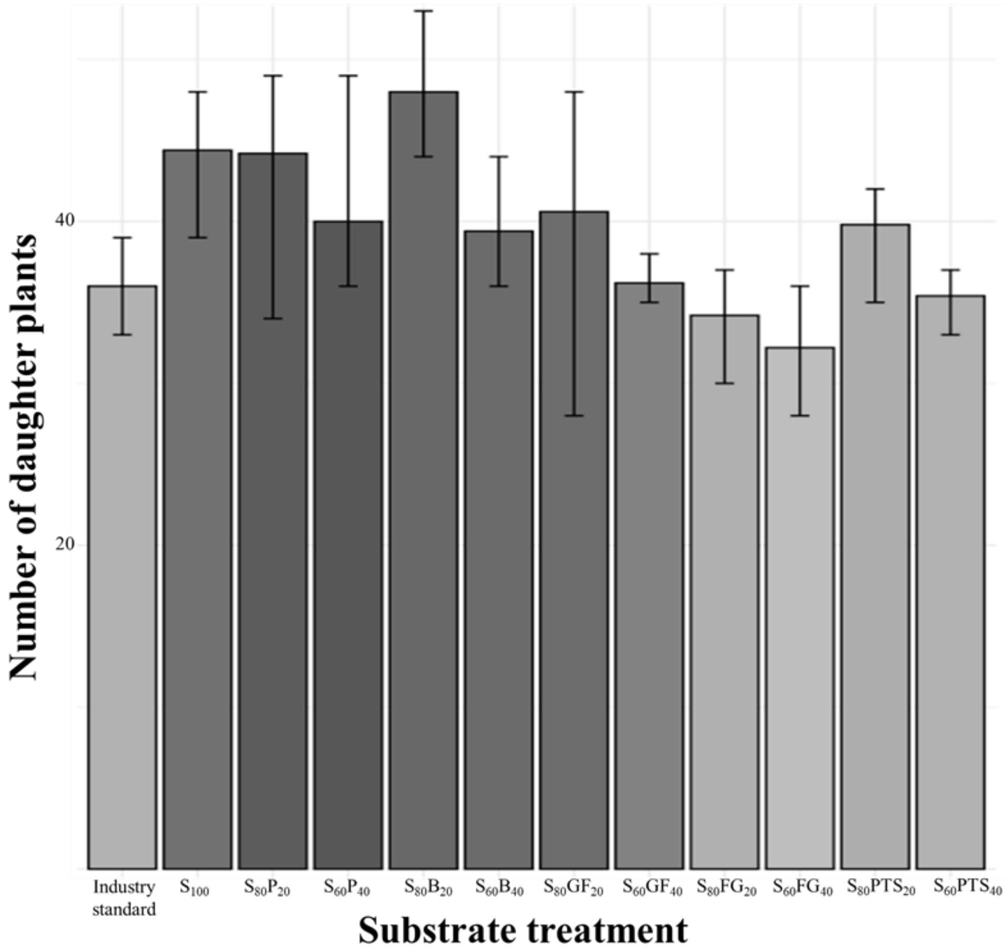

Figure 2.5. Influence of peat (S) amended with 20% or 40% (by volume) with perlite (P), aged pine bark (B), GreenFibre (GF), ForestGold (FG), and processed substrate (PTS) on *Fragaria x anannasa* 'Albion' daughter plant number growth 10 weeks after transplantation.

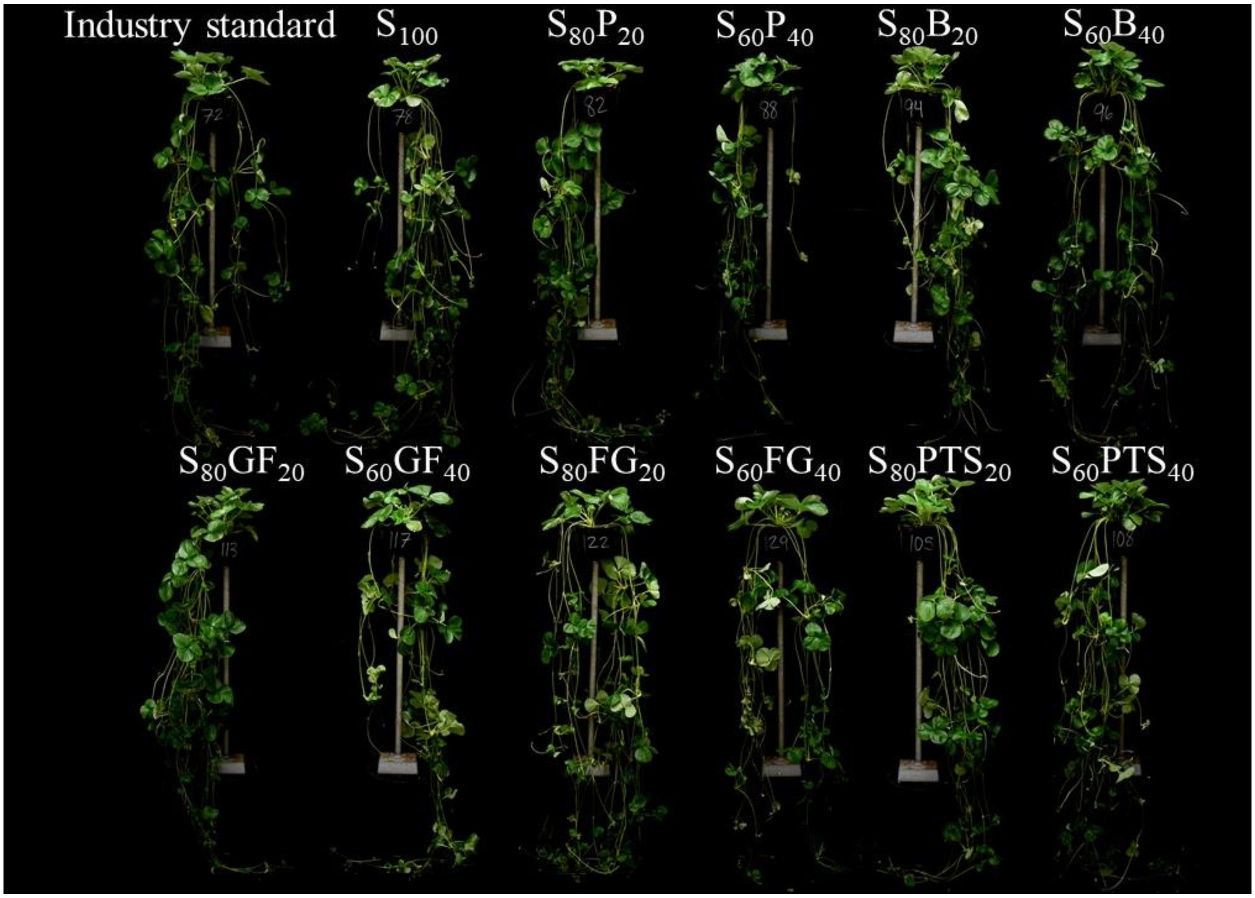

Figure 2.6. Influence of coir (C) amended 20% or 40% (by volume) with perlite (P), aged pine bark (B), GreenFibre (GF), ForestGold (FG), and processed tree substrate (PTS) on *Fragaria x anannasa* ‘Albion’ mother plant growth 10 weeks after transplantation.

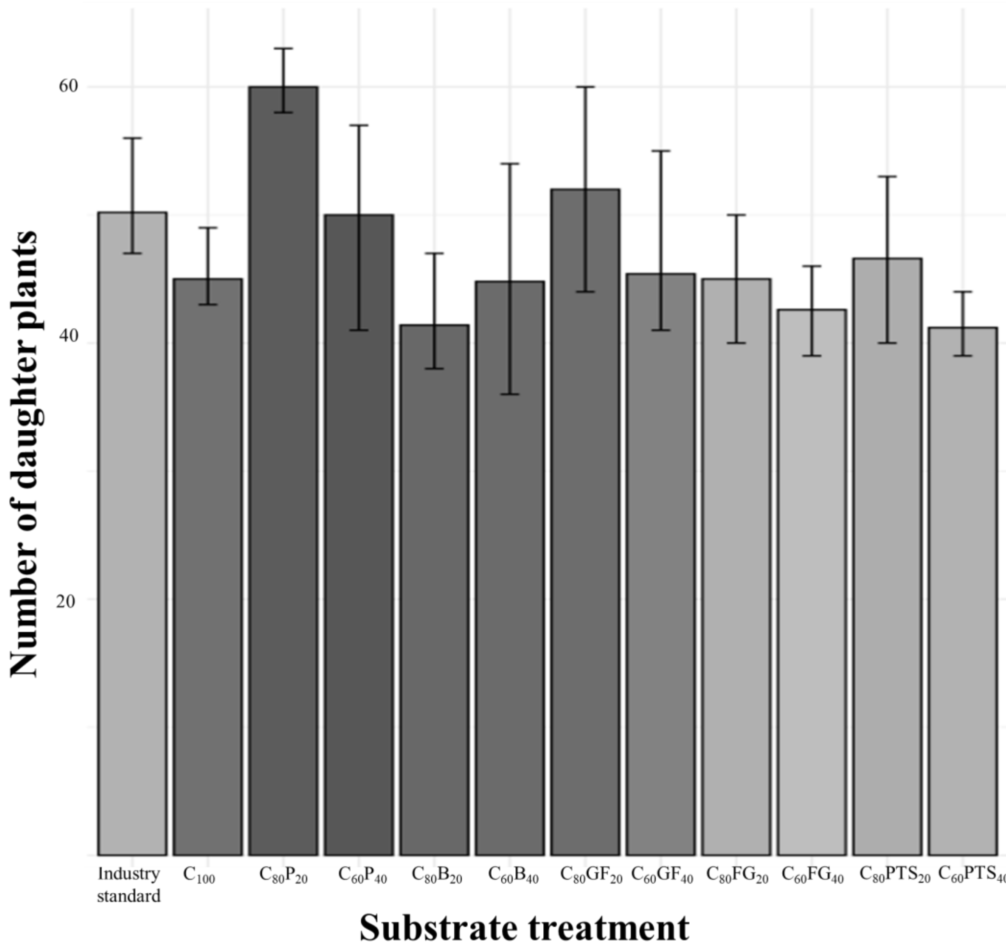

Figure 2.7. Influence of coir (C) amended with 20% or 40% (by volume) with perlite (P), aged pine bark (B), GreenFibre (GF), ForestGold (FG), and processed tree substrate (PTS) on *Fragaria x anannasa* ‘Albion’ daughter plant number growth 10 weeks after transplantation.

Table 2.1. Summary of substrate treatments for physical property determination and evaluation to grow 'Albion' strawberry mother plants

	Substrate components						
Medium	Peat	Coir	Perlite	APB	GF	FG	PTS
S_{100}[z]	100	0	0	0	0	0	0
$S_{80}P_{20}$	80	0	20	0	0	0	0
$S_{60}P_{40}$	60	0	40	0	0	0	0
$S_{80}B_{20}$	80	0	0	20	0	0	0
$S_{60}B_{40}$	60	0	0	40	0	0	0
$S_{80}GF_{20}$	80	0	0	0	20	0	0
$S_{60}GF_{40}$	60	0	0	0	40	0	0
$S_{80}FG_{20}$	80	0	0	0	0	20	0
$S_{60}FG_{40}$	60	0	0	0	0	40	0
$S_{80}PTS_{20}$	80	0	0	0	0	0	20
$S_{60}PTS_{40}$	60	0	0	0	0	0	40
C_{100}	0	100	0	0	0	0	0
$C_{80}P_{20}$	0	80	20	0	0	0	0
$C_{60}P_{40}$	0	60	40	0	0	0	0
$C_{80}B_{20}$	0	80	0	20	0	0	0
$C_{60}B_{40}$	0	60	0	40	0	0	0
$C_{80}GF_{20}$	0	80	0	0	20	0	0
$C_{60}GF_{40}$	0	60	0	0	40	0	0
$C_{80}FG_{20}$	0	80	0	0	0	20	0
$C_{60}FG_{40}$	0	60	0	0	0	40	0
$C_{80}PTS_{20}$	0	80	0	0	0	0	20
$C_{60}PTS_{40}$	0	60	0	0	0	0	40
Industry standard	25	25	50	0	0	0	0

[z]Letters represent the component(s) of the medium (S= peat, P= perlite, B= aged pine bark, GF= GreenFibre, FG= ForestGold, PTS= processed tree substrate, C = coir) and the numbers represent the percent of each component (e.g., $S_{80}P_{20}$ is 80% peat and 20% perlite).

Table 2.2. Particle size distribution of individual substrate components utilized for a substrate composition study evaluating mother plant growth of 'Albion' strawberries.

	Particle size distribution (% of dry weight)					
	Coarse		Medium		Fine	
Component	>6.3 mm	2.0-6.3 mm	0.5-2.0 mm	0.3-0.5 mm	0.106-0.3 mm	<0.106 mm
Peat	4.4 c	27.0 d	20.4 f	19.8 c	15.9 a	12.5 b
Coir	0.2 e	7.6 f	34.0 c	38.7 a	11.9 c	7.6 e
Perlite	0.4 d	66.9 a	20.7 e	2.2 g	2.1 g	7.7 d
APB[z]	16.4 a	38.0 b	20.2 g	10.6 f	8.1 f	6.7 f
GF	0.0 f	7.2 g	47.1 b	25.1 b	12.3 b	8.3 c
FG	14.5 b	29.2 c	21.2 d	11.4 e	10.0 e	13.6 a
PTS	0.0 f	8.0 e	57.1 a	18.9 d	10.4 d	5.6 g
	***[y]	***	***	***	***	***

[z]APB = aged pine bark; GF = GreenFibre; FG = ForestGold; PTS = processed tree substrate.
[y]Data represents least-square means of three replicates, and means separation used Tukey's honestly significant difference at $\alpha = 0.05$. *** indicates significant differences at $P \leq 0.001$.

Table 2.3. Total porosity, air space, container capacity, and dry bulk density measured using the NCSU Porometer method (Fonteno et al., 1995) on peat and coir-based substrates utilized for a study evaluating mother plant growth of 'Albion' strawberries.

		Substrate physical properties			
Peat-based trial	Substrate	Total porosity (% by volume)	Air space (% by volume)	Container capacity (% by volume)	Dry bulk density (g * cm^3)
	Industry standard[z]	75.2 fg	22.8 bc	52.3 e	0.11 cd
	S_{100}[y]	90.6 a	14.0 de	76.6 a	0.09 de
	$S_{80}P_{20}$	85.8 bcd	13.6 e	72.2 b	0.08 e
	$S_{60}P_{40}$	73.4 g	12.7 e	60.7 d	0.20 a
	$S_{80}B_{20}$	87.7 abc	13.9 de	73.8 ab	0.12 c
	$S_{60}B_{40}$	82.0 de	14.9 de	67.2 c	0.18 b
	$S_{80}GF_{20}$	78.3 ef	25.7 ab	52.7 e	0.10 cde
	$S_{60}GF_{40}$	82.8 de	29.2 a	53.6 e	0.10 cde
	$S_{80}FG_{20}$	83.3 cd	18.7 cd	64.6 c	0.10 cde
	$S_{60}FG_{40}$	84.0 bcd	29.6 a	54.4 e	0.09 de
	$S_{80}PTS_{20}$	88.7 ab	15.3 de	73.3 ab	0.10 cde
	$S_{60}PTS_{40}$	85.2 bcd	13.9 de	71.2 b	0.11 cd
Significance[x]		***	***	***	***
Coir-based trial		Total porosity (% by volume)	Air space (% by volume)	Container capacity (% by volume)	Dry bulk density (g * cm^3)
	Industry standard	75.2 f	22.8 ab	52.3 h	0.11 bc
	C_{100}	92.5 a	14.2 c	78.3 ab	0.08 e
	$C_{80}P_{20}$	89.3 bc	10.4 d	78.9 a	0.10 cd
	$C_{60}P_{40}$	87.1 cde	14.2 c	72.9 d	0.12 b
	$C_{80}B_{20}$	90.3 ab	14.0 c	76.3 c	0.10 cd
	$C_{60}B_{40}$	87.7 bcd	17.5 b	70.2 e	0.14 a
	$C_{80}GF_{20}$	84.6 e	24.8 a	59.8 g	0.11 bc
	$C_{60}GF_{40}$	87.1 cde	24.0 a	63.1 f	0.10 cd
	$C_{80}FG_{20}$	85.1 de	15.4 bc	69.7 e	0.10 cd
	$C_{60}FG_{40}$	85.07 de	25.0 a	60.1 g	0.09 de
	$C_{80}PTS_{20}$	92.9 a	16.4 bc	76.5 bc	0.10 cd
	$C_{60}PTS_{40}$	93.0 a	17.2 b	75.8 c	0.11 bc
Significance		***	***	***	***

[z]Industry standard = 50% perlite: 25% coir: 25% peat
[y]Letters represent the component(s) of the medium (S= peat, P= perlite, B= aged pine bark, GF= GreenFibre, FG= ForestGold, PTS= processed tree substrate, C = coir) and the numbers represent the percent of each component (e.g., $S_{80}P_{20}$ is 80% peat and 20% perlite).
[x]Data represents least-square means of three replicates, and means separation used Tukey's honestly significant difference at α = 0.05. *** indicates significant differences at $P \leq 0.001$.

Table 2.4. The pH measurements of experimental peat and coir-based substrates used in the two container grown strawberry mother plant experiments measured by the non-destructive pour-through method (Cavins et al., 2004).

		pH					
Peat-based trial	Substrate	0 DAP[x]	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
	Industry standard[z]	6.7 a	6.8 a	6.9 a	7.0 a	7.2 a	7.2 a
	S_{100}[y]	5.2 h	5.4 g	5.8 fg	6.0 fg	6.1 fg	6.3 f
	$S_{80}P_{20}$	5.6 ef	5.9 e	6.1 de	6.1 ef	6.4 d	6.6 e
	$S_{60}P_{40}$	6.2 b	6.3 b	6.5 b	6.6 c	6.9 bc	6.9 c
	$S_{80}B_{20}$	5.3 gh	5.5 g	5.6 h	5.8 h	6.0 g	6.2 g
	$S_{60}B_{40}$	5.5 fg	5.7 f	5.7 gh	5.9 g	6.2 ef	6.3 f
	$S_{80}GF_{20}$	5.6 ef	5.8 ef	6.0 ef	6.2 e	6.4 d	6.5 e
	$S_{60}GF_{40}$	6.0 c	6.1 cd	6.3 c	6.5 cd	6.8 c	6.8 cd
	$S_{80}FG_{20}$	5.7 de	5.8 ef	5.9 f	5.9 g	6.2 ef	6.4 f
	$S_{60}FG_{40}$	5.8 cd	6.0 d	6.2 cd	6.4 d	6.7 c	6.7 d
	$S_{80}PTS_{20}$	5.6 ef	5.8 ef	6.0 ef	6.1 ef	6.3 de	6.5 e
	$S_{60}PTS_{40}$	5.9 c	6.2 bc	6.5 b	6.7 b	7.0 b	7.1 b
	Significance[w]	***	***	***	***	***	***
Coir-based trial	Substrate	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
	Industry standard	6.8 a	6.9 a	7.1 a	7.1 a	7.2 a	7.2 a
	C_{100}	6.4 b	6.5 b	6.5 bc	6.7 b	6.7 b	6.7 b
	$C_{80}P_{20}$	6.3 b	6.4 c	6.6 b	6.7 b	6.7 b	6.7 b
	$C_{60}P_{40}$	6.3 b	6.5 b	6.6 b	6.7 b	6.8 b	6.8 b
	$C_{80}B_{20}$	5.4 f	5.5 f	5.7 f	5.8 f	6.1 d	6.1 d
	$C_{60}B_{40}$	5.0 g	5.2 g	5.4 g	5.6 g	5.7 e	5.9 e
	$C_{80}GF_{20}$	6.3 b	6.5 b	6.6 b	6.7 b	6.8 b	6.8 b
	$C_{60}GF_{40}$	6.2 bc	6.4 c	6.5 bc	6.7 b	6.8 b	6.7 b
	$C_{80}FG_{20}$	6.0 d	6.2 d	6.4 cd	6.5 cd	6.7 b	6.7 b
	$C_{60}FG_{40}$	5.8 e	6.0 e	6.1 e	6.2 e	6.4 c	6.4 c
	$C_{80}PTS_{20}$	6.1 cd	6.2 d	6.3 d	6.4 d	6.5 c	6.5 c
	$C_{60}PTS_{40}$	5.9 de	6.2 d	6.4 cd	6.6 bc	6.7 b	6.8 b
	Significance	***	***	***	***	***	***

[z]Industry standard = 50% perlite: 25% coir: 25% peat

[y]Letters represent the component(s) of the medium (S= peat, P= perlite, B= aged pine bark, GF= GreenFibre, FG= ForestGold, PTS= processed tree substrate, C = coir) and the numbers represent the percent of each component (e.g., $S_{80}P_{20}$ is 80% peat and 20% perlite).
[x]DAP = Days after planting that the pour-through method was used to measure pH.
[w]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at α = 0.05. *** indicates significant differences at $P \leq 0.001$.

Table 2.5. The electric conductivity (EC) measurements of experimental peat and coir-based substrates used in the two container grown strawberry mother plant experiments measured by the non-destructive pour-through method (Cavins et al., 2004).

