

Cannabis in urban food systems: advancing clonal propagation as a foundation for sustainable
food, fiber, and material innovation

by

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Abstract

Hemp (*Cannabis sativa* L.) is increasingly recognized as a multifunctional crop at the intersection of urban food systems, sustainable material innovation, and circular economic development. This thesis situates hemp within urban food systems, emphasizing its capacity to contribute to food production, industrial applications, and environmental sustainability. Hemp-derived products such as seeds, oils, and protein powders offer nutrient-dense, plant-based alternatives aligned with evolving dietary preferences. Fiber and hurd fractions support applications in textiles, biocomposites, and construction materials. These diverse outputs enable hemp to support all three pillars of sustainability by promoting local economic development, supporting community-based enterprises, and delivering environmental benefits such as carbon sequestration, phytoremediation, and reduced agrochemical inputs.

Despite its versatility, hemp production systems remain largely agronomic and seed-based, prioritizing scalability over uniformity. In contrast, clonal propagation is standard in high-THC *Cannabis* systems to ensure genetic consistency and predictable crop performance. This separation highlights a key limitation in current hemp production: genetic variability can constrain product standardization and market reliability. As urban and controlled-environment agriculture systems demand greater uniformity and efficiency, propagation practices are a key area of innovation. As such, advancing clonal methods adapted to hemp is necessary to enable consistent, high-quality plant material that supports hemp's integration into urban agriculture and value-added supply chains.

This research gap was addressed by experimentally evaluating the effects of fertilization and propagation environment on the quality of rooted hemp cuttings. Across three experiments with multiple cultivars, propagation systems, substrates, and fertilizer regimes, results showed that propagation environment had a greater influence on cutting quality than fertilization. Intermittent mist improved root development, while subirrigation enhanced foliage quality by reducing chlorosis. Fertilization, whether slow-release or soluble, did not significantly improve rooting success under the conditions tested. This research contributes to developing optimized propagation protocols and supports the broader thesis that refining plant production techniques is critical to unlocking hemp's full potential in sustainable, urban, and controlled-environment agricultural systems.

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This work is dedicated to all of you.

Chapter 1: Cannabis in Urban Food Systems

Introduction

Urban food systems have proved to be a crucial focal point in developing modern, sustainable agriculture, indicating recognition that food production and distribution are not purely rural concerns but also urban issues (De Zeeuw & Drechsel, 2015; Zou et al., 2023). An urban food system encompasses the interconnected activities involved in producing, processing, distributing, and consuming food within cities and their surrounding regions. These systems shape—and are shaped by—urban social, economic, and ecological forces, influencing food security, public health, environmental sustainability, and economic development. While cities continue to expand and global food supply chains become increasingly centralized and vulnerable, scholars and policymakers have noted the need to re-localize food production, shorten supply chains, and deliberately consider food systems within urban planning.

Short supply chains, or decreasing physical and social distance between producers and consumers, are an important feature of resilient urban food systems (De Zeeuw & Drechsel, 2015). Localized food networks can lower transportation emissions, decrease food loss and spoilage, and improve transparency within food markets. Historically, cities were closely tied to nearby agricultural production, but industrialization and global trade weakened these connections, creating dependency on long, complex supply chains that are highly susceptible to shocks such as climate change, financial volatility, and public health crises (Bricas & Conaré, 2019). Reintegrating food production into urban and peri-urban realms may mitigate these risks while advancing circular resource flows, such as nutrient recycling and waste reclamation, that align with broader sustainability goals.

From a sustainability perspective, urban food systems function as a link between environmental, social, and economic goals (Van Berkum et al., 2018). The food systems approach emphasizes systems thinking, recognizing feedback loops between production, consumption, environmental outcomes, and socioeconomic conditions. This moves beyond a focus on agricultural output and considers nutrition, equity, resource efficiency, and resilience. Urban food systems offer opportunities to apply this approach with more feasible policy intervention, innovation, and stakeholder cooperation. By integrating food production with urban infrastructure, cities can reduce environmental footprints while improving food access and livelihoods.

Food security is a central concern in urban food systems. Rapid urbanization has concentrated food demand in cities. Disruptions such as pandemics, extreme weather events, and geopolitical instability have exposed vulnerabilities in global supply chains, disproportionately harming low-income urban populations (Munialo & Mellor, 2024; Tolazzi et al., 2025). Urban agriculture and localized food initiatives can enhance food security by diversifying supply sources, stabilizing prices, and improving access to fresh, culturally appropriate foods. Additionally, urban

food systems can contribute to economic development by supporting small and medium enterprises, creating jobs, and retaining food-related value within local economies.

Within this developing discourse, *Cannabis sativa* L. has received attention as a multipurpose crop with significant relevance to food systems, sustainability, and urban development. This crop has been cultivated for thousands of years for its fiber, seed, medicinal, and cultural uses (Small, 2017). Its versatility has established it as an agricultural species capable of delivering diverse functions across food, industrial, and social sectors. Despite long periods of prohibition and stigma, recent policy developments have prompted a global resurgence of interest in *Cannabis* research and production, particularly in its non-psychoactive forms.

Hemp—defined as low-tetrahydrocannabinol (THC), non-intoxicating *Cannabis sativa*—finds its place at a crucial intersection between agriculture, food innovation, and sustainable urban development (Small, 2017). In the United States, industrial total production value reached approximately \$445 million in 2024, representing a 40% increase from the previous year (U.S. Department of Agriculture, National Agricultural Statistics Service, 2025). Production spans multiple market segments, including floral, fiber, and grain, with over 45,000 acres planted nationwide, highlighting the crop's growing economic and agronomic significance. Hemp seeds are nutritionally rich, providing high-quality protein, essential fatty acids, and bioactive compounds suitable for human consumption (Small, 2017). Beyond food uses, hemp fiber and biomass provide a wide array of industrial applications, including textiles, biocomposites, building materials, and biodegradable products. These attributes have positioned hemp as a candidate crop for enabling multiple value streams from a single species.