		EC (dS/m)					
Peat-based trial	Substrate	0 DAP[x]	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
	Industry standard[z]	0.66 a	0.70 a	0.73 a	0.81 c	0.85 b	0.82 d
	S_{100}[y]	0.53 d	0.65 b	0.71 b	0.74 d	0.83 c	0.87 a
	$S_{80}P_{20}$	0.53 d	0.56 e	0.60 g	0.63 g	0.80 d	0.83 c
	$S_{60}P_{40}$	0.52 e	0.54 f	0.58 i	0.63 g	0.67 h	0.70 g
	$S_{80}B_{20}$	0.54 c	0.60 d	0.67 f	0.82 b	0.85 b	0.86 b
	$S_{60}B_{40}$	0.60 b	0.63 c	0.69 d	0.84 a	0.87 a	0.88 a
	$S_{80}GF_{20}$	0.50 f	0.52 g	0.68 e	0.74 d	0.79 e	0.83 c
	$S_{60}GF_{40}$	0.50 f	0.51 h	0.55 j	0.61 h	0.68 g	0.67 h
	$S_{80}FG_{20}$	0.52 e	0.54 f	0.70 c	0.66 e	0.74 f	0.80 e
	$S_{60}FG_{40}$	0.50 f	0.52 g	0.59 h	0.64 f	0.67 h	0.73 f
	$S_{80}PTS_{20}$	0.52 e	0.54 f	0.55 j	0.58 j	0.59 i	0.63 i
	$S_{60}PTS_{40}$	0.50 f	0.52 g	0.55 j	0.59 i	0.58 j	0.60 j
	Significance[w]	***	***	***	***	***	***
Coir-based trial	Substrate	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
	Industry standard	0.72 cd	0.82 d	0.93 d	0.85 d	0.79 f	0.85 e
	C_{100}	0.95 a	1.06 a	1.09 a	1.02 a	0.95 a	1.02 a
	$C_{80}P_{20}$	0.92 b	0.95 b	1.03 b	0.94 c	0.87 c	0.92 c
	$C_{60}P_{40}$	0.90 b	0.92 c	1.02 c	0.96 b	0.90 b	0.95 b
	$C_{80}B_{20}$	0.67 f	0.70 g	0.77 g	0.94 c	0.76 g	0.84 f
	$C_{60}B_{40}$	0.66 f	0.73 e	0.80 e	0.84 e	0.81 e	0.87 d
	$C_{80}GF_{20}$	0.70 de	0.72 f	0.75 h	0.77 g	0.76 g	0.81 g
	$C_{60}GF_{40}$	0.63 g	0.59 j	0.60 j	0.59 k	0.62 j	0.66 j
	$C_{80}FG_{20}$	0.72 cd	0.74 e	0.78 f	0.83 f	0.85 d	0.87 d
	$C_{60}FG_{40}$	0.61 g	0.65 h	0.60 j	0.62 i	0.64 i	0.67 i
	$C_{80}PTS_{20}$	0.73 c	0.63 i	0.62 i	0.63 h	0.66 h	0.69 h
	$C_{60}PTS_{40}$	0.68 ef	0.65 h	0.57 k	0.60 j	0.59 k	0.62 k
	Significance	***	***	***	***	***	***

[z]Industry standard = 50% perlite: 25% coir: 25% peat

[y]Letters represent the component(s) of the medium (S= peat, P= perlite, B= aged pine bark, GF= GreenFibre, FG= ForestGold, PTS= processed tree substrate, C = coir) and the numbers represent the percent of each component (e.g., $S_{80}P_{20}$ is 80% peat and 20% perlite).
[x]DAP = Days after planting that the pour-through method was used to measure pH.
[w]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at α = 0.05. *** indicates significant differences at $P \leq 0.001$.

Table 2.6. Dry weight of ‘Albion’ strawberry plants grown in experimental peat and coir-based substrates used in the two container grown strawberry mother plant experiments.

		Dry weight (g/plant)		
Peat-based trial	Substrate	Total[x]	Stolon network	Mother plant
	Industry standard[z]	49.18 a	31.26 a	17.92 a
	S_{100}[y]	53.36 a	38.10 a	15.26 a
	$S_{80}P_{20}$	51.55 a	36.70 a	14.85 a
	$S_{60}P_{40}$	55.18 a	36.24 a	18.94 a
	$S_{80}B_{20}$	52.06 a	34.81 a	17.25 a
	$S_{60}B_{40}$	50.65 a	35.36 a	15.29 a
	$S_{80}GF_{20}$	52.67 a	34.27 a	18.40 a
	$S_{60}GF_{40}$	48.92 a	32.62 a	16.29 a
	$S_{80}FG_{20}$	51.45 a	34.26 a	17.18 a
	$S_{60}FG_{40}$	50.04 a	35.53 a	14.50 a
	$S_{80}PTS_{20}$	48.69 a	34.35 a	14.34 a
	$S_{60}PTS_{40}$	50.59 a	34.70 a	15.89 a
	Significance[w]	NS	NS	NS
Coir-based trial	Substrate	Total	Stolon network	Mother plant
	Industry standard	65.83 a	51.81 a	14.02 ab
	C_{100}	56.46 bcd	45.74 abcd	10.72 b
	$C_{80}P_{20}$	60.72 ab	48.50 ab	12.22 ab
	$C_{60}P_{40}$	59.79 abc	46.83 abc	12.96 ab
	$C_{80}B_{20}$	59.65 abc	43.81 abcd	15.84 a
	$C_{60}B_{40}$	49.98 d	37.57 d	12.41 ab
	$C_{80}GF_{20}$	61.15 ab	46.85 abc	14.30 ab
	$C_{60}GF_{40}$	58.43 abc	44.48 abcd	14.15 ab
	$C_{80}FG_{20}$	60.25 ab	45.29 abcd	14.96 a
	$C_{60}FG_{40}$	51.86 cd	39.81 cd	12.05 ab
	$C_{80}PTS_{20}$	59.01 abc	43.30 bcd	15.71 a
	$C_{60}PTS_{40}$	55.50 bcd	42.68 bcd	12.83 ab
	Significance	***	***	***

[z]Industry standard = 50% perlite: 25% coir: 25% peat

[y]Letters represent the component(s) of the medium (S= peat, P= perlite, B= aged pine bark, GF= GreenFibre, FG= ForestGold, PTS= processed tree substrate, C = coir) and the numbers represent the percent of each component (e.g., $S_{80}P_{20}$ is 80% peat and 20% perlite).
[x]Total = Stolon network dry weight combined with mother plant dry weight.
[w]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at $\alpha = 0.05$. *, **, or *** indicates statistically significant differences between sample means based on $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively. NS (not significant) indicates the difference between sample means was $P > 0.05$.

Table 2.7. Growth metrics of 'Albion' strawberry plants grown in peat and coir-based experimental substrates used in the two container growth strawberry mother plant experiments

		Measured plant traits							
Peat-based trial	Substrate	Leaf SPAD chlorophyll (35 DAP)	Leaf SPAD chlorophyll (70 DAP)	Flower no. removed per plant	Crown no. per plant	Crown diameter (mm)	Stolon no. per plant	Stolon total length per plant (cm)	Internode length (cm)
	Industry standard[z]	49.96 a	50.38 a	17.6 a	2.4 a	28.73 ab	7.2 a	729.24 b	51.44 a
	S_{100}[y]	48.40 a	51.48 a	8.0 cd	1.8 a	27.01 ab	7.4 a	759.46 b	50.02 a
	$S_{80}P_{20}$	49.95 a	50.32 a	12.6 abc	1.8 a	29.36 ab	6.8 a	794.42 ab	50.24 a
	$S_{60}P_{40}$	49.94 a	51.22 a	12.6 abc	2.6 a	36.70 a	8.8 a	873.10 ab	49.52 a
	$S_{80}B_{20}$	48.64 a	50.82 a	14.8 ab	2.6 a	33.46 ab	8.6 a	926.53 ab	49.99 a
	$S_{60}B_{40}$	49.96 a	50.38 a	7.2 cd	2.0 a	31.05 ab	6.8 a	731.32 b	49.87 a
	$S_{80}GF_{20}$	48.40 a	51.48 a	9.8 bcd	2.4 a	32.42 ab	9.6 a	1079.49 a	49.53 a
	$S_{60}GF_{40}$	49.94 a	51.22 a	8.8 bcd	2.2 a	31.88 ab	8.0 a	907.89 ab	51.34 a
	$S_{80}FG_{20}$	48.64 a	50.82 a	5.2 d	1.6 a	27.62 ab	6.4 a	798.82 ab	50.60 a
	$S_{60}FG_{40}$	49.32 a	51.56 a	10.0 bcd	1.6 a	25.04 b	6.6 a	802.07 ab	49.25 a
	$S_{80}PTS_{20}$	49.32 a	51.56 a	13.6 abc	2.0 a	26.27 ab	7.6 a	808.61 ab	48.80 a
	$S_{60}PTS_{40}$	49.96 a	50.38 a	12.4 abc	2.2 a	31.43 ab	8.0 a	832.73 ab	49.11 a
	Significance[x]	NS	NS	***	NS	*	NS	**	NS
Coir-based trial	Substrate	Leaf SPAD chlorophyll (35 DAP)	Leaf SPAD chlorophyll (70 DAP)	Flower no. removed per plant	Crown no. per plant	Crown diameter (mm)	Stolon no. per plant	Stolon total length per plant (cm)	Internode length (cm)
	Industry standard	51.36 a	51.68 a	13.0 ab	2.2 ab	25.00 a	6.8 a	634.17 ab	50.01 a
	C_{100}	51.28 a	51.36 a	6.8 b	2.2 ab	21.19 a	7.4 a	512.00 b	50.21 a
	$C_{80}P_{20}$	51.12 a	51.28 a	13.0 ab	2.2 ab	22.53 a	7.8 a	602.87 ab	49.96 a
	$C_{60}P_{40}$	52.38 a	51.12 a	12.6 ab	2.0 ab	24.92 a	8.0 a	594.11 ab	50.09 a
	$C_{80}B_{20}$	51.70 a	51.68 a	11.8 ab	2.4 ab	29.57 a	9.2 a	739.90 ab	50.14 a
	$C_{60}B_{40}$	50.90 a	50.96 a	7.6 b	1.8 ab	26.71 a	6.4 a	758.38 a	49.99 a
	$C_{80}GF_{20}$	51.36 a	51.52 a	13.6 ab	2.2 ab	26.15 a	8.2 a	718.50 ab	49.67 a
	$C_{60}GF_{40}$	52.70 a	51.67 a	12.4 ab	1.4 b	23.51 a	6.6 a	626.75 ab	50.15 a
	$C_{80}FG_{20}$	50.38 a	50.99 a	17.6 a	2.8 a	27.41 a	9.0 a	615.82 ab	50.19 a
	$C_{60}FG_{40}$	51.40 a	51.15 a	9.8 ab	2.2 ab	24.56 a	7.6 a	583.40 ab	49.89 a
	$C_{80}PTS_{20}$	51.42 a	51.65 a	9.8 ab	1.8 ab	29.19 a	8.4 a	623.71 ab	50.05 a
	$C_{60}PTS_{40}$	51.56 a	51.45 a	9.6 ab	1.6 ab	25.87 a	10.0 a	726.57 ab	50.16 a
	Significance	NS	NS	**	*	NS	NS	*	NS

[z]Industry standard = 50% perlite: 25% coir: 25% peat

[y]Letters represent the component(s) of the medium (S= peat, P= perlite, B= aged pine bark, GF= GreenFibre, FG= ForestGold, PTS= processed tree substrate, C = coir) and the numbers represent the percent of each component (e.g., $S_{80}P_{20}$ is 80% peat and 20% perlite).
[x]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at $\alpha = 0.05$. *, **, or *** indicates statistically significant differences between sample means based on $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively. NS (not significant) indicates the difference between sample means was $P > 0.05$.

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CHAPTER 3

Container Geometry and Substrate Air Space Influences Vegetative Propagation Efficacy and Growth of 'Albion' Strawberry (*Fragaria* x *ananassa*) Mother Plants in a Precision Indoor Propagation System

Abstract:

In recent years, soilless cultivation methods for strawberry production have gained popularity due to their potential to optimize resource utilization, increase crop yield, and provide an alternative to methyl-bromide dependent field production systems. While previous research has extensively examined various aspects of soilless substrate production for strawberries, there remains a gap in understanding the specific influence of container geometry on strawberry mother plant production. This study investigates the effects of container capacity (CC) and air space (AS) within the substrate, which vary based on container height and volume. Four distinct container sizes were created, representing combinations of two diameters (10.16 cm and 15.24 cm) and four lengths (11.0, 16.5, 24.7, and 37.0 cm), resulting in two distinct volumes: 2 liters and 3 liters, each with short (11.0/16.5 cm) or tall (24.7/37.0 cm) configurations. Identification codes were created for each container, with the first value being container diameter, second letter represents short or tall in response to container height, and the third value is for container volume. Two substrates were examined: a high air space industry standard (50% perlite: 25% peat: 25% coconut coir) and a low air space substrate (20% perlite: 80% coconut coir). Results indicate that container geometry significantly influences daughter plant production. Notably, the study found that different container sizes and substrates yield varying daughter plant numbers. For instance, in the 50% perlite mix, the highest daughter plant number was recorded in the 10T2 container, while in the 20% perlite mix, the highest number was observed in the 15S3 container, with no significant differences between these two. These findings suggest a nuanced relationship between container geometry, substrate composition, and daughter plant yield in strawberry mother plant production, emphasizing the importance of considering these factors in cultivation practices.

Introduction:

In recent years, soilless cultivation methods for strawberry production have surged in popularity due to their potential to enhance resource utilization, increase crop yield, and offer an alternative to methyl-bromide dependent field production systems (Paranjpe et al. 2003). The cultivation of strawberry mother plants is particularly crucial for maintaining a consistent and healthy supply of high-quality planting material (Hoffmann, 2020). Understanding the influence of container geometry on their growth is vital for optimizing production efficiency and ensuring the success of production. Previous research has explored various aspects of soilless substrate production of strawberries, including substrate composition. Massetani et al (2017) researched 'Elsanta' yield per plant in a sphagnum peat, peat perlite mix, and coconut coir and found similar yields in among the three substrates. Alternative substrates, such as wood fiber and biochar have also been evaluated for their potential as substrate materials. Aurdal et al. (2023) shown that that 'Murano' yield was maintained in wood fiber and compost substrates compared to a coconut coir control. However, there is a gap in the literature for the specific effects of container geometry on strawberry mother plant production.

The strategic combination of organic substrates with coarser particle materials, each possessing distinct physical and hydraulic characteristics, has been utilized to optimize the balance between water retention and air space (AS) within substrates. Among the various factors influencing plant development, the geometric characteristics of containers, such as height and volume, play an important role (Gallegos et al. 2020). Owen and Atland (2008) displayed the effect of container height and various bark particle sizes, with fine particles (<0.9 cm) AS being raised from 22% in a 3.8 cm container to 31% in a 15.2 cm container. However, when container height was investigated with more coarse particles (<2.2 cm), the range of AS increased, with the

3.8 cm container displaying a 32% AS and the 15.2 cm with a 44% AS. With the influence that container height has on substrate physical properties, it can significantly impact root structure, nutrient uptake, and overall plant health (Raviteja et al. 2021). Importantly, the same substrate exhibits distinct properties when placed in containers of varying sizes (Ruter and Werken, 1991; Milks et al. 1989). Larger containers produce different results compared to smaller counterparts due to their influence on substrate characteristics such as aeration and water holding capacity (Fonteno, 1988; Milks et al. 1989; Fields et al. 2014; Dufault and Waters, 1985).

Factors such as container capacity (CC) and AS within the substrate vary depending on container height and volume (Fonteno, 1988). While total porosity may remain consistent across containers of different sizes using the same substrate, provided the bulk density remains constant, AS experiences an increase with container height, potentially leading to a decrease in CC (Milks et al. 1989). Conversely, shorter containers may suffer from poor aeration of the substrate, often exacerbated by a post-irrigation "perched water table" (Spomer, 1974). Shorter containers, particularly those utilizing fine-particle-sized substrates, may encounter insufficient substrate AS, thereby increasing the risk of plant desiccation (Owen and Atland, 2008). Container height influences gravitational drainage, making substrate components and container selection critical in maintaining optimal air and water conditions (Bilderback and Fonteno, 1987).

Generally, as container height and width decrease, the amount of pore space diminishes, thereby reducing both substrate water holding capacity and aeration (Bilderback and Fonteno, 1987). Moreover, increasing root mass in the container further diminishes pore space, exacerbating these effects (NeSmith and Duval, 1988). Understanding these intricate relationships between root confinement, container geometry, and substrate selection is crucial for optimizing plant growth and health in controlled cultivation environments.

Plants undergo several physiological and morphological changes in response to reduced rooting volume, impacting several aspects of their growth and development (NeSmith and Duval, 1998). Root and shoot growth, biomass accumulation and partitioning, photosynthesis, leaf chlorophyll content, plant water relations, nutrient uptake, respiration, flowering, and yield are all intricately linked to root restriction and container size (Tschaplinski and Blake, 1985). While these responses have been observed across a wide range of crops, there exists some conflicting data among different species and even within cultivars of the same species.

Various studies have provided insight on the influence of container geometry on plant growth. Chirino et al. (2008), Pemán et al. (2006), and Trinidad et al. (2015) have demonstrated that the depth of a container plays a role with woody species in determining the length of the plant's main root and, consequently, its survival under limiting conditions. Similarly, Heller et al. (2015) investigated the impact of container shape on lettuce yield, ranging from 10 cm to 30 cm tall 4L containers for one month, and found that shape does not affect yield when containers are of identical volume. This data contradicts results with Chowdhury et al. (2024), where tomato seedlings were growth for 14 days in coir, wood fiber-coir mix, fine pine bark, and peat in constructed PVC containers with heights of 3.81 cm, 5.08 cm, 6.35 cm, and 8.89 cm. Here, peat in the 3.8 cm container showed a lower germination performance due to oversaturation of the substrate, while coir and fine pine bark in the 8.9 cm container also exhibited lower growth due to water stress. For all the substrates tested, the highest volumetric water container was in the 3.8 cm container, and the lowest in the 8.9 cm. These findings collectively underscore the intricate relationship between container geometry, root development, and overall plant health for several species of woody and herbaceous plants.

In general, it has been shown for many woody plants that as container volume increases, plant leaf area, shoot biomass, and root biomass tend to increase as well (Cantliffe, 1993; Biran and Eliassaf, 1980). Biran and Eliassaf (1980) investigated the effect of container size in a mixture of volcanic scoria and vermiculite on plant growth, doing so on woody species (*Ficus retusa*, *Pistacia lentisucus* and *Dodonea viscosa*). By increasing container volume, plant growth was also increased. This phenomenon underscores the interdependence of growth rates between shoots and roots (Tonutti and Giulivo, 1990). Roots rely on the aerial portions of plants for photosynthates and various hormones, while the aerial portions depend on roots for water, nutrients, support, and hormonal signaling. The delicate balance between roots and shoots can be disrupted when the root system is confined to a small rooting volume, leading to both short-term and long-term effects on plant growth (NeSmith and Duval, 1998).

Root restriction can mimic the effects of substrate moisture stress even when sufficient moisture is available for normal plant growth (Krizek et al., 1985). Confined roots compete for essential resources, leading to increased root mass and decreased rooting space, which in turn exacerbates competition for available oxygen (Peterson et al., 1991b). Container geometry and substrate selection significantly influence substrate moisture content and aeration.

Container-grown plants exhibit distinct root morphologies compared to their field-seeded counterparts. For instance, restricting tomato *(Lycopersicon esculentum* L.) roots results in a loss of primary roots and an increase in the number of lateral roots (Peterson et al., 1991a). Similarly, transplanted watermelons (*Citrullus lanatus*) may exhibit decreased taproot dominance, and in extreme cases, no taproot at all (Elmstrom, 1973). These alterations in root morphology may be more pronounced with smaller container sizes.

Currently, limited research is available regarding substrate composition and container geometry effect on mother plant production. Yafuso and Boldt (2024) compared numerous soilless production methods for ‘Albion’ strawberry mother plant production and reported that peat-based substrates grown in a 19.1-cm diameter container exhibited a higher root dry mass compared to sand, perlite, or deep water culture systems. It was concluded that this was likely do to the physical and chemical properties of the peat. Similar results were shown by Massetani et al. (2017) where peat based substrates showed higher plant growth and yield compared to other substrates, including coconut coir. However, during this study, two container types were evaluated, including 11L pots with six plants in each and 1m long plastic bags with 12 plants. No significant differences were found in plant architecture and vegetative growth between container types. Root growth was examined in a known sample volume of substrate from each treatment and root density per substrate unit was found to be higher in the plastic bags. Cantliffe et al (2007) displayed that ‘Sweet Charlie’ plants in pine bark, peat mixes, and perlite planted in troughs (12L volume) displayed more plant growth and yield in bark compared to perlite, while bag systems (18L volume) on the ground produced higher yields in perlite. The effect of container volume was further investigated (Massetani et al., 2017), including 11L, 15L, and 18L containers, and it was found that increasing rooting volume continued to increased fruit yield.

In conclusion, furthering the investigation into the interplay effects of container height and volume on strawberry mother plant growth in different substrate mixes represents a step towards optimizing soilless cultivation methods. By hypothesizing that container dimensions influence substrate physical properties and subsequently affect plant growth, this study aims to explore how substrate selection and management techniques may can be better altered for optimal growth. Through systematic examination of these factors, potentially valuable insights into proper substrate selection based on container characteristics for soilless strawberry mother plant cultivation can be gleaned, thereby contributing to the advancement of precision indoor propagation systems and the sustainability of strawberry production.

Materials and Methods:

Container construction. In this study, four distinct container sizes were created and examined, representing combinations of two diameters (10.16 cm and 15.24 cm) and four lengths [11.0, 16.5, 24.7, and 37.0 (Figure 1 and Table 1). This led to the experimental containers being configured into two distinct volumes: 2 liters and 3 liters, each with two heights, short (11.0/16.5 cm) or tall (24.7/37.0 cm). To ensure containers were of known volumes and heights, these were built by hand through cutting Schedule 40 PVC pipe (10.16 cm and 15.24 cm diameter). To facilitate proper substrate support and drainage, 12-mesh plastic screen was affixed to the bottom of each length of PVC pipe using 24" industrial UV protected black zip ties (Figure 1). Identification codes were created for each container, with the first value being container diameter, second letter represents short or tall in response to container height, and the third value is for container volume [for example, 15S2 represents the 15.24 diameter, shorter length (11.0) and 2L volume container (Table 1)].

Substrate preparation. Compressed 5kg blocks of coconut coir (Jiffy Group International, Zwijndrecht, The Netherlands) underwent hydration by sequentially adding 14 liters of water in 1-liter increments. The blocks were manually fluffed until achieving an initial moisture content of 50%. For the first trial, a recognized standard within the strawberry industry was formulated

(McKean et al., 2019), comprising 50% coarse grade perlite (Supreme Perlite, Portland, OR), 25% sphagnum peat (Premier Pro-Moss, Quakertown, PA), and 25% coconut coir (by volume). For a second trial, the same industry standard from trial 1 was made, as well as the addition of a substrate was made with 80% sphagnum peat and 20% coarse grade perlite (by volume). All blending procedures were carried out by hand. The moisture content of the substrate mix was then assessed and adjusted to achieve an initial moisture content of 50%.

The initial substrate pH and electrical conductivity (EC) for each treatment were determined utilizing the 2:1 saturated media extraction method, wherein two parts deionized water were combined with one part substrate (Argo and Fisher, 2002). A handheld pH and EC meter (HI 9813-61; Hanna Instruments, Woonsocket, RI) measured these chemical properties. Subsequent to assessing the initial substrate pH values, it was determined that the incorporation of dolomitic limestone was necessary during substrate blending to raise the pH within the recommended range of 5.2-6.5 for strawberries (Akon, 2019). Both substrate mixes received dolomitic limestone at a rate of 2.97 grams per cubic liter. To achieve lime/pH equilibrium, substrates were incubated for 2 d within sealed plastic bags, following which the pH and EC were re-tested using the previous methodology.

Substrate physical properties. Three representative samples of each substrate were analyzed to determine the physical properties using the NCSU Porometer Method (Fonteno et al. 1995). CC, AS, total porosity, and bulk density were derived from this procedure.

Particle size distribution (PSD) analysis was performed only on the three substrate components (peat, coir, perlite). This involved passing 150g of oven-dried samples through five U.S. Standard sieves with mesh sizes ranging from 0.106 to 6.3 mm, in addition to a bottom pan. The sieves and pan underwent shaking for 5 minutes using an RX-29 RoTap sieve shaker (278 oscillations per min, 150 taps per min; W.S. Tyler, Mentor, OH). Subsequently, the particle fractions retained on each sieve and pan were weighed, and their proportions were determined as a percentage of the total sample.

Greenhouse experiment and experimental design. Trial 1 was conducted from 5 January 2023 to 14 April 2023 and Trial 2 was from 24 April 2023 to 3 July 2023 in a glasshouse at NC State University in Raleigh, NC evaluating container geometry's influence on 'Albion' strawberry mother plant growth (*Fragaria* x *ananassa*) planted in four experimental constructed PVC pipe containers.

Environmental parameters, including daily light integral [DLI (Hobo Data Logger, Cape Cod, MA)], average daily air temperature (ADT), and relative humidity (SensorPush HT, New York, NY) were measured throughout both experimental periods. DLI, ADT, and relative humidity for Trial 1 were reported as (mean ± sd) 13.9 ± 9.3 mol $m^{-2}d^{-2}$ of photosynthetically active radiation, 18.3 ± 8.1 °C, and 72 ± 4.6%, respectively. For trial 2, these were reported as (mean ± sd) 25.2 ± 9.3 mol $m^{-2}d^{-2}$ of photosynthetically active radiation, 22.3 ± 8.1 °C, and 76 ± 4.6%, respectively.

Vegetatively propagated 72-cell plugs of 'Albion' strawberries were purchased from a local nursery specializing in the cultivation of virus-free plants, rooted in a peat moss propagation blend [Fresk-Pik Produce Inc., Wilson, NC (Figure 2A)]. After a one-week acclimation period in the glasshouse, plants exhibiting comparable crown diameter (1.5 cm), leaf count (4.0-5.0), and visually assessed root health were selected (Figure 2B). Subsequently, these chosen plants were randomly transplanted into the four container treatments. The substrate moisture content was modified to ensure standardized initial moisture content of 50% across all substrate treatments for consistency. When filling each container, substrate was placed into the pipe and then lightly dropped from a height of 5 cm to allow for proper settling of the substrate. Each container was uniformly filled and weighed to ensure consistency among replicates with substrate bulk density and volume.

Trial 1 comprised four container treatments, each randomized across 10 blocks on a two greenhouse benches (Figure 3). Within each block, there were 4 total plants, with one of each container treatment per block. This design yielded a total of 40 containers/plants, consisting of 4 treatments with 10 single-plant replications each.

Trial 2 consisted of four container treatments and two substrate treatments, each randomized across five blocks on a single bench. Within each block, there were 8 total plants, with one of each container and substrate combination per block. This design yields a total of 40 containers/plants, consisting of 4 container treatments, 2 substrate treatments, with 5 single-plant replications for each combination of container and substrate.

To accommodate anticipated stolon growth and ensure uniform light distribution, shorter containers were elevated to allow for all plants/top of containers to be a similar height to the tallest container treatment (10T3) by placing a stack of pots of beneath them (Figure 3). Plants were positioned near the edge of the greenhouse bench, which allowed the stolons to cascade down the sides. Regular maintenance involved weekly combing and organization of the stolons to minimize entanglement and shading, thus promoting optimal plant development across all treatments.

Each replicate container underwent individual hand-irrigation at the start of the trials and were brought to effective container capacity (maximum mass of the container, substrate, and plant after gravitational water has drained) as described by Sammons and Struve (2008), then weighed. As the substrate moisture (container weight) declined by 25% from the maximum

ECC, an amount of water equivalent to this decrease plus an additional 30% to allow for the recommended leaching volume (Gontijo et al., 2020) was reapplied. Moisture content was determined through twice-daily weighing of each container, with correlations between container weight and moisture content established using gravimetric techniques for each substrate treatment. Adjustments were made every seven days to accommodate increasing plant growth by reweighing and determining the adjusted effective container capacity.

At each irrigation, plants were fertilized with a commercial complete fertilizer containing micronutrients (Jack's 20-nitrogen (N)-4.4 phosphorus (P)-16.6 potassium (K)-0.15 magnesium (Mg)-0.02 boron (B)-0.01 copper (Cu)-0.1 iron (Fe)- 0.05 manganese (Mn)-0.01 molybdenum (Mo)-0.05 zinc (Zn), sourced from JR Peters, Inc., Allentown, PA) at a concentration of 100 mg L-1 N. Additionally, a supplemental calcium nitrate was applied separately once a week (Jack's 15N-0P-0K, also from JR Peters, Inc., Allentown, PA) at a rate of 75 mg L-1 N. Fertilizer solutions were manually applied directly to the substrate surface and beneath the plant canopy to avoid foliage wetting. From day 45 onwards, all plants were automatically irrigated between 2 to 4 times daily, with each treatment receiving an equal volume of water (150 mL per pot per fertigation event). This adjustment was necessitated by the plants' increasing biomass and stolon network, requiring a more frequent water supply over time.

Measured plant growth traits. Weekly assessments of substrate pH and EC were conducted on each replicate using the nondestructive pour-through method (Cavins et al., 2004), utilizing the same handheld pH and EC meter mentioned previously (Table 2 and Table 3). Prior to each data collection session, plants were irrigated to effective container capacity two hours in advance. Subsequently, 75 mL of deionized water was evenly distributed over the substrate surface, allowing approximately 50 mL of leachate to be collected for pH and EC measurement purposes.

Nondestructive measurement of leaf SPAD chlorophyll content (SPAD 502 Plus Index Meter from Konica Minolta, Tokyo, Japan) was taken for each replicate at d 35 and d 70 (Table 4). Three measurements were taken on the most recently fully expanded leaf, and the values were averaged to determine the SPAD value for each leaf. Throughout the trial, the quantification of flower buds was systematically recorded, and upon their emergence, they were promptly removed (Table 4).

At the conclusion of the trial, the number of daughter plants with at least one leaf was recorded for each replicate (Figure 5 and Figure 6). Additionally, the count of primary stolons directly attached to the mother plant was determined for each replicate. Following the count, each stolon was severed at the crown of the plant, and the length of each stolon was individually measured for every replicate. The measured lengths of all stolons per replicate were combined to calculate the total stolon length per plant. Furthermore, the internode distance between each daughter plant on an individual stolon was measured for all stolons in each replicate (Table 4). The entire stolon network, comprising all stolons and daughter plants on a single plant, underwent a 48-hour drying process at 80 degrees Celsius, after which dry weights were recorded (Table 5).

After stolon removal, each strawberry mother plant underwent evaluation. The number of crowns per mother plant replicate was documented. To ascertain crown diameter, a digital caliper (Fisherbrand, Fisher Scientific) was employed. A measurement was taken, followed by rotating the caliper 90 degrees and taking another measurement, with the average of these measurements representing the crown diameter (Table 4). Subsequently, the mother plant was cut at the substrate surface, and its dry weight was determined following the previously described procedure (Table 5).

Statistical analysis. Plants were cultivated on two benches within the NC State University greenhouse from 5 January to 14 April 2023 and one bench in the same location from 24 April to 3 July 2023, following a Randomized Complete Block Design (RCBD). Analysis of Variance (ANOVA) was conducted on each response variable independently for Trial 1, the effect of container type was further examined through multiple comparisons using Tukey's Honestly Significant Difference (HSD). In Trial 2, each combination of container type and substrate type was defined as an independent treatment, and Tukey's HSD was employed for multiple comparisons to assess the effects of each treatment. Mean separation was conducted using Tukey's HSD with $\alpha = 0.05$ for most analyses. However, when the P-value of a treatment effect in ANOVA fell between 0.1 and 0.05 (e.g., the treatment effect on dry weight in Trial 2), a slightly relaxed significance level of $\alpha = 0.1$ was used.

Results and Discussion:

Particle size distribution. Perlite showed the highest percentage of particles in the coarse-sized fraction (>2.0mm), with 67.3% particles, but very little of this percentage was from the >6.3mm category (0.4%). Coir displayed the least amount of particles in the coarse-sized fraction, with 7.8% shown. In the medium sized fraction (0.3-2.0mm) coir displayed the largest percentage at 72.7%. Perlite contained the least amount of particles in the medium-sized fraction, with 22.9% measured. Peat contained the highest percentage (28.4%) of fine-sized particles (<0.3mm). Perlite contained the least amount of fine-sized particles, with 9.8%.

Trial 1.

Physical properties. The 50 perlite: 25 coconut: 25 peat (v:v) displayed a measured TP of 75.1%. While there are no established standards or guidelines for strawberry substrate TP, various recommendations exist in the literature. Riviere (1980) recommended a TP of 75%. De Boodt and Veronck (1972) and Goh and Haynes (1977) advocated for an ideal substrate with 85% total porosity. It's worth noting that substrates can commonly exceed 85% TP, particularly those with high amendment percentages or rockwool, as observed in studies by Fields et al. (2014) and Bougoul et al. (2005). The AS of this substrate mix was 22.8%, while the CC was at 52.3%. The bulk density of this substrate was 0.11.

Chemical properties. Container type had an effect on the pH and EC of the substrate overtime (Table 2 and Table 3). At time of planting, no difference was observed between container types pH [5.9-6.0 (Table 2)]. However, by d 28, differences became apparent. 10T3 displayed a higher pH (6.1) compared to the other three containers [5.8-5.9 (15S2, 15S3, 10T2)]. This trend remained through d 70, with 10T3 having a pH of 5.8 compared to 5.1-5.2 of the other three containers (Table 2). Substrate EC showed significance between container types from d 0, with the highest observed EC being in 15S2 (0.89) and the lowest in 10T3 [0.72 (Table 3)]. By d 28, the EC's of all treatments reached the highest values, with the same trend as initially. This trend remained consistent through d 70, with 15S2 having the highest final EC at 1.03, and 10T3 having the lowest at 0.70 (Table 3).

Strawberry mother plant growth. By the end of the trial, all strawberry plants across the four container types exhibited dark green foliage and appeared to be of adequate plant quality (Figure 4). The stolon development during this time was not vigorous, likely attributable to the measured lower levels of photosynthetically active radiation and temperature 13.9 ± 9.3 mol

$m^{-2}d^{-2}$ and 18.3 ± 8.1 °C, respectively. The analysis of this first trial revealed significant differences in total plant dry weight and the number of flowers removed, while no significant variation was observed among daughter plant numbers. In response to these findings, an additional substrate mix was investigated with a lower AS was incorporated for a second trial.

Leaf SPAD chlorophyll content, consistently remained within the recommended values across all container types during both times of measurement (Table 4). According to Guler et al. (2006), strawberry plants with adequate nitrogen levels typically exhibit SPAD values exceeding 30 units, suggesting no discernible differences in foliage greenness among treatments. SPAD readings exhibit a direct linear relationship with extracted leaf chlorophyll, serving as a reliable proxy for leaf nitrogen levels (Bullock and Anderson, 1998). With an average SPAD value of 49.68 across container types (Table 4), it is reasonable to infer that nitrogen concentration remained within the optimal range for all treatments.

The number of flowers removed per plant varied significantly across container types, ranging from 15.7 to 21.5, with the 15S3 container displaying the highest count, while the 4L2 treatment exhibited the lowest (Table 4). Interestingly, no significant differences were found between the 15S2 and 4L3 treatments, despite their differing heights and volumes. This observation may suggest that in shorter containers, increased volume correlates with higher flower production, whereas in taller containers, a decrease in volume appears to stimulate flower development. When comparing treatments with the same volume, it is shown that increasing height, thus increasing AS, significantly increased flower numbers.

Mother plant characteristics, such as crown number and crown diameter exhibited no significant differences among container types (Table 4). Crown number had an average between treatments of 2.1 crowns per mother plant. Crown diameter had an average of 22.46 mm.

Stolon network characteristics, including stolon number, stolon length, and stolon internode length, showed no significant differences (Table 4). This is likely due to the stolon growth being minimal for this study due to the environmental parameters of the greenhouse facility not being within range of the recommended for vegetative plant growth. As discussed by Durner et al. (1984), runner production is greatly impacted by photoperiod and temperature for day-neutral cultivars, such as ‘Albion’. The stolon number had an average of 2.3 stolons per mother plant, total stolon length average at 222.7 cm and average internode length at 37.6 cm.

Significant differences in total plant dry weight (stolon network and mother plant) was found (Table 5). The 15S3 container exhibited significantly higher total plant dry mass, while the 10T2 and 10T3 containers displayed significantly lower total plant dry weight. Comparing the 15S3 container to the lower volume 15S2 container revealed a slight significant difference, indicating that decreasing rooting volume leads to a reduction in total plant mass. Conversely, in taller containers, this trend was not observed. However, comparing the 15S3 container to the 10T3 container showed that increasing container height decreased plant growth, a trend also observed between the 15S2 and 10T2 containers. Stolon and mother plant dry weight did not show a significant difference when viewed separately (Table 5).

Daughter plant number was found to not be influenced by container type during this trial (Figure 5). However, the number of daughter plants produced was relatively low, ranging from 7.6 to 8.9 (Figure 5). Environmental parameters, such as photosynthetically active radiation and temperature, was adjusted for the second round. Also, trial 1 evaluated one substrate mix, which had a higher AS. For the second trial, this substrate and a lower AS substrate will be compared in the four container types.

Trial 2.

Physical properties. The components utilized for blending and the rate of the amendment significantly interacted in effect on TP, AS, and CC. Between the two substrates, the highest TP was observed in the 80 peat: 20 perlite (v:v) at 89.3%. The 50 perlite: 25 coconut: 25 peat (v:v) displayed a measured TP of 75.1%. Based on the guidelines mentioned previously by De Boodt and Veronck (1972) and Goh and Haynes (1977), the 20% perlite mix had a similar porosity.

AS was notably influenced by the different rates of perlite in the two mixes. The 20% perlite mix displayed an AS of 10.4%, while the 50% perlite mix displayed more than double the AS at 22.8%. With this, CC was highest among the 20% perlite mix at 78.9%, and lowest in the 50% perlite, at 52.3%. Substrate dry bulk density remained constant between the two substrates (0.11), likely due to each component (coir, peat, perlite) having similar bulk densities.

Chemical properties. Container type and substrate mix had an effect on the substrate pH and EC overtime (Table 2 and Table 3). At the start of the trial, the highest pH was measured in the 10T2 container with the 50% perlite mix (6.1), with the other three containers with the same 50% perlite mix having a similar pH [6.0 (Table 2)]. The lowest initial pH were among all the containers with the 20% perlite mix (5.4-5.5), which remained consistent until d 56. By d 56, the highest pH was among the 10T3 container with 50% perlite, and the lowest were the 15S2 container with 50% perlite and the same container with 20% perlite. By the end of the trial, for both substrates, the 10T3 container had the highest pH and the lowest were among the other three containers with the 20% perlite. The 20% perlite container treatments showed an increase of 0.7 in the 10T3 container compared to the other three, while this container for the 50% perlite showed an increase of 0.6 (Table 2). The elevated pH for the tall, 3L container, may be contributed to the lower measured EC’s overtime.

The EC at the start of the trial was highest in the 15S2 container (0.91) with the 50% perlite substrate and lowest in both of the substrates in the 10T3 container [0.73-0.74 (Table 3)]. On d 28, the highest measured EC's were shown, with the highest value also in the 15S2 container with the 50% perlite substrate at 1.67. The lowest were again among the two substrates in the 10T3 containers. By the end of the project the highest EC measured was 1.21 in the 15S2 container with the 50% perlite substrate, and lowest among the two substrates in the 10T3 containers [0.91-0.99 (Table 3)]. This shows the influence of container geometry, that the taller containers were consistently maintain less EC throughout the trial, regardless of the substrate mix. While the shorter container maintained the highest EC overtime. This could be attributed to the limited leaching in shorter containers, which can limit the vertical movement of water throughout the substrate profile. Consequently, this limited leaching may allow excess salts to accumulate, leading to higher EC levels in the substrate (Bayer et al. 2014). Conversely, taller containers facilitate more excessive leaching, allowing for greater flushing of salts from the substrate and potentially resulting in lower EC levels. Further monitoring of leaching volume over time is required to understand this influence.

Strawberry mother plant growth. By the end of the trial, all strawberry plants, across the two substrate types and four container types, exhibited vigorous growth with dark green foliage (Figure 6). Compared to trial 1, more stolon growth was observed, possibly indicating the measured environmental parameters were more suited for mother plant production. Significant differences were observed in stolon dry weight, mother dry weight, total dry weight, daughter number, and crown diameter.

Leaf SPAD chlorophyll content, consistently remained within the recommended values of past research across all container and substrate treatments. During d 35 and d 70, these values had an average of 48.97 (Table 4), inferring that the nitrogen concentration remained within the optimal range for all treatments, allowing for healthy plant growth.

The number of flowers removed per plant did not exhibit significant differences between substrate types or container geometries, with counts ranging from 23.4 to 25.4 (Table 4). This range contrasts with the flower numbers observed in the first trial, where flower number ranged from 15.7-21.5 (Table 4).

Crown numbers exhibited no significant differences between container or substrate treatments. However, significant variations were measured among the crown diameters (Table 4). Notably, the 15S2 container with a 20% perlite mix displayed the largest crown diameter, while the same container with a 50% perlite mix showed one of the smallest diameters. Similarly, the 10T3 container with a 50% perlite mix exhibited the second-highest crown diameter, contrasting with the lower diameter observed with the 20% mix in the same container (Table 4).

Interestingly, in shorter containers, a lower AS coupled with a higher CC substrate resulted in the highest crown diameter, as evidenced by the 15S2 container. Conversely, in taller containers, increased AS and reduced CC led to an increase in crown diameter, as observed in the 10T3 container. Comparing container volumes, the only treatments that demonstrated a significant difference in crown diameter, from 2 to 3L, were observed in the 15S2 and 15S3 containers with a 20% perlite mix. This indicates that increasing container volume tends to decrease the crown diameter of the mother plant. These results highlight the complex interplay between substrate composition, container geometry, and volume in influencing crown development, providing insights for optimizing strawberry mother plant growth in containerized systems.