Cannabidiol (CBD), a major non-psychoactive cannabinoid produced by *Cannabis sativa*, has become one of the most economically significant and socially influential hemp-derived compounds in recent years. Unlike tetrahydrocannabinol (THC), CBD does not produce intoxicating effects and has been widely studied for its potential therapeutic properties, including anticonvulsant, anxiolytic, anti-inflammatory, and antipsychotic effects (Chesney et al., 2022; Mechoulam et al., 2002). As a result, CBD has driven substantial market growth in the hemp industry, with products ranging from dietary supplements and functional foods to cosmetics and pharmaceuticals. After the 2018 U.S. Farm Bill, hemp-derived cannabinoids—including CBD—were federally legalized as agricultural commodities, greatly expanding opportunities for production and commercialization (Dabrowska, 2019; Johnson, 2018). However, despite rapid market growth, regulatory uncertainty remains, especially regarding CBD's inclusion in food and dietary supplements under FDA oversight (Johnson, 2023). In urban food systems, CBD offers both an opportunity for value-added product development and a challenge that requires careful navigation of regulatory, scientific, and consumer perception issues.

The modern cannabis industry is divided into two primary sectors: industrial hemp and marijuana. In the United States, marijuana accounts for about 87% of total cannabis revenue, while hemp production remains smaller and more specialized in fiber, grain, and cannabinoid extraction (Grand View Research, 2024; USDA-NASS, 2025). Hemp production is mostly field-based, with

most acreage grown outdoors for fiber and floral biomass. Marijuana production is largely conducted indoors or in greenhouses to maximize cannabinoid consistency and product quality. These differences also apply to propagation strategies. Hemp is traditionally seed-propagated, especially for agronomic uses, while marijuana relies heavily on clonal propagation to ensure genetic uniformity and consistent cannabinoid profiles. The growing demand for CBD has begun to blur these distinctions, as some hemp producers adopt clonal and controlled environment practices to improve crop uniformity and regulatory compliance.

Peri-urban agriculture, defined as agricultural production at the interface between urban and rural areas, plays a critical role in supporting the economic vitality of nearby urban areas. It functions as both a production system and a socio-economic link between rural and urban economies (Brinkley, 2012; Rogus & Dimitri, 2015). Peri-urban hemp systems contribute to local economic development through job creation, income generation, and stimulating small and medium-sized enterprises involved in cultivation, processing, and distribution (Rao et al., 2022). The labor-intensive nature of high-value hemp production, especially for floral biomass and CBD extraction, creates employment opportunities across production and post-harvest handling. It also supports secondary industries such as extraction, packaging, and retail (International Labour Organization, 2017). Proximity to urban markets enhances economic efficiency by reducing transportation costs and enabling direct-to-consumer and short supply chain models. These are especially relevant for perishable or regulated hemp-derived products (Rogus & Dimitri, 2015). Additionally, the peri-urban landscape suits hemp production due to the crop's traditionally agronomic, field-based nature. This allows producers to maintain scalable outdoor systems while benefiting from close access to urban markets and infrastructure.

From a sustainability standpoint, hemp offers several agronomic and environmental merits. It is distinguished by its rapid growth, high biomass production, and adaptability traits to diverse climatic conditions (Rivža et al., 2012; Small, 2017). Hemp cultivation has been associated with reduced pesticide requirements, improved soil structure, and applications in phytoremediation, making it especially relevant for urban and peri-urban environments where soil degradation and contamination are common constraints.

The introduction of hemp into urban and regional food systems also carries socioeconomic and cultural significance. As regulatory systems evolve, hemp creates opportunities for small-scale farmers, urban growers, and food entrepreneurs to participate in emerging markets. It has historical and cultural relevance as a crop that links traditional agricultural knowledge alongside modern innovation. When embedded within urban food systems, hemp can contribute not only to food security and sustainability but also to community development, education, and place-based economic resilience.

Taken together, the literature suggests that urban food systems offer a persuasive framework for reimagining food production and distribution in cities, while hemp is a uniquely adaptable crop that can simultaneously address multiple sustainability objectives (De Zeeuw & Drechsel, 2015; Small, 2017). By placing *Cannabis sativa*—and hemp in particular—within the

wider context of urban food systems, this review explores how this multipurpose crop can support resilient, localized, and sustainable food futures.

Historically, hemp production has relied on agronomic, field-based systems where crops are established from seed and managed at large scales for fiber, grain, or biomass. In these systems, an attempt at uniformity is achieved through breeding and seed selection rather than vegetative propagation. As a result, clonal propagation has not been widely used in industrial hemp production because of logistical challenges, labor demands, and the economic costs of producing and maintaining a large number of plants. In contrast, high-tetrahydrocannabinol (THC) *Cannabis* production, especially within controlled environment agriculture (CEA), has made clonal propagation standard to ensure genetic consistency, uniform cannabinoid profiles, and predictable crop performance. This difference in propagation strategies highlights a key distinction within *Cannabis* production systems and is important when considering the integration of hemp into technologically intensive and urban-oriented agricultural models.

The literature review in this chapter was developed through a structured search and synthesis of peer-reviewed and authoritative sources on *Cannabis* and urban food systems. Primary literature was identified using academic databases, with search terms such as “hemp production,” “Cannabis urban agriculture,” “urban food systems,” and “clonal propagation.” The focus was on peer-reviewed journal articles, foundational texts, and recent publications to provide both historical context and current relevance. Alongside academic literature, industry reports and statistical data from the United States Department of Agriculture (USDA), especially the National Agricultural Statistics Service (NASS), were included to contextualize production trends and economic significance. Sources were selected for their relevance to key themes of sustainability, multifunctionality, and integration into urban and peri-urban systems. They were synthesized to develop a comprehensive understanding of hemp’s role within evolving food system frameworks.