Similar to the first trial, no significant differences were shown in the number of stolons per plant (Table 4). However, the average during this trial showed a notably higher average of 7.2 stolons, compared to 2.3 stolons per mother plant. Stolon length also did not demonstrate significance in this trial. However, it's worth noting that stolon internode length showed no significant differences among treatments in both trials. Interestingly, the internode length was markedly higher across all treatments in Trial 2, with an average of 50.2 cm, compared to an average of 37.6 cm in Trial 1 (Table 4). These observations provide insight into the dynamics of stolon development in response to varying experimental conditions, but not due to the container type or substrate.

Significant differences in total plant dry weight (including stolon network and mother plant) were observed (Table 5). Higher total plant dry weight was measured in the 10T3 container with a 20% perlite treatment, while the 15S2 container with the same treatment exhibited lower plant dry weight (Table 5). These finds may suggest that in lower AS mixes, increasing volume and height can enhance plant growth under the same irrigation regeme. However, when compared to the 50% perlite treatment, increasing height and volume did not significantly influence plant growth across all treatments. This indicates that with high AS substrates, changings in container geometry had minimal impact on plant growth, whereas with low AS substrates, taller containers with a 3L volume increased overall plant growth. Varying irrigation techniques could also affect these growth differences by changing the air-water profiles within the substrate (Biernbaum and Versluys, 1998).

A significantly higher stolon network dry mass was measured in the 10T3 container with a 20% perlite treatment, while the lowest was observed in the 15S2 container with the same treatment (Table 5). Additionally, reducing substrate volume from 3L to 2L for taller containers with a 20% perlite mix resulted in a slight decrease in stolon growth. Similarly, a slight decrease in stolon growth was observed when comparing 3L tall containers to 3L short containers. Among the 50% perlite substrates, there were no significant differences between the short 3L container (15S3) and tall 2L container (10T2). However, a decrease in stolon growth was observed when comparing these containers with the short 2L (15S2) and tall 3L (10T3) containers (Table 5). These findings indicate that increasing container height and volume among low AS mixes enhances stolon network growth. However, with high AS mixes, these effects vary, with the taller option displaying better growth with a 2L volume and the shorter option showing better growth with a 3L volume. No significant difference was found in either trial regarding mother plant dry weight.

During Trial 1, daughter plant number was not influenced by container type; however, significant differences were found between container type and substrate type in Trial 2 (Figure 7). In the 50% perlite mix, the highest daughter plant number was recorded in the 10T2 container (33.0), while in the 20% perlite mix, the highest number was observed in the 15S3 container (33.8), with no significant differences between these two (Figure 7). This suggests that with a high AS mix, a tall 2L container performed equivalently to a low AS mix in a short 3L container.

Further examination of container geometry revealed that the lowest daughter plant number was found in the 15S2 container with a 20% perlite mix (Figure 7). In this case, the combination of a low AS mix and a short container likely led to inadequate AS and excess water, resulting in decreased plant growth. However, when the 50% perlite mix was used in this short container, an increase in daughter plant number was observed, indicating the need for more AS in a short, low-volume container.

For the 20% perlite substrate, increasing container volume from 2L to 3L in the short container increased daughter plant number, but did not significantly affect the number in the taller containers for this substrate (Figure 7). Conversely, for the 50% perlite substrate, increasing container volume from 2L to 3L in the tall container decreased daughter plant number, but had no effect on the shorter containers.

In the 15S2 container, the 50% perlite mix showed a significant increase in daughter plant number, while in the 15S3 container, the 20% perlite mix showed a significant increase (Figure 7). Similarly, in the 10T2 container, the 50% perlite mix showed a significant increase in daughter plant number, while in the 10T3 container, no difference was observed in plant growth between the two substrates.

These findings may suggest that in 2L containers, a higher AS mix with lower CC increases daughter plant yield, while in shorter 3L containers (such as the 16.5cm tall container), the lower AS mix increases daughter plant number. However, in the tallest 3L container (10T3), there were no differences in daughter plant number between the two substrates, likely due to the relatively high AS in both of these containers, influenced by their height.

Conclusion:

The findings from this study underscore the interplay between container geometry and substrate physical properties in influencing the growth and development of strawberry mother plants. The observed variations in total plant dry weight, stolon network growth, crown diameter, and daughter plant yield highlight the significance of carefully selecting container types and substrate compositions in containerized strawberry production systems.

Understanding how container geometry affects substrate physical properties such as total porosity, AS, and CC is essential for optimizing plant growth and maximizing yields. Growers can utilize this knowledge to tailor their cultivation practices, selecting container types and substrate mixes that provide optimal conditions for root development, nutrient uptake, and overall plant health.

Moreover, this study emphasizes the importance of considering the dynamic interactions between container design and substrate properties in greenhouse production systems. By elucidating these relationships, growers can make informed decisions to improve crop productivity. Future research endeavors should delve deeper into exploring the intricate mechanisms underlying these interactions, paving the way for advancements in containerized crop production methodologies.

Irrigation management plays a pivotal role in optimizing plant growth through the manipulation of air and water within the substrate. Proper irrigation practices influence substrate moisture content and oxygen levels, all of which directly impact the plant health and productivity. The frequency and volume of irrigation can affect substrate physical properties, such as AS and CC, thereby influencing root growth and nutrient uptake. Irrigation practices interact intricately with container design, as containers of different heights and volumes may require varying irrigation regimes to maintain optimal moisture levels throughout the root zone. Therefore, integrating knowledge of irrigation management alongside container geometry and substrate properties is needed for achieving desired outcomes for a more controlled soilless production of strawberries. The integration of irrigation management with container and substrate considerations is crucial for advancing controlled soilless production methods and improving production efficiency.

This research from this study look into the effects of container geometry on strawberry mother plant production under a greenhouse environment. However, future research endeavors should further explore the synergistic effect of irrigation practices and container-substrate interactions to develop comprehensive cultivation strategies to maximize plant performance. In conclusion, this study highlights the importance of integrating knowledge of container geometry and substrate physical properties into strawberry cultivation practices. By leveraging this understanding, growers can enhance the efficiency and efficacy of their production systems, ultimately contributing to the sustainability and profitability of greenhouse strawberry production.

Figures and Tables:

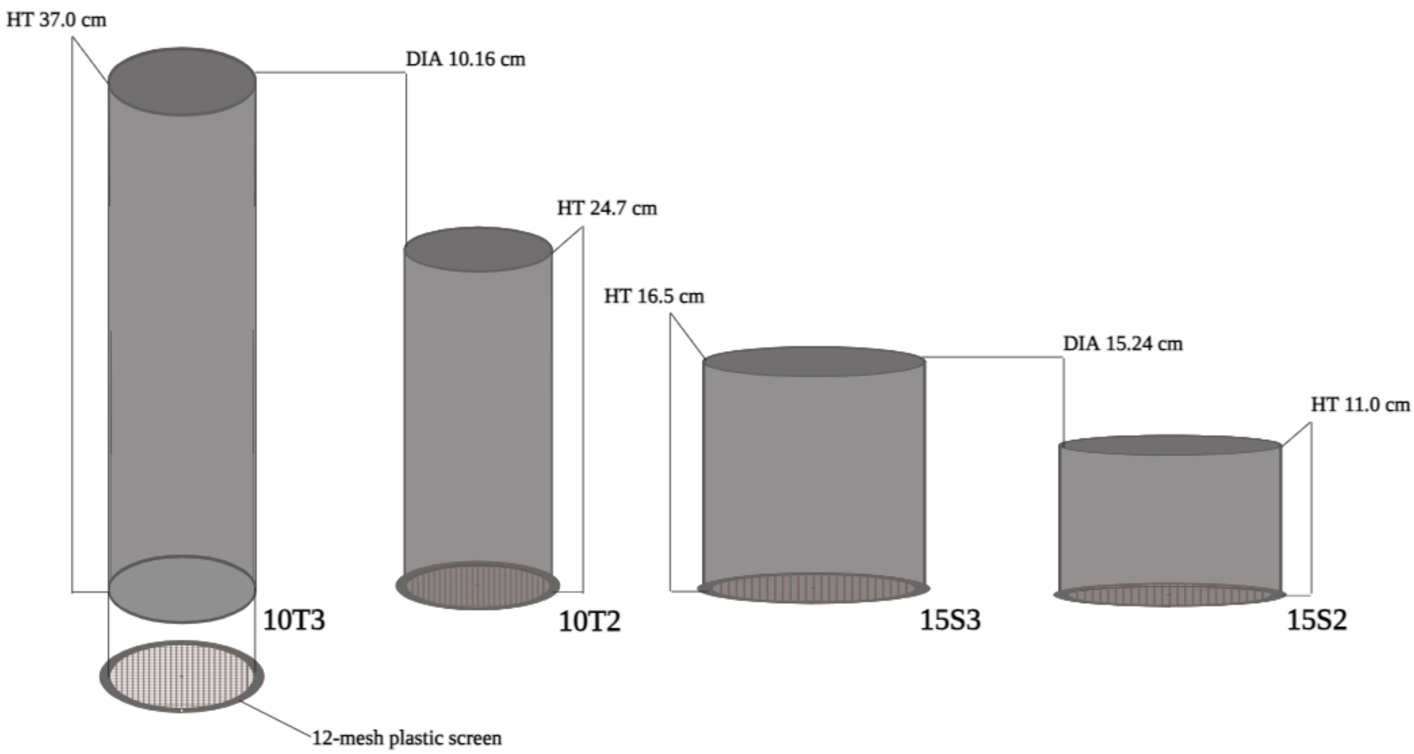

Figure 3.1. Four constructed PVC pipe containers used to study the effect of container geometry on 'Albion' strawberry mother plant growth. Identification code represent container diameter, container height, and container volume. PVC diameter: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume.

Figure 3.2. (**A**) 72-cell plug flat and (**B**) individual plug of 'Albion' strawberry plants utilized for the research trial analyzing the effects of container geometry on 'Albion' mother plant growth.

Figure 3.3. Greenhouse layout for the experiment evaluating 'Albion' strawberry mother plant growth with treatments consisting of four constructed PVC pipe containers filled with a 50% perlite: 25% peat: 25% coconut coir substrate. Shorter containers were elevated to allow for all plants/top of containers to be a similar height to the tallest treatment (10T3) by placing a stack of pots of beneath them.

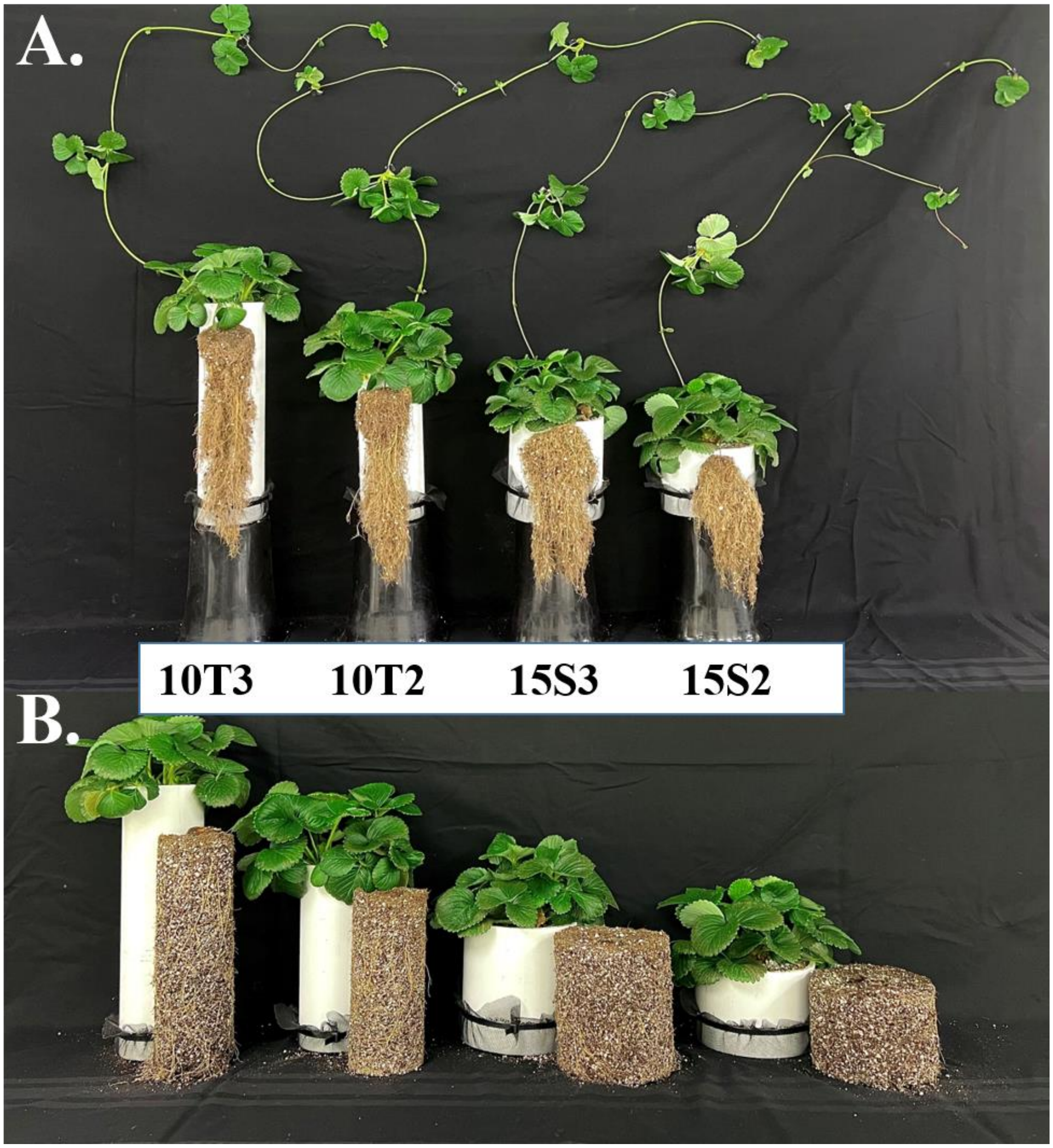

Figure 3.4. (**A**) Influence of container geometry on 'Albion' stolon development and roots. (**B**) Influence of container geometry on 'Albion' mother plants and root ball. Plants are from Trial 1, which was conducted in a glasshouse at NC State University from 5 January 2023 to 14 April 2023. Treatments consisting of four constructed PVC pipe containers filled with a 50% perlite: 25% peat: 25% coconut coir substrate. Identification code represent container diameter, container height, and container volume. PVC diameter: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume.

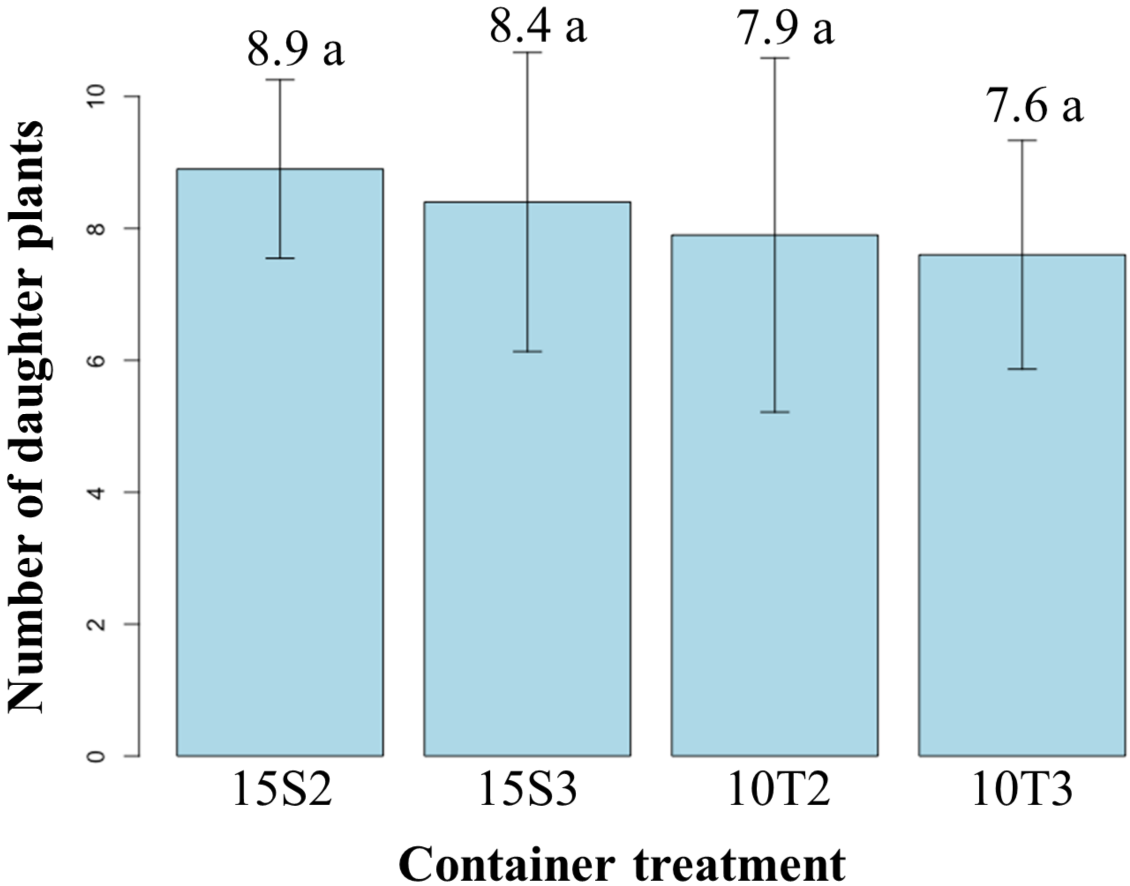

Figure 3.5. Total number of daughter plants of ‘Albion’ strawberry mother plants grown in four different constructed PVC containers filled with 50% perlite: 25% peat: 25% coconut coir during Trial 1, which was conducted at NC State University’s glasshouse from 5 January 2023 to 14 April 2023. Container treatment identification code represent container diameter, container height, and container volume. PVC diameter: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume. Data represents least-square means of five replicates, and means separation used Tukey’s honestly significant difference at α = 0.05.

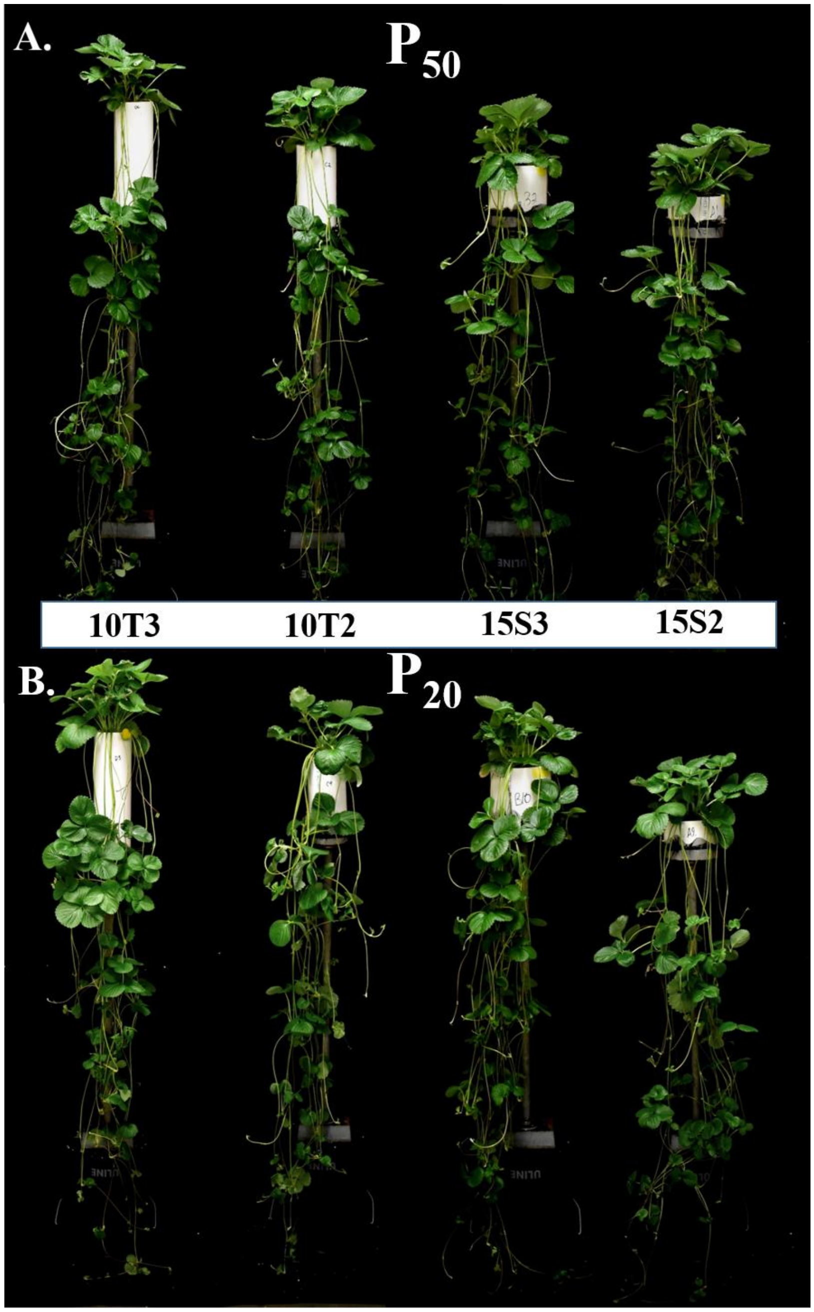

Figure 3.6. Influence of container geometry and substrate on ‘Albion’ mother plant growth. Plants shown are from Trial 2, which was conducted in a glasshouse at NC State University from 24 April 2023 to 3 July 2023. (**A**) Substrate used is 50% perlite: 25% peat: 25% coconut coir (P_{50}). (**B**) Substrate used is 20% perlite: 80% coconut coir (P_{20}). Container treatments identification code represent container diameter, container height, and container volume. PVC diameter: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume.

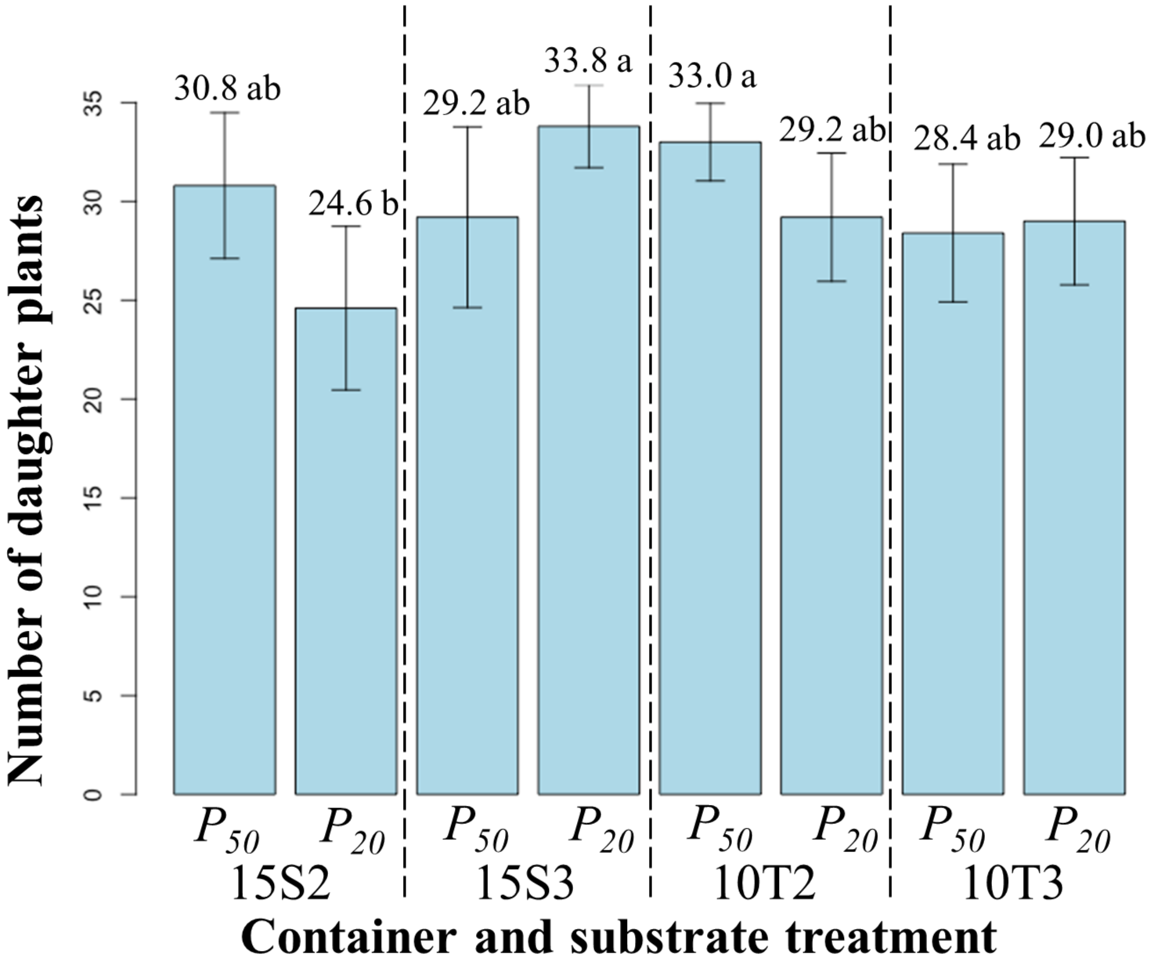

Figure 3.7. Total number of daughter plants of 'Albion' strawberry mother plants grown in four different constructed PVC containers and two different substrates during Trial 2, which was conducted at NC State University's glasshouse from 24 April 2023 to 3 July 2023. P_{50} = 50% perlite: 25% peat: 25% coconut coir. P_{20} = 20% perlite: 80% peat. Container treatment identification code represent container diameter, container height, and container volume. PVC diameter: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume. Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at α = 0.05.

Table 3.1. Dimensions of various constructed PVC pipe containers used to study the effects of container geometry on 'Albion' strawberry mother plant growth.

	Container dimensions		
Identification code[Z]	Diameter (cm)	Height (cm)	Volume (L)
15 S 2	15.24	11.0	2
15 S 3	15.24	16.5	3
10 T 2	10.16	24.7	2
10 T 3	10.16	37.0	3

[Z]Characteristics of the identification code represent container diameter, container height, and container volume. PVC diameters: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume.

Table 3.2. The pH measurements of 'Albion' strawberry mother plants overtime grown in four different constructed PVC containers and two different substrates [50% perlite: 25% peat: 25% coconut coir and 20% perlite: 80% coconut coir (Trial 2)] measured by the non-descriptive pour-through methods (Cavins et al., 2004).

Trial 1[z]							
		pH					
Container[x]	Substrate[w]	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
15 S 2	P_{50}	5.9 a	6.1 a	5.9 b	5.7 b	5.5 b	5.1 b
15 S 3	P_{50}	6.0 a	6.0 a	5.9 b	5.7 b	5.4 b	5.2 b
10 T 2	P_{50}	6.0 a	6.1 a	5.8 b	5.8 b	5.5 b	5.2 b
10 T 3	P_{50}	6.0 a	6.1 a	6.1 a	6.1 a	6.0 a	5.8 a
Significance[v]		NS	NS	***	***	***	***

Trial 2y							
		pH					
Container	Substrate	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
15 S 2	P_{50}	6.0 ab	6.2 a	6.0 ab	5.8 b	5.4 c	5.3 b
15 S 3	P_{50}	6.0 ab	6.2 a	5.9 ab	5.8 b	5.5 bc	5.2 bc
10 T 2	P_{50}	6.1 a	6.1 ab	6.0 ab	5.8 b	5.5 bc	5.3 b
10 T 3	P_{50}	6.0 ab	6.1 ab	6.2 a	6.1 a	5.9 a	5.9 a
15 S 2	P_{20}	5.5 b	5.6 b	5.6 bc	5.6 bc	5.4 c	5.1 c
15 S 3	P_{20}	5.5 b	5.6 b	5.7 b	5.6 bc	5.5 bc	5.1 c
10 T 2	P_{20}	5.4 b	5.6 b	5.7 b	5.6 bc	5.5 bc	5.1 c
10 T 3	P_{20}	5.5 b	5.5 bc	5.6 bc	5.5 bc	5.7 b	5.8 ab
Significance		***	***	***	***	***	***

[z]Trial 1 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with a 50% perlite, 25% peat, and 25% coconut coir substrate blend grown in a glasshouse at NC State University from 5 January 2023 to 14 April 2023.

[y]Trial 2 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with two substrates (50% coarse perlite, 25% peat, and 25% coconut coir) and (80% coconut coir and 20% coarse perlite) grown in a glasshouse at NC State University from 24 April 2023 to 3 July 2023.

[x]Characteristics of the container code represent container diameter, container height, and container volume. PVC diameters: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume. For example, 15S2 = 15.24-cm diameter, short height (11.0-cm), and 2 L volume.

[w]Percentage of perlite amended with coconut coir or coconut coir and peat mixture. P_{50} = 50% perlite, 25% peat, and 25% coconut coir. P_{20} = 20% perlite and 80% coconut coir.

[v]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at $\alpha = 0.05$. *, **, or *** indicates statistically significant differences between sample means based on $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively. NS (not significant) indicates the difference between sample means was $P > 0.05$.

Table 3.3. The electrical conductivity (EC) measurements of 'Albion' strawberry mother plants overtime grown in four different constructed PVC containers and two different substrates [50% perlite: 25% peat: 25% coconut coir and 20% perlite: 80% coconut coir (Trial 2)] measured by the non-descriptive pour-through methods (Cavins et al., 2004).

		Trial 1[z]					
		EC					
Container[x]	Substrate[w]	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
15 S 2	P_{50}	0.89 a	1.03 a	1.89 a	1.28 ab	1.35 a	1.03 a
15 S 3	P_{50}	0.78 b	0.97 b	1.65 b	1.32 a	1.27 ab	0.98 ab
10 T 2	P_{50}	0.77 b	0.71 c	1.58 bc	1.33 a	1.16 b	0.85 b
10 T 3	P_{50}	0.72 c	0.61 d	1.36 c	1.24 b	1.01 c	0.70 c
Significance[v]		NS	***	***	***	***	***

		Trial 2[y]					
		EC					
Container	Substrate	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
15 S 2	P_{50}	0.91 a	1.04 a	1.67 a	1.55 a	1.51 a	1.21 a
15 S 3	P_{50}	0.85 b	1.01 ab	1.65 ab	1.52 ab	1.49 a	1.19 ab
10 T 2	P_{50}	0.81 c	0.93 bc	1.58 bc	1.45 bc	1.40 ab	1.15 ab
10 T 3	P_{50}	0.74 d	0.85 c	1.35 d	1.38 c	1.31 b	0.99 c
15 S 2	P_{20}	0.86 b	1.01 ab	1.62 b	1.51 ab	1.46 ab	1.16 ab
15 S 3	P_{20}	0.85 b	0.98 b	1.61 b	1.48 b	1.44 ab	1.13 b
10 T 2	P_{20}	0.80 cd	0.95 bc	1.55 c	1.44 bc	1.41 ab	1.07 bc
10 T 3	P_{20}	0.73 d	0.81 cd	1.33 d	1.31 d	1.29 bc	0.91 cd
Significance		***	***	***	***	***	***

[z]Trial 1 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with a 50% perlite, 25% peat, and 25% coconut coir substrate blend grown in a glasshouse at NC State University from 5 January 2023 to 14 April 2023.
[y]Trial 2 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with two substrates (50% coarse perlite, 25% peat, and 25% coconut coir) and (80% coconut coir and 20% coarse perlite) grown in a glasshouse at NC State University from 24 April 2023 to 3 July 2023.
[x]Characteristics of the container code represent container diameter, container height, and container volume. PVC diameters: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume. For example, 15S2 = 15.24-cm diameter, short height (11.0-cm), and 2 L volume.
[w]Percentage of perlite amended with coconut coir or coconut coir and peat mixture. P_{50} = 50% perlite, 25% peat, and 25% coconut coir. P_{20} = 20% perlite and 80% coconut coir.

[v]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at $\alpha = 0.05$. *, **, or *** indicates statistically significant differences between sample means based on $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively. NS (not significant) indicates the difference between sample means was $P > 0.05$.

Table 3.4. Growth metrics of ‘Albion’ strawberry mother plants grown in four different constructed PVC containers and two different substrates [50% perlite: 25% peat: 25% coconut coir and 20% perlite: 80% coconut coir (Trial 2)].

Trial 1[z]

Container[x]	Substrate[w]	Leaf SPAD chlorophyll (35 DAP)	Leaf SPAD chlorophyll (70 DAP)	Flower no. removed per plant	Crown no. per plant	Crown diameter (mm)	Stolon no. per plant	Stolon total length per plant (cm)	Internode length (cm)
15 S 2	P_{50}	51.45 a	47.73 a	17.1 ab	1.9 a	23.17 a	2.3 a	240.60 a	35.41 a
15 S 3	P_{50}	51.01 a	46.67 a	21.5 a	2.5 a	23.59 a	2.5 a	250.44 a	39.14 a
10 T 2	P_{50}	51.23 a	47.93 a	15.7 b	1.9 a	22.10 a	2.3 a	185.74 a	35.91 a
10 T 3	P_{50}	50.26 a	47.68 a	20.9 ab	2.2 a	20.99 a	2.1 a	213.87 a	37.61 a
Significance[v]		NS	NS	*	NS	NS	NS	NS	NS

Trial 2[y]

Container	Substrate	Leaf SPAD chlorophyll (35 DAP)	Leaf SPAD chlorophyll (70 DAP)	Flower no. removed per plant	Crown no. per plant	Crown diameter (mm)	Stolon no. per plant	Stolon total length per plant (cm)	Internode length (cm)
15 S 2	P_{50}	50.1 a	47.2 a	23.4 a	2.4 a	25.4 b	7.4 a	522.4 a	50.9 a
15 S 3	P_{50}	50.5 a	49.8 a	24.6 a	2.4 a	24.1 b	5.8 a	539.2 a	49.6 a
10 T 2	P_{50}	50.6 a	50.8 a	24.8 a	1.6 a	26.5 ab	7.0 a	727.8 a	50.1 a
10 T 3	P_{50}	50.3 a	49.3 a	25.4 a	2.0 a	31.0 ab	7.8 a	615.8 a	50.3 a
15 S 2	P_{20}	50.3 a	50.9 a	23.6 a	2.2 a	35.0 a	8.8 a	648.6 a	48.7 a
15 S 3	P_{20}	50.9 a	49.4 a	24.8 a	2.4 a	29.0 ab	7.0 a	572.3 a	51.4 a
10 T 2	P_{20}	49.9 a	49.3 a	25.0 a	1.8 a	25.5 b	7.4 a	619.5 a	49.6 a
10 T 3	P_{20}	50.6 a	48.7 a	23.2 a	2.0 a	23.5 b	6.2 a	583.4 a	52.1 a
Significance		NS	NS	NS	NS	**	NS	NS	NS

[z]Trial 1 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with a 50% perlite, 25% peat, and 25% coconut coir substrate blend grown in a glasshouse at NC State University from 5 January 2023 to 14 April 2023.

[y]Trial 2 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with two substrates (50% coarse perlite, 25% peat, and 25% coconut coir) and (80% coconut coir and 20% coarse perlite) grown in a glasshouse at NC State University from 24 April 2023 to 3 July 2023.

[x]Characteristics of the container code represent container diameter, container height, and container volume. PVC diameters: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume. For example, 15S2 = 15.24-cm diameter, short height (11.0-cm), and 2 L volume.

[w]Percentage of perlite amended with coconut coir or coconut coir and peat mixture. P_{50} = 50% perlite, 25% peat, and 25% coconut coir. P_{20} = 20% perlite and 80% coconut coir.
[v]Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at $\alpha = 0.05$. *, **, or *** indicates statistically significant differences between sample means based on $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively. NS (not significant) indicates the difference between sample means was $P > 0.05$.

Table 3.5. Plant dry weights of 'Albion' strawberry mother plants grown in four different constructed PVC containers and two different substrates [50% perlite: 25% peat: 25% coconut coir and 20% perlite: 80% coconut coir (Trial 2)].

Trial 1[z]				
		Dry weight (g/plant)		
Container[x]	Substrate[w]	Total[v]	Stolon network	Mother plant
15 S 2	P_{50}	24.20 ab	10.24 a	13.97 a
15 S 3	P_{50}	26.72 a	11.54 a	15.17 a
10 T 2	P_{50}	22.55 b	9.26 a	13.29 a
10 T 3	P_{50}	23.57 b	8.65 a	14.92 a
Significance[u]		**	NS	NS

Trial 2[y]				
		Dry weight (g/plant)		
Container	Substrate	Total	Stolon network	Mother plant
15 S 2	P_{50}	40.0 ab	24.6 bc	15.4 a
15 S 3	P_{50}	45.1 ab	29.3 ab	16.0 a
10 T 2	P_{50}	43.6 ab	28.6 ab	15.0 a
10 T 3	P_{50}	43.0 ab	24.3 bc	18.8 a
15 S 2	P_{20}	37.8 b	19.3 c	18.6 a
15 S 3	P_{20}	42.1 ab	26.5 ab	15.6 a
10 T 2	P_{20}	42.3 ab	25.3 ab	17.0 a
10 T 3	P_{20}	45.6 a	30.90 a	14.7 a
Significance		*	***	NS

[z]Trial 1 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with a 50% perlite, 25% peat, and 25% coconut coir substrate blend grown in a glasshouse at NC State University from 5 January 2023 to 14 April 2023.

[y]Trial 2 evaluated four container types (15S2, 15S3, 10T2, and 10T3) with two substrates (50% coarse perlite, 25% peat, and 25% coconut coir) and (80% coconut coir and 20% coarse perlite) grown in a glasshouse at NC State University from 24 April 2023 to 3 July 2023.

[x]Characteristics of the container code represent container diameter, container height, and container volume. PVC diameters: 15 and 10, represent 15.24- and 10.16-cm diameter PVC pipe, respectively. S = short (11.0- and 16.5-cm) and T = tall (24.7- and 37.0-cm). 2 = 2.0 L and 3 = 3.0 L container volume. For example, 15S2 = 15.24-cm diameter, short height (11.0-cm), and 2 L volume.

[w]Percentage of perlite amended with coconut coir or coconut coir and peat mixture. P_{50} = 50% perlite, 25% peat, and 25% coconut coir. P_{20} = 20% perlite and 80% coconut coir.

[v]Total dry weight is the sum of the stolon network dry weight and mother plant dry weight.

[u] Data represents least-square means of five replicates, and means separation used Tukey's honestly significant difference at α = 0.05. *, **, or *** indicates statistically significant differences between sample means based on $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively. NS (not significant) indicates the difference between sample means was $P > 0.05$.

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CHAPTER 4

Substrate Hydro-physical Properties in Soilless Agriculture: Investigating the Role of Container Geometry on Substrate Air and Water Profiles

Abstract:

The cultivation of specialty crops in soilless growing systems has emerged as a pivotal practice in modern agriculture. The adoption of container-based production, particularly through soilless culture systems, is witnessing a significant uptrend among specialty crop producers. The challenges associated with cultivating plants in containers are extensively documented, particularly in navigating the delicate balance between insufficient and excess water. Shallow containers often result in excessive water, limiting air availability, while the confined volume of containers imposes restrictions on the water supply for optimal plant growth. Air and water capacity (AWC) model was utilized to determine basic physical properties, such as total porosity (TP), air space (AS), and container capacity (CC), for a substrate in specific-sized and shaped containers. AWC models offer a comprehensive tool for estimating hydrophysical properties across multiple substrate/container combinations simultaneously. The existing literature lacks direct reporting on these specific container types, primarily focusing on modeling the air and water profiles of traditional containers that the floriculture industry utilized, leading to a notable gap in data concerning the dynamic interplay between air and water profiles within these containers and their impact on the rooting environment. 19 substrates and 30 commercially used container selections were modeled to understand their air-water profiles. The results underscore the effect of container geometry on substrate air-water profiles, necessitating different management approaches for the same substrate in different containers. Container height stands out as a critical factor, exerting a substantial influence on substrate characteristics and subsequently affecting air and water values.

Introduction:

The cultivation of specialty crops in soilless growing systems has emerged as a pivotal practice in modern agriculture (Gruda, 2021). This transformative approach to agriculture serves multifaceted purposes, addressing the need to sustain food production, enhanced human well-being through ornamentals, and contribute to essential ecosystem services, including ecological restoration of annual agricultural land (Landis and Nisley, 1990). The adoption of container-based production, particularly through soilless culture systems, is witnessing a significant uptrend among specialty crop producers. This shift is prompted by several factors, including the diminishing availability of resources such as arable land and freshwater, challenges in pesticide availability leading to increase pest pressure, increased environmental concerns and regulations on the use of soil fumigants, efforts to minimize transport distances to marketplaces, and the need to combat food deserts spurred by urbanization, among others. Additionally, there's a necessity for adaptability in a dynamically evolving global marketplace and a recent surge in demand for specialty crops fueled by global events such as the COVID-19 pandemic (Landis and Nisley, 1990, USDA, 2017, Blok et al., 2021, Claire et al., 2018, Kingston et al., 2017).

In response to these evolving trends, the global trajectory predicts a >400% increase in soilless substrate utilization worldwide (Blok et al., 2021). Soilless culture systems have become indispensable to produce ornamentals, vegetables, small fruit, and other emerging crops, especially in regions where soil conditions are unsuitable or water is limited (Claire et al., 2018; Kingston et al., 2017). The efficiency gains offered by soilless culture, both in terms of space utilization and resource efficiency, particularly in water and nutrients, contribute to increased yields, making year-round production and multiple crop cycles possible (Sambo et al., 2019; Raviv et al., 2008). Notably, soilless cultivation has become the preferred option in urban areas plagued by soil contamination, ensuring a clean and viable environment for plant growth (Pennisi et al., 2016).

The selection of an ideal soilless substrate becomes paramount in achieving optimal plant growth and health, as it serves as the foundation for implementing horticultural crop production management strategies. A delicate balance between water availability and root zone aeration is crucial, a balance intricately linked to the physical and hydraulic properties of the substrate. Typically, the strategic combination of organic substrate materials with coarser particles, each possessing distinct physical and hydraulic characteristics, has been utilized as an avenue to optimize this balance to increase root zone air space (AS). Argo (1997) described one of the primary selectors of soilless substrates as aeration. Aeration is described as the volume of air in a substrate, after saturation and gravitational draining, but before evaporation (Bugbee and Frink, 1989)

The challenges associated with cultivating plants in containers are extensively documented, particularly in navigating the delicate balance between insufficient and excess water. Shallow containers often result in excessive water, limiting air availability, while the confined volume of containers imposes restrictions on the water supply for optimal plant growth (Spomer, 1974). This was demonstrated by Milks et al. (1989) where short containers (2.2 cm tall) had less than 2% AS unless a large particle size media with a high amendment rate of vermiculite in peat was used; however, this then significantly lowered the container capacity (CC) of the substrate, which could lead to plant desiccation.