Cannabis and Food Systems

Nutritional Products Derived from Hemp

Hemp has gained attention in food systems research for its exceptional nutritional value and potential as a food ingredient (House et al., 2010; Small, 2017). Hemp seeds and their derived products—including oils and protein powders—offer a combination of macronutrients, essential fatty acids, and micronutrients that fit with dietary trends emphasizing plant-based nutrition, functional foods, and sustainable protein sources. As urban food systems seek nutrient-dense ingredients to support dietary diversification, hemp-derived nutritional products act as a promising category in alternative and sustainable food markets.

Hemp Seed: Protein, Essential Fatty Acids, Vitamins, and Minerals

Whole hemp seed is a nutritionally dense food ingredient, supplying substantial quantities of high-quality protein, lipids, and micronutrients. On a dry-weight basis, hemp seeds typically contain approximately 24–25% protein and 30–35% lipid content, with the remaining fraction

composed of carbohydrates, fiber, and inorganic mineral residue (House et al., 2010). Unlike many plant-based protein sources, hemp seed protein contains all nine essential amino acids, qualifying it as a complete protein (El-Sohaimy et al., 2022). Although lysine is the first limiting amino acid, the overall amino acid profile compares favorably with that of cereal grains, nuts, and some legumes (House et al., 2010).

In addition to protein, hemp seeds are valued for their lipid content, which is mainly composed of polyunsaturated fatty acids (PUFAs). Hemp seed contains a nutritionally beneficial ratio of omega-6 (linoleic acid) to omega-3 (α -linolenic acid), typically close to 3:1, a ratio often cited as optimal for human health (Matran et al., 2010). This proportion is difficult to achieve in most conventional vegetable oils, which are commonly disproportionately high in omega-6 fatty acids (DiNicolantonio & O’Keefe, 2021). Hemp seed has been increasingly studied as a functional ingredient for improving dietary fatty acid profiles. Beyond fatty acids, hemp seeds also contain essential minerals, including magnesium, phosphorus, potassium, iron, and zinc, which are often deficient in highly processed diets (Ruszkowska et al., 2025).

Hemp Seed Oil: Culinary Uses, Health Foods, and Supplements

Hemp seed oil, typically produced through cold-press extraction, is one of the most commercially significant hemp-derived food products. Nutritionally, hemp seed oil retains the fatty acid profile of the seed, including high concentrations of linoleic acid, α -linolenic acid, and smaller amounts of γ -linolenic acid (GLA), a fatty acid associated with anti-inflammatory and cardioprotective effects (Matran et al., 2010). This unique lipid composition has brought interest to hemp seed oil as both a culinary oil and a dietary supplement.

In food preparation, hemp seed oil is most commonly used as a finishing oil rather than a cooking oil, due to its low smoke point and susceptibility to hydrolysis, oxidation, and polymerization under high heat (Liang et al., 2025). It is frequently incorporated into salad dressings, spreads, smoothies, and cold-prepared foods, where it adds a mild, nutty flavor and provides nutritional benefits. From a health food perspective, hemp seed oil is marketed for its role in supporting cardiovascular health, lipid metabolism, and inflammatory regulation, primarily owing to its balanced omega-6 to omega-3 ratio (Matran et al., 2010).

Hemp seed oil is also widely available in capsule form as a dietary supplement, appealing to consumers seeking plant-based sources of essential fatty acids. The demand for non-fish-derived omega-3 supplements—driven by sustainability concerns, dietary choices, and allergen avoidance—has elevated hemp oil’s importance in alternative nutrition markets. Although hemp oil does not contain long-chain omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), its α -linolenic acid content can contribute to endogenous synthesis pathways, making it a complementary option within plant-based diets (Hashemian & Nouri, 2023).

Hemp Protein Powders: Plant-Based Diets and Alternative Protein Markets

Hemp protein powder, typically produced from defatted hemp seed meal following oil extraction, has proved to be a key product within the plant-based protein sector. Hemp protein

powders generally contain 30%-50% protein, depending on the processing methods of refinement (House et al., 2010). In addition to protein, these powders maintain high levels of dietary fiber and minerals, adding to their functional value in food.

From a nutritional quality standpoint, hemp protein has moderate to high digestibility, with protein digestibility-corrected amino acid scores (PDCAAS) comparable to or exceeding those of some grains and nuts (House et al., 2010). While hemp protein does not reach the PDCAAS values of soy or animal-derived proteins, its balanced amino acid profile, high content of the semi-essential amino acid arginine, and absence of major allergens make it attractive for multiple consumer groups. These attributes are particularly relevant in urban food systems, where nutritional variety, allergen sensitivity, and plant-forward eating patterns are becoming increasingly widespread.

Recent food innovation research shows the functional potential of hemp protein powders in processed foods. Ruskowska et al. (2025) demonstrated that incorporating hemp protein into extruded snack products considerably increased protein and mineral content while retaining acceptable texture and storage stability. This illustrates the hemp protein's suitability for value-added food products, including snacks, bakery items, and fortified staples.

The expanded uses of hemp protein coincides with trends in alternative protein markets, including flexitarianism, veganism, and sustainability-driven consumer behavior. Compared with animal-based proteins, hemp protein production requires fewer inputs and generates lower environmental impacts, reinforcing its relevance as a sustainable ingredient within future-oriented food systems.