This challenge of balancing the air and water profiles of a substrate in containers has garnered considerable attention, particularly as agriculture embraces a shift towards alternative containers to accommodate a diverse range of crops, including small fruits, vegetables, leafy greens, hemp, and floriculture crops (Arumugam et al., 2021). A rise in popularity of containers such as propagation cubes, plugs, liners, lay flat grow bags, troughs, fruiting pots, and open-top grow bags has shown that inadequate and excessive water balanced with appropriate AS still remains a central challenge for this type of production as well (Albaho et al., 2013; Waldo et al., 1998; Bauerle, 1984; Karimi et al., 2013). Assessing a substrate's capacity to retain and release water, and how the air and water dynamic changes depending on container geometry, is essential for enhancing the water use efficiency in these crops (Fonteno, 1988).

The determination of substrate hydrophysical properties through moisture retention curves (MRC’s) unveils essential characteristics, including CC, AS, easily available water, and water-buffering capacity (De Boodt and Verdonck, 1972). These values, discerned from specific levels on the MRC, accurately predict how a substrate manages water at low tensions. Bilderback and Fonteno (1987) further refined the concepts, describing CC and AS as a function intricately linked to container geometry.

Fonteno (1989) illustrated how MRC’s can elucidate the availability and unavailability of water in substrates within containers. Water retention is not uniform across different tensions, leading to distinctive water desorption patterns in individual substrates. A five-parameter nonlinear model was subsequently introduced, offering improved accuracy in predicting relationships between volumetric water content and water potential compared to earlier models (Van Genuchten and Nielsen, 1985). Milks et al. (1989) further refined this model for horticultural substrates, enabling more precise predictions of the relationships between volumetric water content (ϴ) and water potential (Y). The model is articulated as follows:

$$\boldsymbol{\Theta = \Theta_r + (\Theta_s - \Theta_r) / [1 + (\alpha \times h)^n]^m}$$

where Θ represents volumetric water content, $Θ_s$ is the content at saturation (0 kPa), $Θ_r$ is the residual content (-30 kPa), h is the height of the column or the moisture tension, α is the inverse of the "air entry value," and n and m are curve-fitting parameters. Values obtained from this model, specifically $Θ_s$ and $Θ_r$, are employed in an Equilibrium Capacity Variable (ECV) model to determine basic physical properties, such as total porosity (TP), AS, and CC, for a substrate in specific-sized and shaped containers (Bilderback and Fonteno, 1987; Milks et al., 1989). Container size significantly alters substrate properties, impacting plant growth and development (Bish et al., 1997; Milks et al., 1989; Owen and Atland, 2008). In this paper, the ECV model previously described by Milks et al. (1989) will be denoted as the air and water capacity (AWC) model.

The interaction between substrate and container dimensions, as elucidated by AWC models, holds implications for crucial aspects such as plant support, aeration, and moisture levels. Container dimensions play a pivotal role in shaping media characteristics, influencing aeration and water-holding capacity (Dufault and Waters, 1985). Notably, the same substrate exhibits distinct properties when placed in containers of varying sizes; larger containers yield different results than smaller counterparts (Fonteno 1988; Milks et al., 1989; Fields et al., 2014).

AWC models offer a comprehensive tool for estimating hydrophysical properties across multiple substrate/container combinations simultaneously. While TP may remain consistent across containers of different volumes using the same substrate, provided the bulk density remains constant, AS experiences an increase with container height, thus CC would decrease (Milks 1989). As demonstrated by Spomer (1974), the increased drainage in taller containers was a result of the increased gravitational forces drawing more water out of the smaller void spaces in taller containers. The challenges associated with growing plants in shorter containers arise from poor aeration of the growing media, exacerbated by a post-irrigation "perched water table" (Spomer, 1974). Small containers, especially those employing large-particle-sized media, may encounter insufficient AS. The influence of container size is evident in significant alterations to substrate properties, thereby impacting plant growth and development (Bish, 1997; Milks, 1989; Owen and Atland, 2008).

The aim of this study was to utilize the AWC models derived from MRCs to conduct a comparative analysis of various substrate components and amendment rates and to encompass commercially available alternative container sizes and geometries. The existing literature lacks direct reporting on these specific container types, primarily focusing on modeling the air and water profiles of traditional containers that the floriculture industry utilized, leading to a notable gap in data concerning the dynamic interplay between air and water profiles within these containers and their impact on the rooting environment. This research seeks to address this void and contribute valuable insights to our understanding of the complexities inherent in from various substrates in different container sizes.

Materials and Methods:

Substrate sourcing and preparation. Sphagnum peat-moss (Pro-Moss Sphagnum Peat, Quakertown, PA) was obtained from a compressed bale, then loosened and fluffed before being moistened by hand to achieve a target moisture content of 50% by weight. The peat moss utilized in this study was sourced from Premier Pro-moss (Pro-Moss Sphagnum Peat, Quakertown, PA).

To create the experimental mixes, ForestGold, a disk-refined wood fiber (Pindstrup, Denmark) was analyzed in its pure form (100%) and in volumetrically mixed ratios with Canadian peat at 20% and 40%, resulting in three samples. The same ratios of wood to peat were applied to two other types of wood substrates: GreenFibre, a screw-extruded wood fiber from Klassman-Deilmann (Geeste, Germany), and a hammer-milled processed tree substrate (PTS, *Pinus taeda*) processed at the NC State University Substrate Processing and Research Center (SPARC) located at the NC State University horticulture field lab in Raleigh, NC.

The remaining five substrates were 100% Premier Pro-moss sphagnum peat (Canadian), 100% European peat sourced from Klassman-Deilmann in Germany, and 100% medium-grade horticultural perlite obtained from Carolina Perlite Company (Gold Hill, NC). Additionally, mixes of peat and perlite were formulated in ratios of 80:20 and 60:40 (v:v) utilizing Canadian peat and perlite from Carolina Perlite Company. Aged pine bark sourced from Pacific Organics (Henderson, NC), aged and turned monthly for six months in outdoor windrows, and an engineered horizontal rockwool slab from Grodan (Milton, Canada) were also included in the analysis. Furthermore, propagation mixes from Jiffy Group (Zwijndrecht, the Netherlands) and Ball Horticultural (West Chicago, IL) were incorporated into the study. In total, all 19 substrates were prepared to undergo evaluation for their hydro-physical properties.

Procedures for determining initial physical properties. To determine the initial physical properties, including CC, AS, TP, and bulk density, the NC State University Porometer method was used and procedures followed as outlined in the NC State University Horticulture Substrates Laboratory Manual (Fonteno et al., 1995). This method utilizes specialized base plates designed for soil sample aluminum cores measuring 7.6 cm tall, 7.6-cm i.d. These plates enable the substrate to be fully saturated, with excess water drained into a graduated cylinder, representing the AS. First, the wet weight of the sample is recorded. Then, the sample is subjected to drying completely in an oven at 105 degrees C for 48 hr. The dry weight is then recorded, enabling the calculation of water held at CC using the formula:

wet weight (g) - dry weight (g) = water (g) held at CC.

CC and AS are subsequently summed to derive the TP of the substrate.

Moisture retention curves. MRC's were determined following the protocols outlined in the NC State University Horticulture Substrates Laboratory Manual (Fonteno and Harden, 2010). Each sample was inserted into a 7.6 cm tall, 7.6-cm i.d. aluminum core and positioned within Volumetric Pressure Plate Extractors (VPPE; Soilmoisture Corp., Santa Barbara, CA) equipped with 50-kPa ceramic plates (Soilmoisture Corp.). The experiments were conducted in a controlled-temperature chamber located at the NC State University Horticultural Substrates Laboratory, maintained at 22°C.

Four samples of each substrate, packed to the same bulk density, underwent a stepwise saturation process with tap water. After 48 hours of equilibration, the samples were allowed to freely drain for an additional 48 hours, recording water effluent volumes. Subsequently, pressures of 1.0, 2.0, 4.0, 5.0, 7.5, 10, 20, and 30 kPa were applied individually for 24 hours, with drainage from each substrate sample recorded. After 24 hr exposure to 30 kPa pressure, samples were removed from VPPEs, weighed, dried at 105°C for 48 hr, and reweighed, allowing for the calculation of volumetric water content (Θ).

Plotting the moisture retention curves and AWC modeling. Following the acquisition of Θ values corresponding to desired suctions, a scatterplot was generated to illustrate the relationship between moisture content and suctions. Substrate water-holding abilities, represented by easily available water and water buffering capacity were calculated following the method proposed by de Boodt and Verdonck (1972). Predicted means for each substrate, obtained through the NLIN procedure of SAS (Version 9.2; SAS Institute, Cary, NC), were plotted to fit the five-parameter Van Genuchten model for horticultural substrates (Milks et al., 1989).

Air and water capacity models. Using values derived from the MRC's with Van Genuchten's models, AWC models were executed to simulate physical properties of the 19 substrates in various sized and shaped containers (Milks et al., 1989). These models incorporated Θ_s and Θ_r, along with three curve-fitting parameters (a, n, and m), as well as individual container geometries and volumes. By integrating moisture retention data with volumes calculated for incremental height-based zones, it becomes possible to ascertain the actual moisture volumes within each zone. The summation of these volumes up to the substrate surface height enables the determination of the percent moisture volume for the entire container at its capacity (Figure 1). The subtraction of CC from TP yields the percentage of AS. Similarly, the AS for each zone can be calculated using the same approach employed for determining CC.

The selected containers for these models were composite representations of various containers tailored to three distinct production categories for crops, with each section comprising 10 containers, for a total of 30 containers modeled. Section 1 focused on propagation and included containers such as cubes, plugs, and liners (Table 2 and Figure 2), Section 2 encompassed lay flat grow bags and troughs (Table 3 and Figure 3), while Section 3 featured pots and open-top grow bags (Table 4 and Figure 4). The substrates selected for each section aimed to mirror potential substrates suitable for the respective type of production.

Furthermore, an additional experiment was performed on the four open-top growbags, where they were modeled under the condition of being fully filled and comparing this to the manufacturer's pre-filled level. These containers, initially received in a dry state, contained a coconut coir brick that was subsequently hydrated. The fill level and container dimensions after substrate hydration was documented. This approach enables the collection of data for a comprehensive comparison of the physical characteristics and root volume of these containers when filled to capacity versus the manufacturer's pre-filled level after hydration and full expansion.

A final experiment involved the modification of a mathematical description representing a container with a 15-cm top diameter, 10.6-cm bottom diameter, and 14.4-cm height, such as Fonteno displayed in 1987. This description was adjusted to create four simulated containers of equal height, each possessing distinct geometries: (1) normal taper, (2) straight sides (top and bottom diameters = 15 cm), (3) double taper (top diameter = 30 cm; bottom diameter = 10.6 cm), (4) inverted normal taper (top diameter = 10.6 cm; bottom diameter = 15 cm). These simulated containers were integrated into the media regression models and air and water values were predicted for the resulting container-media combinations.

Two fundamental assumptions underpinned the utilization of these models. Firstly, it was assumed that the bulk density and TP of the media within containers equated to the bulk density and TP of the samples outlined in the MRC. Secondly, given that the MRC's primarily represented desorption curves, all simulated irrigation was applied to saturation and allowed to drain freely before pressures were applied (Bilkerback and Fonteno, 1987).

Tables 5, 6, 7, 8, 9 and figures 5, 6, and 7 were generated using mathematically derived modeling algorithms, necessitating the calculation of means from repetitions to derive curve-fitting parameters for integration into the models. To validate the model, the means of moisture retention data were juxtaposed with corresponding Θ values and model predictions, employing the 7.6-cm aluminum cylinder as the designated container and comparing to actual data for this container.

Results and Discussion:

Initial substrate physical properties. Based on the NCSU Porometer method (Fonteno et al., 1995) the highest TP was observed in the rockwool slab (96.1%) and coir (93.8%), whereas the lowest was recorded in the 100% perlite (76.7%) and Can peat [77.2% (Table 1)]. European peat exhibited a higher TP of 85.7% compared to Canadian peat. It was evident that the incorporation of perlite, GF, FG, and PTS into Canadian peat resulted in an increase in TP. However, little change in TP was observed when perlite was amended from 20% to 40%.

CC and AS were influenced by the blend percentage and substrate type (Table 1). The highest CC values were observed in the two commercial propagation mixes, with Jiffy at 82.3% and Ball at 78.9%, which were comparable to Canadian peat at 77.2%. Conversely, the lowest CC values (<60.0%) were observed in rockwool, 100% perlite, 100% aged pine bark, 100% ForestGold, and 20% GreenFibre.

The highest AS was predominantly observed in rockwool at 37.1%, while the lowest was displayed in Canadian peat at 6.4% (Table 1). European peat exhibited a significantly higher AS compared to Canadian peat, with a difference of 17.5%, showcasing AS values of 23.9%. These findings underscore the impact of material source (peat type) and component blend rate on the physical properties of the substrates.

Although the Porometer method offers quick, reliable, and consistent data, issues have arisen with the TP measurements due to their susceptibility to changes in bulk density and moisture content. These parameters are influenced by the substrate preparation and packing method, as the method involves manually packing metal 7.6-cm cores. Fonteno (1993) demonstrated variations in AS, CC, and TP when Porometer samples of a 1:1 peat and vermiculite substrate were set to moisture contents of 160% and 250%, with higher moisture content resulting in higher AS and lower CC. Additionally, the data obtained originates from a 7.6-cm metal core, which may not accurately represent the substrate-container combination. For a more precise assessment of reported substrate hydro-physical properties, utilizing moisture retention curves and the AWC model is recommended.

Various container sizes hydro-physical properties. Regardless of the container's size and shape, the percentage of solids and, consequently, the TP remained constant within a single substrate (Tables, 5, 6, 7, 8, and 9). This outcome aligns with expectations, as TP remains unaffected by container size, provided the bulk density and initial moisture content remains constant, as established by previous research (Milks et al., 1989). Notably, changes in container size were associated with alterations in CC and AS of the substrate. TP was not reported, as it is inferred by the CC and AS values, the sum of which equals TP.

Section 1.

Cubes, plugs, and liners. The investigation across container sizes, ranging from the 3.5-cm cube to the 22.8-cm liner, unveiled consistent patterns of AS increase and CC decrease (Table 5). Notably, the 128-cell, 48-cell, and 72-cell containers exhibited similar AS and CC values, a phenomenon attributed to their minimal height distinctions, ranging from 5.0 cm to 5.4 cm (Table 2). This emphasizes the influential role of container height in shaping substrate dynamics.

Regarding European peat, a discernible 22% decrease in CC and a concurrent increase in AS were observed from the 3.5-cm cube to the 22.8-cm liner (Table 5). In contrast, Canadian peat displayed an 11.9% decrease in CC with a corresponding increase in AS. Throughout the analysis, European peat consistently maintained lower CC and substantially higher AS, which can be linked to the harvesting methods employed for sphagnum peat moss (block cut peat in

Europe and field milled peat in Canada (Edwards, 2020). As the container size increases, the distinctions between the characteristics of European and Canadian peat AS become less prominent. With the 3.5-cm cube, the European peat AS exhibits a fivefold increase compared to the Canadian peat. However, in the 22.8-cm liner, this difference narrows, with the European peat AS being only 2.5 times higher than the Canadian. Fields (2014) showed a similar trend comparing 70:30 (v:v) amendment ratios of perlite, shredded pine wood, and pine wood chips in a plug tray compared with a 3.9 L container, with the taller container showing little difference among materials.

Coconut coir and rockwool demonstrated the highest TP, at 93.9% and 96.1%, respectively (Table 5). In the 3.5-cm cube, coir exhibited a higher CC of 84.3% compared to rockwool's 80.4%, while rockwool had a higher AS of 15.7% compared to coir's 9.6%. However, with increasing container height, the divergence in their AS and CC values underwent changes. Rockwool experienced a substantial 55.2% decrease in CC, resulting in 25.2%, and increased in AS from the 3.5-cm cube to the 22.8-cm liner. Coir had a 28.5% decrease in CC and increase in AS. Perlite displayed the lowest TP of 76.7%, with the CC in the smallest container being 63.9% with an AS of 12.8%. Increasing the container height to 22.8-cm led to a 250% increase in AS in perlite.

Both of Jiffy and Ball propagation mixes exhibited relatively low AS levels, with Jiffy having 4.7% and Ball with 3.7% in the smallest container (Table 5). However, with an increase in container height, the AS levels became more comparable to those of European peat, coir, and perlite, falling within a range of roughly 10%. These propagation mixes displayed consistent characteristics across all container sizes, with the largest container showing Jiffy at 25.5% AS and Ball at 26.4% AS. Throughout all containers these mixes consistently possessed the highest

CC among others, except in the 22.8-cm height container, where Canadian peat slightly surpassed them with 68.8%, while Jiffy had a 67.8%, and Ball had 62.8%.

Section 2.

Layflat growbags and troughs. The analysis of commercially utilized lay flat growbags and trough containers showed a diverse range of container dimensions (Table 3). The heights of these containers ranged from 6.7-cm, represented by the BVB Strawberry Growbag, to 14.8-cm, represented by the Klasmann Growbag Advanced. Additionally, there was a considerable variability in the length and width of these containers, with top length ranging from 20.3-cm to 105.4-cm and top width ranging from 10.5-cm to 24.0-cm (Table 3). With a height difference of approximately 8-cm from the shortest to tallest container, the AS levels across most materials did not differ as greatly as between other containers. However, there was still a consistent pattern observed of AS increase and CC decrease as container height increased. Notably, the comparison of container lengths revealed that length does not have a great effect on the AS, emphasizing that it is the height that influences it. For instance, the 11L trough is 46.4-cm long with a height of 11.8-cm, while the California substrate trough is more than two times longer with a length of 96.8-cm, with a similar height of 11.8-cm. However, the difference between their AS values across all substrates does not exceed 1% (Table 6).

In European peat, the CC displayed a decrease from 63.3% in the BVB growbag to 53.9% in the 9L trough, representing nearly a 10% difference, as well as with AS (Table 6). Conversely, Canadian peat exhibited a higher CC of 77.9% in the BVB growbag, which decreased to 72.8% in the 9L trough, indicating only a 5% change in both CC and AS. Throughout all containers, European peat consistently maintained a lower CC and higher AS compared to Canadian peat. The AS of European peat was four times greater than Canadian in the BVB growbag, but three times great in the 9L trough.

Coconut coir displayed a CC of 76.3% with an AS of 17.5%, while rockwool exhibited a lower CC of 63.1%, but higher AS of 33.1% in the shortest container (Table 6). However, the differences became more pronounced in the larger 9L container, with coir having a 63.7% CC and 30.1% AS, and rockwool with only a 37.9% CC and 58.3% AS.

Among the wood products tested, PTS exhibited the highest CC in the BVB growbag, but all four products showed CC values within a 10% range of each other (Table 6). PTS had the lowest AS at 16%, while the others had approximately 24% AS in the BVB growbag. However, with an increase in container height, the discrepancy in AS became more pronounced. PTS, for instance, had 23.2% AS, while FG had 40.3%, but still maintained the highest CC among other wood substrates.

As the size of the container is increased, the variations in AS and CC among different amendment rates and amendment products become less pronounced (Table 7). For example, the 20:80 perlite and Canadian peat mix in the shortest container (BVB growbag) had 7.0% AS, in contrast to the 20% GF with an AS over three times higher at 22.1%. With the increase in container size, the disparities in AS among the four amendment products (perlite, PTS, FG, GF) at 20% and 40% rates diminish, resulting in much less deviation among any of the amendments (Table 5). This suggests the potential for taller containers to be utilized as a means to enhance AS without relying solely on amending materials with coarse aggregates.

Section 3.

Open top growbags and pots. Commercial open top growbags and pots were analyzed in the model. In this study, notable changes were observed in the characteristics of European peat, Canadian peat, coconut coir, and various wood products across different container sizes and amendment rates. Height of these containers ranged from 15.9-cm, being the 4.7L square pot, to 33.3-cm, being the 25L round pot, representing a 17.4-cm difference in height from shortest to tallest (Table 4). However, there was still a consistent pattern observed of AS increase and CC decrease as container height increased. Among several containers there were no great differences in AS or CC, including between the Root Kandy open top and the 5 gallon open top, with their heights both being 26.7-cm, even with their radius being 11.1-cm in Root Kandy and 17.2-cm in the 5 gallon open top bag, displaying heights integral role in changing the air and water status in the containers.

European peat's CC decreased by 7.8%, while the AS increased by the same amount, transitioning from a 4.7L to 25L pot (Table 8). In contrast, Canadian peat in the 4.7L pot exhibited a 19.5% higher CC compared to European peat, a difference that persisted across larger container sizes. The 25L pot revealed a 20.5% higher CC for Canadian peat compared to its European counterpart. Additionally, European peat consistently maintained higher AS in all container sizes compared to Canadian peat.

Among the wood products, PTS consistently maintained the lowest AS across all container sizes, with only a 6% increase from smallest to the largest container (Table 8). FG displayed the highest AS, ranging from an initial 43.4% to 54.9% in the largest container. However, FG demonstrated a lower capacity to retain moisture, reflected in its 28.6% CC in the largest container.

Comparing different amendment types and rates revealed similar trends in CC across container sizes (Table 9). In the 4.7L square pot, the range was from 54.4% (40% PTS) to 63.8% (20% perlite), representing a difference of 9.4%. In the 25L pot, the range was from 44.8% (40%

PTS and 40% FG) to 53.5% (20% perlite), with a slightly lower difference of 8.7%. Regarding AS, 40% PTS maintained a higher AS in all container sizes, while 20% perlite consistently exhibited the lowest AS. The difference from the highest to the lowest AS in the 4.7L pot was 15.7, reducing slightly to 15.0% in the 25L pot.

Notably, as container height increased, the differences in AS among amendments decreased for some materials (Table 9). For example, the difference in AS from 40% perlite to 20% GF in the shortest container was 8.7%, but in the 25L pot, it reduced to only 3.2%. Furthermore, increasing the amendment rate from 20% to 40% for perlite and GF in larger containers showed minimal impact on CC or AS.

Growbag Fill Level.

Manufacturer filled growbag compared to growbag filled to capacity. AWC models were ran based on both the manufacturer's pre-filled amount after hydrating the coconut coir block completely and the scenario where the bags were completely filled within the containers (Figure 5). Analyzing the manufacturer's fill, the 1-gallon bag exhibited 30.7% AS and 63.1% CC with a coconut coir substrate. However, when fully filled, a slight increase in AS and decrease in CC by 2.6% were observed. Similar trends were evident in the other bags with Root Kandy experiencing a 5.8% change, 5-gallon showing a 2.3% change, and True Blue revealing a 3.5% change.

The assessment of root volume was conducted considering the manufacturer's pre-filled amount and a scenario where the bags were filled to capacity. This analysis revealed a consistent increase in root volume for all bags when filled to their maximum capacity (Figure 5). Specifically, Root Kandy demonstrated a 45.08% increase in root volume, followed by the 1-

gallon bag with a notable 14.78% increase, True Blue had a 7.57% increase, and the 5-gallon bag with a 3.49% increase.

This volumetric expansion indicates a uniform enhancement in the availability of air and water for root growth across all bags. For example, the Root Kandy bag showed an additional 1.5 liters of water when filled completely, while the True Blue bag presented nearly 3.0 liters more water under the same conditions (Figure 5). Although the True Blue bag exhibited only a 3.5% change in CC, the substantial increase in available water volume becomes evident when viewed in the context of root growth potential through the volume of water present. Bilderback and Fonteno (1987) investigated the volume of water present in various container sizes, showing that a 3.8 L container had two times more water compared to a 15.3 cm container, even though the CC value was only 2% different. These outcomes highlight the dynamic relationship between recommended fill levels, CC, and root volume, emphasizing the potential impact on the root environment and growth conditions within the open-top grow bags.

Artificial Containers.

Artificial containers with unique geometry. The air and water values for 100% coconut coir in the artificial containers are illustrated in Figure 6. All containers were assumed to have the same height, allowing for an analysis of the influence of other container parameters on the distribution of air and water. The simulation models indicate that altering the container design from a normal taper did not significantly affect the percentage of air and water values. However, substantial changes occurred in the actual volumes of air and water available for root growth, influenced by variations in container volume. One exception was observed where there was no volume change from the normal taper to the inverted normal container. The percentage of solids remained constant across all containers due to the uniform TP of the substrates. Inverting the container resulted in less available air but increased the amount of water. The modifications in container configuration, especially transitioning to a smaller taper at the top, led to a reduction in drainable pore space compared to the normal taper.

Similar trends were observed in the 60% peat + 40% perlite substrate across the four simulated containers (Figure 7). Discrepancies in air and water values between the coconut coir and 40% perlite + 60% peat substrate stemmed from variations in the MRC of the two substrates. This experiment underscores that not only does container height influence air-water profiles, but the distinct geometries of the container also play a crucial role in shaping these profiles. Bilderback and Fonteno (1987) showed similar results in a 3 pine bark: 1 sand and 1 peat: 1 vermiculite media.

Conclusions:

The predicted AWC models have illustrated the variations in air and water profiles of numerous substrates utilized in different containers, which are used for various crop types and stages of crop production. Noteworthy differences emerge in amendments used for smaller-sized containers, such as lay flat growbags and troughs. However, in representations of larger-sized containers, where these amendments are more likely to be utilized, the physical properties exhibit minimal differences between amendments. Insights from Biran and Eliassaf (1980), Keever et al. (1985), and Tilt et al. (1987) emphasize the significance of matching container shape to the natural growth habit of plant species for optimal growth response, considering both genetic capacities and container physical properties. The data collected during this study affirm that media type and container combinations significantly influence air and water values, emphasizing the importance of selecting an appropriate medium/container combination tailored to the specific needs of plant root characteristics.

To predict air and water content accurately, a comprehensive understanding of the substrates MRC and a mathematical model for container geometry are imperative (Bilderback and Fonteno, 1987). Although the NCSU Porometer method (Fonteno et al., 1995) provides fast and repeatable data, this may not serve as the most precise hydro-physical property indicator due to the influence of container geometry, and this method utilizing a 7.6-cm core. The impact of container type and size extends beyond only the physical characteristics, significantly affecting production costs (Dufault and Waters, 1985). This underscores the importance of adopting a holistic approach in the selection of substrates and containers.

Container height stands out as a critical factor, exerting a substantial influence on substrate characteristics and subsequently affecting air and water values. The volume of containers also contributes significantly to changes in physical properties, thereby influencing plant growth responses (Bish et al., 1997; Latimer, 1991; Marsh and Paul, 1988; Dufault and Waters, 1985). Considerations regarding the number of plants within containers, especially in the context of substrate grow bags, unveil subtle nuances in air and water availability for individual plants (Amundson et al., 2012; Dijkstra et al., 1992). Moreover, the decision to fill bags completely or not introduces variations in root volume, consequently impacting air and water values. The choice between sub-irrigation and top irrigation adds another layer of complexity, particularly in taller containers where capillarity of substrates becomes a crucial consideration (Schulker et al., 2021). In essence, these findings collectively emphasize the intricate relationship between container dimensions, substrate characteristics, and the formulation of effective container management strategies.

Another utility of these models may be in providing a baseline for determining irrigation efficiency in each container/substrate combination. The underlying premise for the models is the saturation of these substrates and free drainage. This produces a maximum water retention and a minimum air space value after drainage. It is well known that there are many factors that can influence the volume of water captured and retained after irrigation, such as irrigation time and frequency as well as substrate conditions such as water content prior to irrigation and the hydrophobic level for each substrate (Schulker et al., 2020). Comparisons of irrigation results with model values will provide valuable measures of irrigation efficiency, which will be critical in determining water use in the future.

In conclusion, this study highlights the connection between substrate and container geometry, challenging the conventional treatment of these factors as independent entities. The dimensions of containers, specifically their height and volume, emerge as determining factors in shaping the air and water content of horticultural substrates. This influence remains consistent across diverse media, with variations influenced by the moisture retention patterns. Moreover, it's crucial to note that while most containers will accommodate plants for two to 12 months, certain crops such as fruit-bearing plants and other perennials may reside in them for three to eight years. The longer lifespan of these crops necessitates additional planning and consideration of the substrate and container type to ensure sustained growth and health over an extended period.

Figures and Tables:

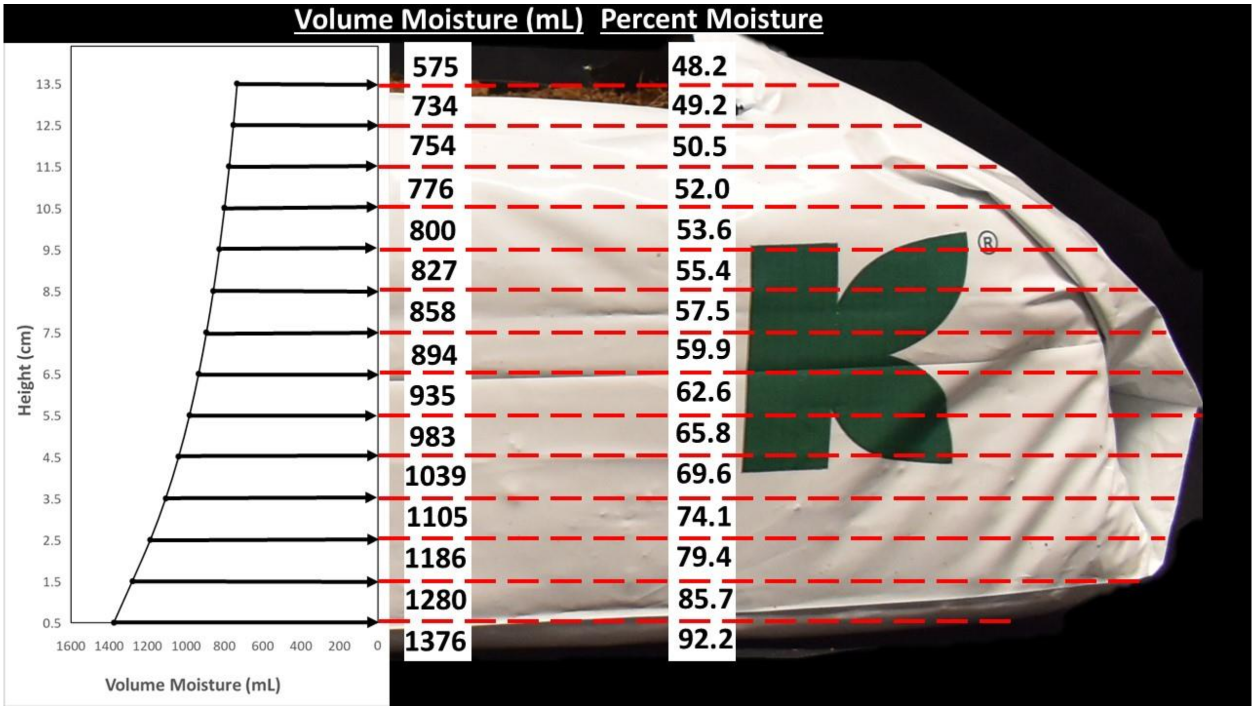


Figure 4.1. Volume and percent moisture retained in 1 cm zone increments in a lay flat growbag container derived from the moisture retention curve of 100% coconut coir.

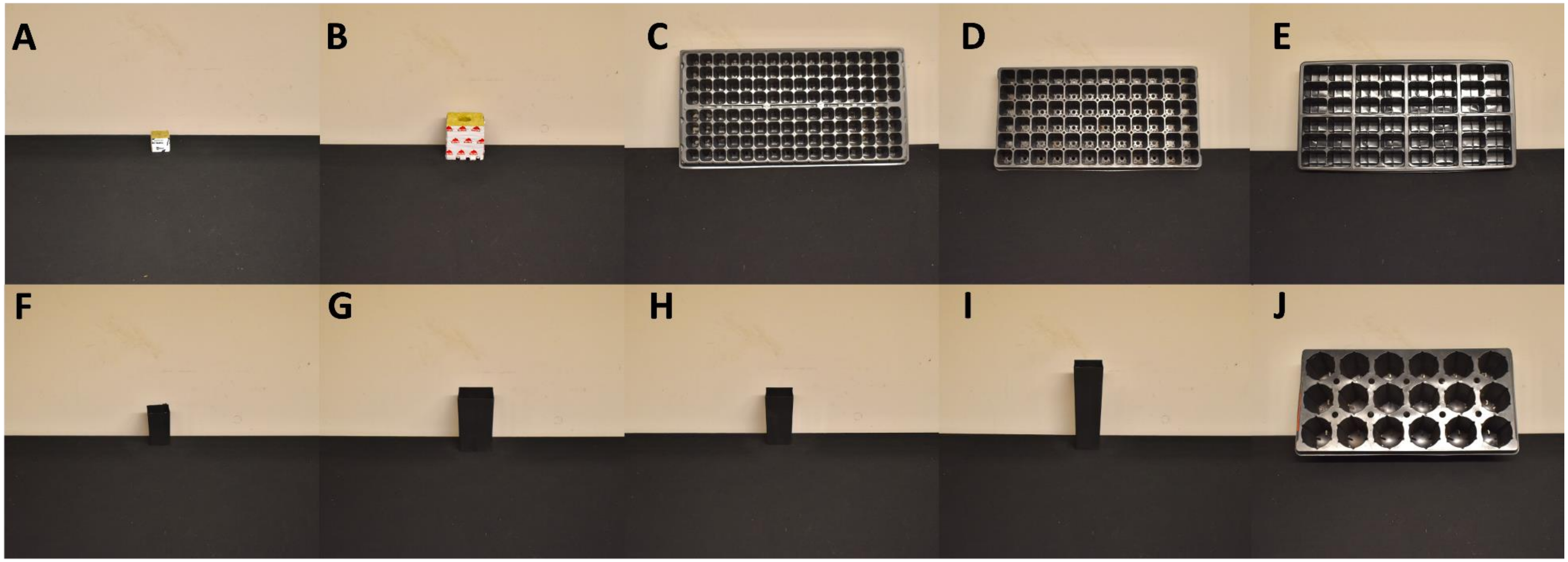


Figure 4.2. Images of cubes, plugs, and liner container treatments used in the air and water capacity (AWC) models. Containers used included (**A**) mini blocks, (**B**) grow blocks, (**C**) 128 square, (**D**) 72 square, (**E**) BP plant cell, (**F**) 2 3/8" x 3 ¾", (**G**) 2 7/8" x 5 ½", (**H**) 3 5/8" x 6", (**I**) 2 7/8" x 9", and (**J**) Boost18™.

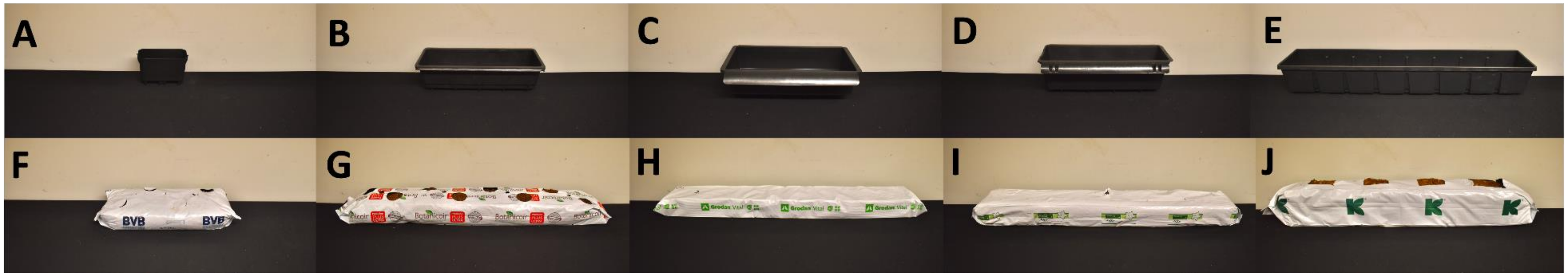


Figure 4.3. Images of lay flat growbags and trough container treatments used in the air and water capacity (AWC) models. Containers used included (**A**) 1.85-L raspberry pot, (**B**) 9L trough, (**C**) 8L trough, (**D**) 11L trough, (**E**) California trough, (**F**) strawberry growbag (BVB), (**G**) precision plus ultra-growbag (Botanicoir), (**H**) GT master (Grodan), (**I**) finesse growbag (Jiffy), and (**J**) growbag advanced (Klasmann-Deilmann).

Figure 4.4. Images of open top growbags and pot container treatments used in the air and water capacity (AWC) models. Containers used included (**A**) 4.7L lightweight, (**B**) 7L square pot, (**C**) 10L square pot, (**D**) 20L square pot, (**E**) 15L square pot, (**F**) 1 gallon PCM open top, (**G**) Root Kandy, (**H**) 5 gallon PCM open top, (**I**) True Blue, and (**J**) 25L round pot.

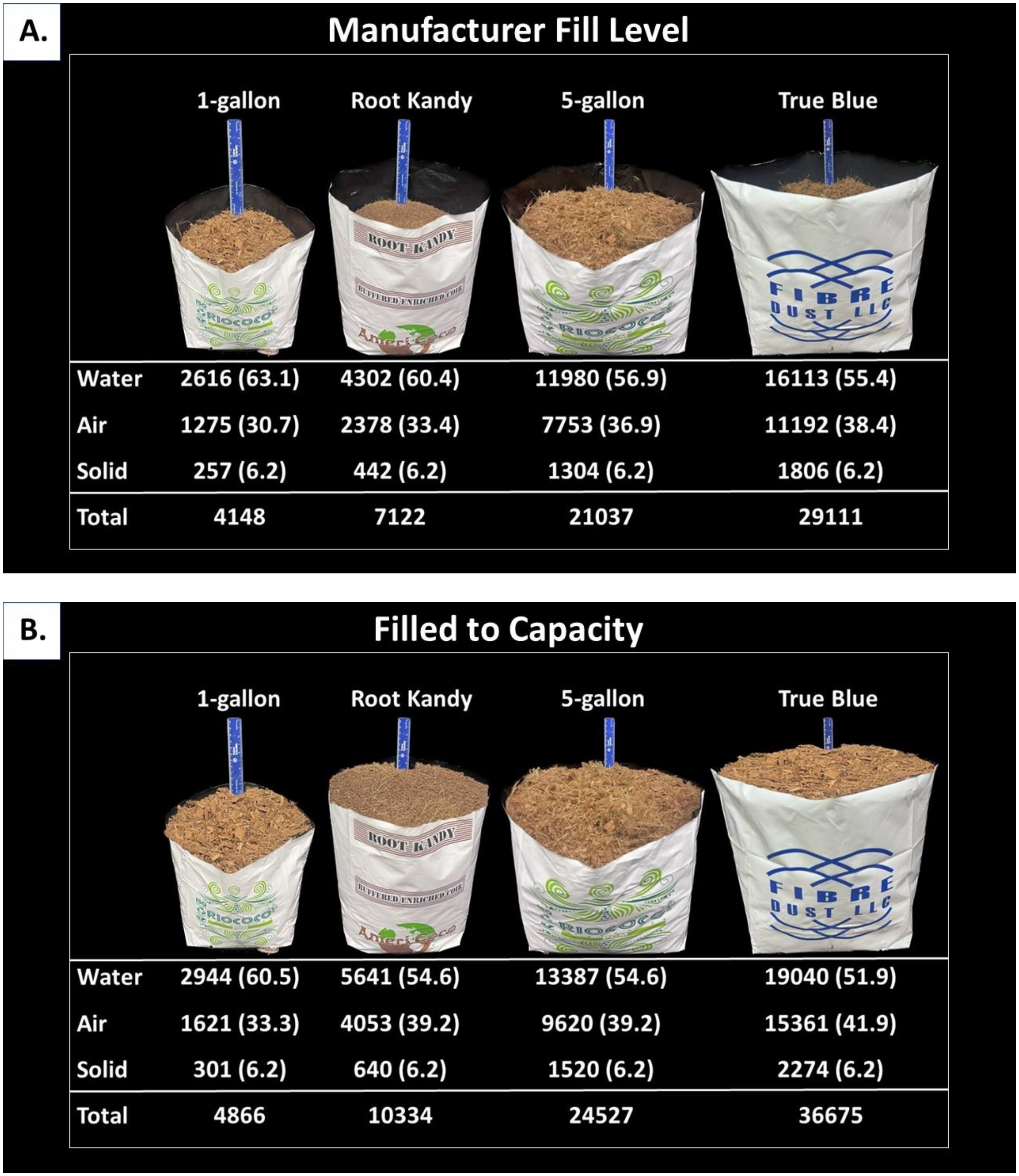
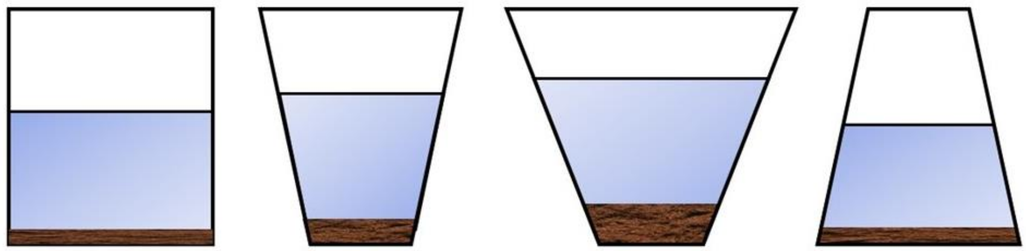


Figure 4.5. Four open top growbags modeled using the air-water capacity (AWC) model. These containers were compared based on the manufacturer fill level, and filled to capacity. The first values are the amount of water, air, or solids in mL, and the value is () is the percentage. For example, 2944 is 2944 mL with 60.5% water.