The Rise of CBD

Cannabidiol (CBD) has become a central driver of contemporary hemp markets, reflecting a shift toward high-value, bioactive compounds within agricultural systems. CBD is one of over 100 cannabinoids produced by *Cannabis sativa* and is distinguished by its non-intoxicating properties compared to THC, the primary psychoactive compound in cannabis (Johnson, 2023). Interest in CBD has expanded rapidly due to its proposed therapeutic applications, including treatment of epilepsy, anxiety, inflammation, and psychotic disorders, although scientific evidence remains variable across conditions (Dabrowska 2019; Chesney et al., 2022). Hemp-derived CBD is incorporated into a wide range of products, including oils, tinctures, edibles, beverages, cosmetics, and nutraceuticals. This makes it one of the fastest-growing segments of the hemp industry (Johnson, 2018)

Despite this growth, the regulatory landscape for CBD remains complex. Although the 2018 Farm Bill legalized hemp and its derivatives, the U.S. Food and Drug Administration (FDA) maintains authority over CBD-containing products, especially those marketed as foods or dietary supplements (Dabrowska, 2019; Johnson, 2023). Current federal guidance restricts adding CBD to food products in interstate commerce, creating uncertainty for producers and limiting CBD's

integration into formal food systems. Due to these restrictions, CBD represents a unique opportunity for agriculture, health, and entrepreneurship within more local food systems.

Cannabis Beyond Food: Urban Materials and Circular Systems

Hemp Fibers and Industrial Uses

Industrial hemp has a long history as a fiber crop and remains one of the most versatile plant-based sources of industrial raw materials. Hemp fibers are derived primarily from the bast (phloem) tissues of the stem, while the woody core (hurds or shiv) is often applied to industrial applications. Hemp fiber was once fundamental to the production of textiles, ropes, sails, and paper, and for centuries served as a common material in maritime economies (Small, 2017; Small & Marcus, 2002). Contemporary interest in hemp fibers has been renewed by advances in processing technologies and the growing desire for sustainable alternatives to petroleum-based materials.

In textile and cordage applications, hemp fibers are valued for their high tensile strength, durability, and resistance to microbial degradation. Compared with cotton, hemp requires fewer chemical inputs during cultivation and produces fibers with greater longevity, making it attractive for apparel, upholstery, and technical textiles (Small & Marcus, 2002). Beyond customary uses, hemp fibers have gained traction as components of bioplastics and composite materials. Hemp fiber composites can achieve mechanical properties similar to glass fiber composites while offering superior biodegradability along with lower environmental impacts (Shahzad, 2012). These characteristics have driven their adoption in automotive components, packaging, and consumer goods, where weight reduction and sustainability are prioritized.

The woody core of the hemp stem further expands its industrial utility, particularly in the construction sector. Hemp-lime composites, commonly referred to as hempcrete, combine hemp shiv with lime-based binders to form a lightweight, insulating building material. Hemp-lime is not load-bearing, but it provides excellent thermal performance, humidity regulation, and fire resistance, rendering it suitable for wall infill and insulation (Duffy et al., 2013). The hemp used in hempcrete sequesters carbon during crop growth and can offset emissions associated with construction materials, making it a low-carbon alternative in sustainable building design. Life-cycle assessments show that hemp-lime systems can contribute to net reductions in greenhouse gas emissions compared with conventional concrete-based materials (Duffy et al., 2013; Ip & Miller, 2012).

Sustainability Advantages of Hemp-Based Materials

The sustainability advantages of hemp fibers and hemp-derived industrial materials are central to their place in food systems and urban sustainability discussions. Hemp is a rapidly renewable annual crop with high biomass yields and broad climatic adaptability. Its cultivation has been associated with reduced pesticide use, efficient nutrient uptake, and compatibility with crop

rotations, which support soil health and agroecosystem resilience (Small, 2017). These agronomic characteristics separate hemp from many fiber crops that depend heavily on chemical inputs or long growing intervals.

From a materials perspective, hemp-based products deliver considerable environmental benefits due to their biodegradability and lower embodied energy, which refers to associated greenhouse gas emissions throughout a product's life cycle (Shahzad, 2012). Hemp fiber composites and bioplastics can lower reliance on fossil-fuel-derived polymers and reduce pressure on landfills, as many hemp-based materials can be composted or recycled at the end of their use (Shahzad, 2012). Similarly, hemp-lime construction materials have low embodied carbon and the capability for reuse or reintegration following demolition (Duffy et al., 2013).

Integration into Circular Urban Economies

Hemp's multifunctionality makes it a strategic crop for adoption into circular urban economies. Circular economy frameworks focus on waste reduction, material reuse, and the creation of closed-loop systems in which outputs from one process become inputs for another (Nobre & Tavares, 2021). More broadly, circular economy frameworks emphasize moving away from linear "take-make-dispose" systems toward regenerative systems that prioritize continual use and restoration of resources across value chains. This includes maintaining materials at their highest utility through closed-loop flows where waste is minimized or redefined as a resource input. Value is retained through reuse, remanufacturing, and recycling processes (Geisendorf & Pietrulla, 2018). Such frameworks operate across multiple scales, from firm-level production systems to broader urban economies, requiring coordinated design, logistics, and policy mechanisms to enable circularity effectively. Hemp fits this model because nearly all parts of the plant can be utilized. Fibers can be directed toward textiles and composites, hurds toward construction and insulation materials, and residual biomass toward animal bedding, bioenergy, or soil amendments (Small & Marcus, 2002). Hempcrete and fiberboard, for example, can be produced using regionally-grown hemp and relatively low-tech processing methods, supporting decentralized production models that fit urban and peri-urban settings (Duffy et al., 2013).

Within urban contexts, the use of hemp-based materials can reduce dependence on imported construction inputs and synthetic products while supporting localized manufacturing and green employment.

Hemp in Urban Agriculture Frameworks

Hemp holds considerable opportunity within urban agriculture frameworks, especially in community-based and multifunctional enterprise models. Urban agriculture is increasingly conceptualized not only as food production but as a platform for social innovation, education, and diversification (Tolazzi et al., 2025). Hemp's ability to generate multiple product streams—food, fiber, and value-added goods—makes it well-suited to such models (Johnson, 2018).

Community-scale urban farms integrating hemp cultivation to support multiple revenue streams could reduce economic risk associated with single-crop systems. For example, hemp seed

could be processed into food products or sold to local markets, while fibers and hurds could supply small-scale manufacturing of textiles, insulation, or biocomposite materials. This multifunctionality is consistent with emerging urban agriculture strategies that value resilience, inclusivity, and local value retention.

Moreover, hemp-based enterprises can serve educational and social functions within cities by reconnecting residents with material production processes and environmentally conscious design principles. By demonstrating closed-loop systems that integrate food, fiber, and construction materials, urban hemp projects can aid broader sustainability and societal engagement. As regulatory systems continue to evolve, hemp's utility and environmental performance suggest that it could play a meaningful role in shaping resilient, circular urban food systems that go beyond nutrition alone (Johnson, 2018; Small, 2017).

Social, Economic, and Environmental Impacts of Hemp in Urban Food Systems

Introducing industrial hemp into urban food and agricultural systems has positive impacts that go beyond agronomic productivity and material outputs. Hemp's multifunctionality could impact economic development, social relations, and environmental health, making it a strong case study for evaluating how alternative crops can contribute to resilient urban systems. Hemp has the potential to support local economies, address complex social perceptions, and yield measurable environmental benefits while conforming to the three pillars of sustainability—economic, social, and environmental.

Contribution to Local Economies: Job Creation, Entrepreneurship, and Local Processing

Hemp has been characterized as a high-value agricultural commodity capable of supporting diverse local and regional economies. Hemp enables multiple product streams—fiber, seed, oil, cannabinoids, and secondary industrial materials—creating opportunities for decentralized processing systems (Johnson, 2018). Such diversification increases employment potential across cultivation, processing, manufacturing, and distribution stages.

Local processing infrastructure is an important element of hemp's economic impact. Studies show that regions able to locally process hemp fiber, shiv, and seed capture significantly more value than those reliant on exporting raw materials (Small & Marcus, 2002). In urban and peri-urban contexts, small-scale decortication facilities, food-grade oil pressing, and materials fabrication can support entrepreneurship while lowering transportation costs and emissions. These localized enterprises align with broader urban economic development goals by promoting small- and medium-sized businesses, retaining capital within communities, and generating green jobs linked to sustainable production systems (Sharma & Subba, 2025).

Hemp-based industries can repurpose urban industrial spaces, such as warehouses and former manufacturing sites. This flexibility supports hemp's relevance to cities seeking to revitalize post-industrial areas through sustainable economic activity. As Johnson (2018) notes, the expansion of hemp markets following regulatory reform has already stimulated new agricultural and processing ventures, suggesting notable potential for job creation when regulatory and infrastructural barriers are addressed.

Social Acceptance and Stigma: Navigating Cannabis in Urban Spaces

Despite its industrial and nutritional applications, hemp remains socially entangled with the wider cultural and political history of *Cannabis*. This association has contributed to a persistent stigma and public misunderstanding, especially in urban environments where visibility and regulatory scrutiny are apparent. Small (2017) documents how hemp's conflation with psychoactive *Cannabis* has historically obstructed research, cultivation, and commercialization, even though industrial hemp contains negligible levels of tetrahydrocannabinol (THC).

In urban contexts, social acceptance shapes whether hemp projects are perceived as legitimate components of food systems or as controversial land uses. Community concerns commonly center on aesthetics, legality, and perceived associations with illicit drug production. However, research indicates that educational efforts, transparent governance, and visible value creation—such as food products, building materials, or environmental remediation—can considerably improve public perception (Johnson, 2018).

Importantly, hemp's incorporation into community-based enterprises and urban sustainability initiatives could reframe *Cannabis* from a stigmatized symbol to a means for social good. When hemp production is linked to food security, green jobs, and environmental restoration, it coincides more closely with accepted narratives of urban agriculture and ecological stewardship. This reframing is essential for steering regulatory environments as well as promoting activity in emerging hemp economies.

Environmental Benefits: Soil Remediation, Carbon Sequestration, and Reduced Input Needs

The environmental benefits of hemp cultivation are among the most extensively documented aspects of the crop. Hemp's rapid growth, high biomass production, and extensive root system add to its capacity for carbon sequestration and soil improvement (Jurga et al., 2025).

Beyond its carbon dynamics, hemp has shown significant potential for phytoremediation of contaminated urban and industrial soils. Empirical studies indicate that *Cannabis* can tolerate and accumulate heavy metals such as zinc, cadmium, and lead, primarily in root tissues, allowing aboveground biomass to be safely utilized for industrial applications (Ejaz et al., 2024; Jurga et al., 2025). This is particularly relevant in metropolitan areas, where soil contamination often limits the implementation of agricultural and green infrastructure projects (Yang & Zhang, 2015). Through

integrating hemp into remediation strategies, cities can convert degraded land into productive spaces while diminishing environmental risks.

Hemp cultivation is also associated with lower agrochemical inputs than many conventional crops. Its dominant growth habit suppresses weeds, lessening reliance on herbicides, and its hardiness to pests reduces the need for intensive pesticide use (Shahzad, 2012). These characteristics support lower ecological burdens and boost compatibility with organic and low-input urban farming systems.

Alignment with Sustainability Pillars: Economic, Social, and Environmental Integration

Taken together, the economic, social, and environmental parts of hemp cultivation illustrate its strong alignment with sustainability. Economically, hemp can support diversified income streams, entrepreneurship, and local value retention. Socially, it offers opportunities for community engagement, workforce development, and the normalization of *Cannabis*-derived products within food and material systems—provided stigma is actively addressed. Environmentally, hemp contributes to climate mitigation, soil remediation, and efficient use of resources across agricultural and industrial supply chains.

From a circular economy perspective, hemp is an example of a crop that supports closed-loop systems, cutting waste and continually repurposing biomass. Nobre and Tavares (2021) emphasize that circular economy frameworks are most effective when economic activity simultaneously advances social well-being and environmental health. Hemp's multifunctionality makes this crop an enabler of integrated sustainability strategies in urban contexts.