Container Designs

100% Coconut Coir

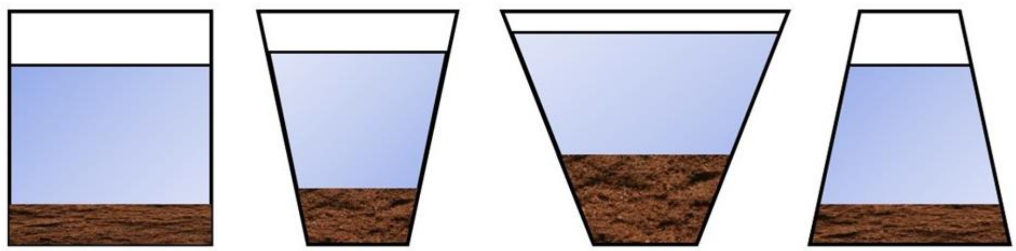


Air	**837 (30.3)**	**675 (32.7)**	**969 (34.2)**	**577 (27.9)**
Water	**1752 (63.5)**	**1263 (61.1)**	**1684 (59.6)**	**1361 (65.9)**
Solid	**169 (6.2)**	**128 (6.2)**	**175 (6.2)**	**128 (6.2)**
Total	**2758**	**2066**	**2828**	**2066**

Figure 4.6. Four artificial container geometries modeled using the air-water capacity (AWC) model with 100% coconut coir. The first values are the amount of water, air, or solids in mL, and the value is () is the percentage. For example, 837 is 837 mL with 30.3% air. The brown colored fill represents solids, blue represents water, and white represents air.

Container Designs

60% Peat + 40% Perlite



Air	465 (16.9)	378 (18.3)	546 (19.3)	318 (15.4)
Water	1742 (63.1)	1275 (61.7)	1717 (60.7)	1335 (64.6)
Solid	551 (20.0)	413 (20.0)	565 (20.0)	413 (20.0)
Total	2758	2066	2828	2066

Figure 4.7. Four artificial container geometries modeled using the air-water capacity (AWC) model with 60% peat: 40% perlite. The first values are the amount of water, air, or solids in mL, and the value is () is the percentage. For example, 465 is 465 mL with 16.9% air. The brown colored fill represents solids, blue represents water, and white represents air.

Table 4.1. Total porosity, air space, and container capacity measured on substrates utilized on the substrates in the AWC models. Physical properties were measured using the North Carolina State University Porometer Method (Fonteno et al., 1995).

Substrate[z]	Total porosity (% by volume)	Container capacity (% by volume)	Air space (% by volume)
Euro Peat	85.7	61.8	23.9
Can Peat	83.6	77.2	6.4
Coir	93.8	74.4	19.4
Rockwool	96.1	59.0	37.1
Perlite	76.7	56.1	20.6
Jiffy	93.2	82.3	10.9
Ball	89.2	78.9	10.3
APB	83.4	57.0	26.4
GF	89.8	64.3	25.5
FG	83.5	56.6	26.9
PTS	84.6	67.5	17.1
20% Per	80.7	72.6	8.1
40% Per	80.0	70.0	10.0
20% GF	81.7	59.1	22.6
40% GF	83.2	68.8	14.4
20% FG	79.2	68.4	10.8
40% FG	82.2	69.9	12.3
20% PTS	86.0	67.1	18.9
40% PTS	87.0	65.6	21.4

[z]Euro peat = European peat, Can peat = Canadian peat, Jiffy = Jiffy propagation mix (Jiffy Group International), Ball = Ball propagation mix (Ball Horticultural), APB = aged pine bark, GF = GreenFibre, FG = ForestGold, PTS = processed tree fiber, and Per = perlite. Percentages display the amount of material blended with peat moss.

Table 4.2. Cubes, plugs, and liners. Product name, manufacturer, container shape, and dimensions of containers utilized for the equilibrium capacity variable model.

Product name[z]	Manufacturer	Round or Square	Container Height (cm)	Top Length (cm)	Top Width (cm)	Bottom Length (cm)	Bottom Width (cm)	Top Radius (cm)	Bottom Radius (cm)
Mini Blocks	Grodan, Roermond, the Netherlands	Square	3.5	4.5	5.0	4.5	5.0	-	-
Grow Blocks	RedRock, Los Angeles, CA	Square	9.5	10.0	10.0	10.0	10.0	-	-
128 square	Blackmore Company, Belleville, MI	Square	TBD	TBD	TBD	TBD	TBD	-	-
72 square	Greenhouse Megastore, Danville, IL	Square	5.4	4.0	4.0	2.25	2.25	-	-
BP Plant Cell	The HC Companies, Twinsburg, OH	TBD	TBD	TBD	TBD	TBD	TBD	-	-
Boost18™	Fall Creek Nursery, Lowell, Oregon	Round	11.5	-	-	-	-	3.75	2.9
2 3/8” x 3 ¾”	Anderson Die & Mfg Co., Portland, Oregon	Square	9.5	6.0	6.0	5.5	5.5	-	-
2 7/8” x 5 ½”	Anderson Die & Mfg Co., Portland, Oregon	Square	13.9	7.0	7.0	6.5	6.5	-	-
3 5/8” x 6”	Anderson Die & Mfg Co., Portland, Oregon	Square	15.2	9.0	9.0	8.3	8.3	-	-
2 7/8” x 9”	Anderson Die & Mfg Co., Portland, Oregon	Square	22.8	7.0	7.0	6.0	6.0	-	-

[Z]As indicated in manufacturers on-line or printed catalogs.

Table 4.3. Lay flat growbags and troughs. Product name, manufacturer, container shape, and dimensions of containers utilized for the equilibrium capacity variable model.

Product name[z]	Manufacturer	Round or Square	Container Height (cm)	Top Length (cm)	Top Width (cm)	Bottom Length (cm)	Bottom Width (cm)	Top Radius (cm)	Bottom Radius (cm)
GT Master	Grodan, Roermond, the Netherlands	Square	7.3	102.9	19.2	102.9	19.2	-	-
Strawberry Growbag	Kekkilä-BVB, De Lier, the Netherlands	Square	6.7	49.5	24.0	49.5	24.0	-	-
Finesse Growbag	Jiffy Group Internation, Zwijndrecht, the Netherlands	Square	8.9	102.9	14.3	102.9	14.3	-	-
Growbag Advanced	Klasmann-Deilmann, Geeste, Germany	Square	14.8	105.4	14.2	105.4	14.2	-	-
Precision Plus Ultra Growbag	Botanicoir Ltd, London, United Kingdom	Square	10.8	104.8	14.5	104.8	14.5	-	-
9 L Trough	Plantlogic ltd, Zapopan, Mexico	Square	14.1	48.6	15.6	44.5	12.9	-	-
8 L Trough	Plantlogic ltd, Zapopan, Mexico	Square	11.1	47.6	18.3	44.5	14.1	-	-
11 L Trough	Beekenkamp Verpakkingen BV, Maasdijk, The Netherlands	Square	11.8	46.4	23.5	44.5	21.6	-	-
California Trough	Beekenkamp Verpakkingen BV, Maasdijk, The Netherlands	Square	12.3	96.8	17.8	94.5	14.6	-	-
1.85 L Raspberry Pot	Beekenkamp Verpakkingen BV, Maasdijk, The Netherlands	Square	10.0	20.3	10.5	17.0	8.5	-	-

[Z]As indicated in manufacturers on-line or printed catalogs.

Table 4.4. Open top growbags and pots. Product name, manufacturer, container shape, and dimensions of containers utilized for the equilibrium capacity variable model.

Product name[z]	Manufacturer	Round or Square	Container Height (cm)	Top Length (cm)	Top Width (cm)	Bottom Length (cm)	Bottom Width (cm)	Top Radius (cm)	Bottom Radius (cm)
True Blue	Fibredust LLC, Cromwell, CT	Round	32.1	-	-	-	-	19.1	19.1
1 Gallon PCM Open Top Bag	Riococo Worlwide, Irving, TX	Round	18.3	-	-	-	-	9.2	9.2
Root Kandy	Ameri-coco, Irving, TX	Round	26.7	-	-	-	-	11.1	11.1
5 Gallon PCM Open Top Bag	Riococo Worlwide, Irving, TX	Round	26.7	-	-	-	-	17.2	17.2
25 Liter Round Pot (Wide Leg)	Plantlogic ltd, Zapopan, Mexico	Round	33.3	-	-	-	-	17.8	13.4
7 Liter Square Pot	Plantlogic ltd, Zapopan, Mexico	Square	25.6	19.5	19.5	14.6	14.6	-	-
4.7 Litre lightweight Pot	Beekenkamp Verpakkingen BV, Maasdijk, The Netherlands	Square	15.9	19.1	19.1	15.3	15.3	-	-
10 Liter Square Pot	Plantlogic ltd, Zapopan, Mexico	Square	21.6	25.2	25.2	18.9	18.9	-	-
15 Liter Square Pot	Plantlogic ltd, Zapopan, Mexico	Square	28.7	26.7	26.7	21.0	21.0	-	-
20 Liter Square Pot	Plantlogic ltd, Zapopan, Mexico	Square	28.6	30.5	30.5	23.5	23.5	-	-

[Z]As indicated in manufacturers on-line or printed catalogs.

Table 4.5. Mathematically derived physical properties of European peat, Canadian peat, coconut coir, rockwool slab, perlite, Jiffy seedling mix, and Ball seedling mix, modeled with commercially available propagation cubes, plugs, and liners, derived from modeling equilibrium capacity variable values.

Substrate[z]	Container Size (Propagation Cubes, Plugs, and Liners)										
	7.6-cm Core	3.5 cm Cube	128 Cell Flat	48 Cell Flat	72 Cell Flat	10 cm Cube	9.5 cm Liner	18 Cell Flat	13.9 cm Liner	15.2 cm Liner	22.8 cm Liner
	Container capacity (% vol)										
Euro Peat	61.8	70.6	64.3	64.3	63.5	59.2	58.7	55.5	54.4	53.4	48.6
Can Peat	77.2	80.7	78.6	78.5	78.2	75.9	75.7	73.9	73.1	72.4	68.8
Coir	74.4	84.3	77.8	77.8	76.8	71.0	70.4	66.2	64.4	62.9	55.8
Rockwool	59.0	80.4	66.7	66.5	64.5	52.0	50.8	42.2	39.2	36.5	25.2
Perlite	56.1	63.9	58.3	58.3	57.6	53.9	53.4	50.6	49.7	48.8	44.8
Jiffy	82.3	88.6	84.7	84.7	84.1	79.9	79.5	76.4	74.9	73.8	67.8
Ball	78.9	85.5	81.7	81.6	81	76.2	75.8	72.3	70.7	69.4	62.8
	Air space (% vol)										
Euro Peat	23.9	15.1	21.4	21.4	22.2	26.5	27	30.2	31.3	32.4	37.1
Can Peat	6.4	2.9	5.0	5.1	5.4	7.7	7.9	9.7	10.5	11.3	14.8
Coir	19.4	9.6	16	16	16.9	22.8	23.4	27.6	29.4	30.9	38.0
Rockwool	37.1	15.7	29.4	29.6	42.2	44.1	45.4	53.9	56.9	59.6	70.9
Perlite	20.6	12.8	18.4	18.4	19.1	22.8	23.3	26.1	27.0	27.9	31.9
Jiffy	10.9	4.7	8.5	8.5	9.1	13.3	13.7	16.8	18.3	19.5	25.5
Ball	10.3	3.7	7.5	7.6	8.2	12.9	13.4	16.8	18.5	19.9	26.4

[z]Euro peat = European peat, Can peat = Canadian peat, Jiffy = Jiffy propagation mix (Jiffy Group International), and Ball = Ball propagation mix (Ball Horticultural).

Table 4.6. Mathematically derived physical properties of 100% European (Euro) peat, Canadian Peat (Can), coconut coir (Coir), rock wool slab material, Aged Pine Bark (APB), GreenFibre (GF), and ForestGold (FG) modeled with commercially available lay flat growbags and troughs, derived from modeling equilibrium capacity variable values.

	Container Size (Lay Flat Growbags and Troughs)									
Substrate[z]	Strawberry Growbag (BVB)	GT Master (Grodan)	Finesse Growbag (Jiffy)	Precision Plus (Botanicoir)	1.85 L Raspberry Pot	8 L Trough	11 L Trough	California Substrate Trough	Growbag Advanced (Klasmann)	9 L Trough
					Container capacity (% vol)					
Euro Peat	63.3	62.3	60.0	57.7	57.6	56.5	56.3	55.6	54.1	53.9
Can Peat	77.9	77.5	76.3	75.1	75.1	74.4	74.3	73.9	72.8	72.8
Coir	76.3	75.0	72.0	69.0	69.0	67.4	67.2	66.2	63.9	63.7
Rockwool	63.1	60.4	54.1	48.0	47.8	44.7	44.3	42.4	38.5	37.9
APB	59.4	57.8	54.3	51.2	50.8	49.3	49.3	48.3	46.7	46.2
GF	65.7	64.7	62.5	60.3	60.2	59.1	58.9	58.2	56.7	56.5
FG	59.2	57.4	53.4	49.6	49.4	47.5	47.3	46.0	43.6	43.2
PTS	68.6	67.8	66.1	64.4	64.3	63.4	63.3	62.8	61.6	61.4
					Air space (% vol)					
Euro Peat	22.4	23.4	25.7	28.0	28.1	29.2	29.4	30.1	31.6	31.8
Can Peat	5.7	6.1	7.3	8.5	8.5	9.2	9.3	9.7	10.8	10.8
Coir	17.5	18.8	21.8	24.8	24.8	26.4	26.6	27.6	29.9	30.1
Rockwool	33.1	35.7	42.0	48.2	48.3	51.4	51.8	53.7	57.7	58.3
APB	24.0	25.6	29.1	32.2	32.6	32.1	34.1	35.1	36.7	37.2
GF	24.1	25.1	27.3	29.5	29.6	30.7	30.9	31.6	33.1	33.3
FG	24.3	26.1	30.1	33.9	34.1	36.0	36.2	37.5	39.9	40.3
PTS	16.0	16.8	18.5	20.2	20.3	21.2	21.3	21.8	23.0	23.2

[z]Euro peat = European peat, Can peat = Canadian peat, Coir = coconut coir, APB = aged pine bark, GF = GreenFibre, FG = ForestGold, and PTS = processed tree fiber.

Table 4.7. Mathematically derived physical properties of Canadian Peat amended with 20 and 40 percent perlite, GreenFibre (GF), ForestGold (FG), and hammer milled Processed tree substrate (PTS) modeled with commercially available lay flat growbags and troughs, derived from modeling equilibrium capacity variable values.

	Container Size (Lay Flat Growbags and Troughs)									
Amendment[z]	Strawberry growbag (BVB)	GT master (Grodan)	Finesse Growbag (Jiffy)	Precision Plus (Botanicoir)	1.85 L Raspberry Pot	8 L Trough	11 L Trough	California Substrate Trough	Growbag Advanced (Klasmann)	9 L Trough
	Container capacity (% vol)									
20% Per	73.7	73.0	71.2	69.3	69.4	68.3	68.1	67.4	65.8	65.7
40% Per	71.1	70.4	68.6	66.7	66.8	65.8	65.6	65.0	63.4	63.3
20% GF	59.6	59.2	58.1	57.1	57.0	56.5	56.5	56.1	55.5	55.4
40% GF	69.9	69.1	67.3	65.5	65.5	64.5	64.4	63.8	62.4	62.3
20% FG	69.7	68.9	66.7	64.3	64.4	63.1	62.8	62.0	60.1	60.0
40% FG	71.4	70.4	67.9	65.2	65.4	63.9	63.6	62.7	60.5	60.3
20% PTS	68.4	67.5	65.4	63.3	63.2	62.1	62.0	61.2	59.7	59.5
40% PTS	67.3	66.2	63.6	61.0	60.9	59.6	59.4	58.6	56.8	56.5
	Air space (% vol)									
20% Per	7.0	7.7	9.5	11.4	11.3	12.4	12.6	13.3	14.9	15.0
40% Per	8.9	9.6	11.4	13.3	13.2	14.2	14.4	15.0	16.6	16.7
20% GF	22.1	22.5	23.6	24.6	24.7	25.2	25.2	25.6	26.2	26.3
40% GF	13.3	14.1	15.9	17.7	17.7	18.7	18.8	19.4	20.8	20.9
20% FG	9.5	10.3	12.5	14.9	14.8	16.1	16.4	17.2	19.1	19.2
40% FG	10.8	11.8	14.3	17.0	16.8	18.3	18.6	19.5	21.7	21.9
20% PTS	17.6	18.5	20.6	22.7	22.8	23.9	24.0	24.8	26.3	26.5
40% PTS	19.7	20.8	23.4	26.0	26.1	27.4	27.6	28.4	30.2	30.5

[z]GF = GreenFibre, FG = ForestGold, PTS = processed tree fiber, and Per = perlite. Percentages display the amount of material blended with peat moss.

Table 4.8. Mathematically derived physical properties of 100% European (Euro) peat, Canadian Peat (Can), coconut coir (Coir), aged pine bark (APB), GreenFibre (GF), ForestGold (FG), and hammer milled Processed tree substrate (PTS), modeled with commercially available open top growbags and pots, derived from modeling equilibrium capacity variable values.

	Container Size (Open Top Growbags and Pots)									
Substrate[z]	4.7 L Square Pot	1 Gal Open Top	10 L Square Pot	Root Kandy Open Top	5 Gal Open Top	7 L Square Pot	True Blue Open Top	15 L Square Pot	20 L Square Pot	25 L Round Pot
					Container capacity (% vol)					
Euro Peat	52.1	51.8	48.5	47.8	47.8	46.7	46.0	45.9	45.8	44.3
Can Peat	71.6	71.1	68.8	68.0	68.0	67.2	66.3	66.3	66.3	64.8
Coir	61.1	60.5	55.7	54.6	54.6	53.0	51.9	51.7	51.6	49.3
APB	44.1	44.1	40.5	40.4	40.4	39.0	39.0	38.4	38.4	37.2
GF	54.8	54.4	51.1	50.4	50.4	49.3	48.6	48.4	48.4	46.8
FG	40.2	39.8	34.6	33.8	33.8	32.0	31.3	30.8	30.8	28.6
PTS	60.1	59.8	57.2	56.7	56.7	55.8	55.3	55.1	55.1	53.9
					Air space (% vol)					
Euro Peat	33.6	34.0	37.2	38.0	38.0	39.0	39.7	39.8	39.9	41.4
Can Peat	12.0	12.5	14.8	15.7	15.7	16.4	17.3	17.3	17.3	18.8
Coir	32.7	33.3	38.1	39.2	39.2	40.8	41.9	42.1	42.2	44.5
APB	39.3	39.3	42.9	43.0	43.0	44.4	44.4	45.0	45.0	46.2
GF	35.0	35.4	38.7	39.4	39.4	40.5	41.2	41.4	41.4	43.0
FG	43.3	43.7	48.9	49.7	49.7	51.5	52.2	52.7	52.7	54.9
PTS	24.5	24.8	27.4	28.0	28.0	28.8	29.4	29.5	29.5	30.7

[z]Euro peat = European peat, Can peat = Canadian peat, APB = aged pine bark, GF = GreenFibre, FG = ForestGold, and PTS = processed tree fiber.

Table 4.9. Mathematically derived physical properties of Canadian Peat amended with 20 and 40 percent perlite, GreenFibre (GF). ForestGold (FG), and hammer milled Processed tree substrate (PTS) modeled with commercially available open top growbags and pots, derived from modeling equilibrium capacity variable values.

Amendment[z]	Container Size (Open Top Growbags and Pots)									
	4.7 L Square Pot	1 Gal Open Top	10 L Square Pot	Root Kandy Open Top	5 Gal Open Top	7 L Square Pot	True Blue Open Top	15 L Square Pot	20 L Square Pot	25 L Round Pot
	Container capacity (% vol)									
20% Per	63.8	63.1	59.5	58.2	58.2	57.1	55.8	55.8	55.8	53.5
40% Per	61.6	61.1	57.7	56.7	56.7	55.6	54.5	54.5	54.5	52.5
20% GF	54.6	54.5	53.0	52.6	52.6	52.2	51.8	51.8	51.8	51.0
40% GF	60.7	60.3	57.3	56.4	56.4	55.5	54.6	54.5	54.5	52.8
20% FG	57.8	57.0	52.7	51.4	51.4	50.0	48.6	48.6	48.6	46.1
40% FG	57.9	57.0	52.2	50.7	50.7	49.2	47.7	47.6	47.6	44.8
20% PTS	57.8	57.3	54.0	53.1	53.1	52.1	51.2	51.1	51.1	49.3
40% PTS	54.4	54.0	50.0	49.1	49.1	47.8	46.9	46.7	46.7	44.8
	Air space (% vol)									
20% Per	16.9	17.6	21.2	22.5	22.5	23.6	24.9	24.9	24.9	27.2
40% Per	18.4	18.9	22.3	23.3	23.3	24.4	25.5	25.5	25.5	27.5
20% GF	27.1	27.3	28.7	29.1	29.1	29.5	29.9	29.9	29.9	30.7
40% GF	22.5	22.9	25.9	26.8	26.8	27.7	28.6	28.7	28.7	30.4
20% FG	21.4	22.2	26.5	27.9	27.9	29.2	30.6	30.6	30.6	33.1
40% FG	24.3	25.2	30.0	31.5	31.5	33.0	34.5	34.6	34.6	37.4
20% PTS	28.2	28.7	32.0	32.9	32.9	33.9	34.8	34.9	34.9	36.7
40% PTS	32.6	33.1	37.0	37.9	37.9	39.2	40.1	40.3	40.3	42.2

[z]GF = GreenFibre, FG = ForestGold, PTS = processed tree fiber, and Per = perlite. Percentages display the amount of material blended with peat moss.

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