Overall, the literature suggests that hemp's efficient integration into urban food systems depends not solely on its agronomic or industrial performance, but on its ability to deliver benefits across sustainability domains. By supporting local economies, confronting environmental challenges, and reshaping social perceptions of *Cannabis*, hemp has a place in a more resilient, inclusive, and sustainable urban food systems.

Linking Propagation to Hemp Research and Production Importance

The rapid expansion of hemp and broader *Cannabis* markets has intensified the call for consistent, high-quality plant material capable of fulfilling diverse end-use requirements. As demand grows across food, fiber, and cannabinoid sectors, production systems must deliver uniform results with predictable chemical and morphological traits. Recent research emphasizes that improving cultivation practices—including propagation—is essential to achieving consistent cannabinoid profiles, yield, and quality in an increasingly competitive and regulated industry.

(Weingarten et al., 2024). Within this context, propagation research has emerged as an integral element of modern hemp production systems.

Despite clonal propagation offering well-documented advantages for maintaining genetic uniformity, its use in hemp production remains limited compared to its widespread adoption in high-THC *Cannabis* systems (Casillas, 2017). Industrial hemp is generally cultivated as a broadacre agronomic crop, where seed-based propagation is preferred for its scalability, lower initial costs, and compatibility with mechanized field operations. Implementing clonal propagation at this scale introduces significant logistical and financial challenges, such as the need for specialized propagation infrastructure, increased labor requirements, and difficulties related to transplanting and establishment. Nevertheless, as hemp markets diversify and demand for consistent plant material increases across food, fiber, and cannabinoid-related sectors, interest in vegetative propagation is expanding. Insights from CEA-based *Cannabis* production, where cloning is standard, may inform how propagation strategies could be adapted or selectively integrated into hemp systems to enhance uniformity, while maintaining the feasibility of large-scale production.

Expanding Demand and the Need for Uniform Plant Material

Market diversification in *Cannabis* and hemp has produced highly specialized cultivars developed for fiber, food, pharmaceutical cannabinoids, and other value streams. However, the supply chain for *Cannabis*-derived products depends heavily on preserving consistent attributes. Chandra et al. (2020) note that one of the major challenges in moving *Cannabis* from cultivation to commercial or pharmaceutical use is ensuring a steady supply of plant material with uniform cannabinoid composition. Variability introduced through sexual reproduction, cross-fertilization, or heterogeneous seeds can undermine standardization and legal compliance. Consequently, controlled propagation and multiplication of plants have become central strategies for stabilizing production.

The significance of reliable propagule production is emphasized by the biological characteristics of *Cannabis*. The species exhibits dioecy and heterozygosity, which complicate conventional seed-based production systems (Das, 2024). These genetic complexities reinforce the need for vegetative and micropropagation approaches that can maintain cultivar integrity spanning production cycles.

Role of Clonal Propagation in Genetic Uniformity

Clonal propagation—most commonly through tip and stem-section cuttings—remains the leading method for producing genetically uniform *Cannabis* plants. Vegetative propagation enables growers to replicate genotypes while preserving key traits such as cannabinoid profile, fiber quality, plant architecture, and flowering behavior. Compared with seed propagation, cloning offers consistent outcomes in genetics, gender expression, and yield potential (Weingarten et al., 2024).

Cannabidiol (CBD) production highlights the importance of genetic uniformity in *Cannabis* cultivation. Unlike fiber or grain hemp systems, CBD production requires consistent cannabinoid profiles, maintaining high CBD concentrations while keeping tetrahydrocannabinol (THC) levels below the legal limit of 0.3% (Dabrowska, 2019). Seed-propagated hemp populations often show substantial genetic variability (Stack et al., 2021; Trubanová et al., 2025). This can cause inconsistent cannabinoid expression and the risk of “hot” crops that exceed THC limits. Therefore, clonal propagation could serve as a key strategy for producers targeting CBD markets.

Propagation success is influenced by factors, including cutting preparation, hormone use, and rooting environment. For instance, Caplan et al. (2018) reported that application of indole-3-butyric acid (IBA) significantly improved rooting success and root quality in *Cannabis* stem cuttings, illustrating the importance of protocol optimization in commercial propagation systems. Such refinements are critical for ramping up production while maintaining plant health and uniformity.

Beyond traditional cloning, micropropagation offers additional opportunities for rapid multiplication and disease-free plant production. However, challenges related to reproducibility, genotype responsiveness, and cost remain barriers to broad adoption (Das, 2024). Additional research is therefore necessary to develop robust, scalable propagation platforms suitable for diverse hemp markets, including fiber and seed oil types that have generally relied more on seed.

Importance for Urban Food System Innovation

As urban food systems move toward more technologically intensive and controlled production environments, the reliability of plant propagation becomes increasingly important. Urban and controlled environment agriculture (CEA) operations depend on predictable crop performance, rapid turnover, and efficient space utilization. Vegetative propagation systems have demonstrated the capability to boost rooting efficiency, conserve resources, and support high-density production models (Weingarten et al., 2024).

Reliable propagation also supports the diversification strategies that characterize many urban agriculture enterprises. Because hemp can produce food, fiber, and bio-based materials, consistent planting stock is essential for synchronizing multi-stream production systems. Inconsistent genetics or uneven plant development can disrupt processing, reduce product quality, and hurt the economic viability of integrated urban hemp operations. Thus, propagation research directly supports the feasibility of incorporating hemp into urban agriculture frameworks.

Propagation Research as the Foundation for Hemp’s Future Potential

Advances in propagation science are fundamental to enabling hemp’s full potential across food, fiber, and sustainability-oriented markets. While the crop’s versatility is well established, its commercial success depends on the ability to produce uniform, high-performing plants at scale. Propagation research addresses key bottlenecks in genetic stability, plant health, and production efficiency.

Moreover, as regulations tighten—particularly for cannabinoid products—the demand for reproducible plant material will likely intensify. Controlled propagation systems provide a pathway to meet these standards while supporting innovation in breeding, controlled environment cultivation, and the integration of urban agriculture. Research should therefore prioritize scalable propagation protocols, improved clonal performance, and system-level optimization tailored to specific hemp end uses.

In this way, propagation science serves not solely as a technical subfield of horticulture but as a strategic enabler of hemp's role in sustainable food systems, bio-based manufacturing, and circular urban economies.

Conclusion

The literature in this thesis positions hemp as a uniquely multifunctional crop operating at the intersection of urban food systems, material innovation, and sustainable development. Across the sustainability and food system domains, hemp regularly demonstrates an uncommon capacity to simultaneously contribute to human nutrition, industrial materials, and circular urban economies. Within urban food systems, hemp-derived products such as seed, oil, and protein powders provide nutrient-dense, plant-based alternatives that correspond closely with evolving dietary trends and the growing demand for resilient local food sources. Among hemp-derived products, CBD shows the crop's ability to produce high-value, multifunctional outputs, but its integration into food systems depends on evolving regulatory and scientific frameworks. At the same time, hemp's fiber and hurd fractions extend its relevance far beyond food, promoting applications in textiles, biocomposites, construction materials, and other bio-based products that support low-carbon and circular production models.

Hemp's value does not lie in any single output but in its capacity to generate multiple benefits across economic, social, and environmental dimensions. The crop supports local economic development through diversified value chains and opportunities for decentralized processing and entrepreneurship. Socially, hemp's adoption into legitimate food and material systems creates an avenue to reframe longstanding stigma through education, transparency, and visible community benefits. Environmentally, hemp contributes to soil remediation, carbon sequestration, reduced agrochemical reliance, and biodegradable material streams—traits that align with the three pillars of sustainability emphasized in urban food system frameworks. Taken together, the literature supports hemp's emerging role as a strategic crop for cities seeking multifunctional, resource-efficient, and locally rooted production systems.

However, realizing hemp's full potential in urban agriculture depends fundamentally on the reliability and uniformity of plant production systems. As hemp markets diversify across food, fiber, and cannabinoid applications, the demand for consistent, high-quality plant material has intensified. Genetic variability associated with seed propagation creates major challenges for maintaining predictable crop performance at a commercial scale. Consequently, clonal

propagation has been a cornerstone technique in modern *Cannabis* production, allowing the replication of genotypes with stable morphological and biochemical traits.

While clonal propagation is foundational in high-THC *Cannabis* production, its role in hemp is more complex because hemp is mainly a field-grown agronomic commodity. The economic and logistical realities of large-scale hemp production have favored seed-based systems, which allow efficient establishment across extensive acreage. As a result, directly translating cloning practices from CEA-grown *Cannabis* systems to hemp production is not always feasible at scale. This does not diminish the importance of propagation research; it highlights the need to contextualize clonal approaches within specific production goals and system constraints. As hemp diversifies into higher-value and more controlled production environments, including urban and CEA systems, targeted clonal propagation may become more relevant. Propagation research is not a replacement for existing agronomic practices, but a complementary tool that can enhance uniformity, quality, and system adaptability where appropriate.

Advancing propagation science is therefore not purely a technical refinement but a key requirement for supporting hemp's broader integration into urban food and material systems. Controlled propagation protocols influence downstream outcomes, including yield uniformity, product quality, regulatory compliance, and economic viability. Despite its importance, significant knowledge gaps remain regarding best management practices for hemp cutting propagation, particularly across the various environmental systems used in commercial and research settings. These gaps are especially relevant for urban and CEA operations, where space efficiency, crop predictability, and input optimization are paramount. A routine observation of propagation under intermittent mist is that foliage becomes chlorotic. Could fertilization during propagation overcome this issue? The research presented in Chapter 2 of this thesis directly addresses this critical issue by evaluating how fertilization and propagation environment influence the rooting and foliage quality of hemp cuttings.

This review argues that the future scalability and sustainability of hemp-based urban systems depend not only on the crop's versatility but also on refining production technologies, including propagation practices, to ensure reliable, uniform plant material. Ongoing research combining physiology, environmental control, and production economics is essential to fully unlock hemp's role in resilient urban food systems and circular bio-based economies.

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Chapter 2: Effects of Fertilization and Environment during Propagation on Rooted Cutting Quality of *Cannabis sativa*

Key words: clonal propagation, hemp, intermittent mist, plastic-encapsulated fertilizer, rockwool, slow-release fertilizer, stem cuttings, subirrigation

Summary

Producing high-quality rooted cuttings of *Cannabis* has proven challenging for many producers, with chlorotic foliage and/or poor rooting often observed. Three experiments were conducted using four hemp cultivars in two common propagation environments: intermittent mist and subirrigation systems, as well as with two different substrates, to determine whether slow-release or soluble fertilizer could enhance rooted cutting quality. Specifically, this research assessed whether cuttings rooted under intermittent mist would exhibit reduced chlorosis when fertilizer was applied. Terminal cuttings performed better than subterminal cuttings. Rooting percentages were similar across environments; however, intermittent mist resulted in poorer foliage but higher root ratings, whereas subirrigation produced superior foliage with comparable rooting percentage. Neither controlled-release nor soluble fertilizer improved foliage quality. These findings indicate that subirrigation offers an effective method for producing high-quality rooted cuttings that supports better foliage quality.

Introduction

Cannabis sativa has historically been a significant crop with diverse applications including agriculture, chemical, medicinal, and commercial uses. Its propagation can be achieved through both sexual and asexual methods, with clonal propagation of leafy stem cuttings being the most widely utilized technique (Casillas, 2017). *Cannabis* growers often prefer this method due to its low cost and ability to produce genetically uniform plants with consistent growth rates and cannabinoid production compared to seed propagation (Coffman & Gentner, 1979; Potter, 2009). In this approach, stock plants are cultivated to produce numerous lateral shoots that are cut for rooting once sufficiently developed. The cuttings are treated with an auxin and placed in sterile growing media, such as rockwool. They are regularly misted or kept under a humidity dome to maintain optimal environmental conditions that support root development, which generally occurs within 7 to 14 days. These techniques are used for increasing the relative humidity around the cuttings until root formation occurs. Low relative humidity, with a vapor pressure deficit

(VPD) over 0.3 kPa, can increase transpiration, causing cuttings to wilt more quickly and potentially die (Owen, 2018).

Nutrient applications in clonal *Cannabis* propagation are often from proprietary commercial nutrient formulations, often comprised of amino acid and salt solutions containing food-grade precursors, that are used to increase production yield and reduce individual cloning time (Howard et al., 2022). In typical commercial nursery propagation, either no fertilizer or controlled-release fertilizer is used during propagation (Dole & Gibson, 2006, pg. 80). Healthy green foliage during propagation is desirable, as yellowing of the leaves is an indication of reduced chlorophyll content. This negatively impacts the photosynthetic system, resulting in weak and slower growth rates (Xiao et al., 2013; Zhu et al., 2014).

Our primary objective was to determine whether supplemental fertilization during propagation would mitigate leaf yellowing (chlorosis) and promote root development during clonal propagation of *Cannabis* cuttings. We also assessed differences in foliage and root quality under two commonly used propagation environments, intermittent mist and subirrigation environments, with two different substrates and across four different cultivars. The variety ‘Cherry’ was selected as a control because it has been observed to maintain green foliage during propagation and has been one of the highest yielding cultivars with greatest CBD content (Jason Griffin, personal communication). ‘Otto II Stout’ has rooted moderately well and has a moderate level of CBD content, almost never exceeding THC limits. In addition, its foliage has been observed to become very yellow during propagation, making it a good test variety. ‘Cherry HD’ and ‘AST 530’ industrial hemp varieties had unknown rooting potential.

Materials and methods

Three experiments were conducted using intermittent mist and/or subirrigation to evaluate rooting of *Cannabis* cuttings with various fertilizer treatments and substrates (Table 1). Expt. 1 occurred from 8 Jun to 11 Jul 2023 with hemp ‘Cherry’ in Manhattan, KS, USA; Expt. 2 occurred from 19 Feb to 27 Mar 2024 with hemp ‘Otto II Stout’, ‘Cherry HD’, and ‘AST 530’ in Manhattan, KS; and Expt. 3 occurred from 21 April to 26 May with hemp ‘Cherry’, ‘Cherry HD’, and ‘Otto II Stout’ at the John C. Pair Horticulture Research and Extension Center (JCPHRC) in Haysville, KS.

Data Collected. Foliage was evaluated by measuring leaf greenness weekly with a SPAD meter (Konica Minolta, Ramsey, NJ; three readings averaged per experimental unit) and with foliage ratings (Fig. 1a) on a scale of 1 to 5, with 5 being highest commercial

quality, at end of the experiment. In all experiments, rooting quantity was evaluated by percent rooting, which was based on the number of cuttings that developed any root in each experimental unit. In Expt. 1 and 2, root ratings were evaluated on a scale of 0 (dead or no callus) to 5 (well rooted; (Fig. 1b). In Expt. 1 only, length of root mass from bottom of the green stem to end of longest root at the end of the experiment. In Expt. 3 only, rooting was also evaluated by root number per rooted cutting.

In Expts. 1 and 2, the variance of the factorial treatment structure was analyzed with the 'fit model' function of JMP Pro ver.16.0.0 (SAS Institute Inc., Cary, NC, USA). All tests were conducted at the 0.05 significance level. Least square means were separated using Tukey's mean separation procedure. In Expt. 3, data were analyzed using analysis of variance (ANOVA) and means separated by Fisher's Protected LSD.

Expt. 1. Two cutting types, terminal (from the shoot tip with an active terminal growing point) and subterminal (stem-section with no active terminal growing point), with four fertilizer treatments of pre-plant incorporated Osmocote Plus 15-9-12 (3 to 4 month release, ICL Fertilizers, St. Louis, MO, USA) at rates of control (no fertilizer), low ($1.8 \text{ g}\cdot\text{L}^{-1}$), medium ($4.7 \text{ g}\cdot\text{L}^{-1}$), and high ($7.1 \text{ g}\cdot\text{L}^{-1}$) were rooted under intermittent mist (averages of 28.2 and 23.2 °C day and night temperature, respectively; 100% relative humidity). Only terminal cuttings with the four fertilizer treatments were rooted via subirrigation under a humidity dome (averages of 29.7 and 26.0 °C day and night temperature, respectively; 84.4% relative humidity). After 37 and 38 days of rooting, rooting quality, rooting percentage, rooting length, and foliage quality were determined. The experimental design was completely random with four replications and five cuttings per experimental unit (e.u.) for a total of 160 cuttings under mist and 80 cuttings under subirrigation.

Stock plants from which cuttings were harvested were produced at the JCPHRC in Haysville, KS. Terminal and subterminal cuttings of four nodes were prepared from ~0.5 m stems of the stock plants. The basal 1 cm of each terminal and subterminal cutting was dipped in 0.1% K-IBA (potassium salt of indole-3-butyric acid, Sigma-Aldrich, St. Louis, MO, USA) dissolved in distilled water for 5 sec, trimmed a third of the leaves to reduce transpiration, and then stuck into the treatment substrate, which was 3 perlite (Therm-O Rock East, Inc., New Eagle, PA, USA) : 2 peat (v/v; Fertilome Canadian sphagnum peat moss, Lambert Peat Moss Inc., Rivière-Ouelle, Québec, Canada) that had been amended at treatment fertilizer rates. Cuttings were stuck into 50-cell black plastic liner sheets (T.O. Plastics, Clearwater, MN) that had been filled with treatment substrates. Cuttings were rooted and grown in a glass-glazed greenhouse (Throckmorton Plant Sciences Center; TPSC) under 52% white shade cloth (PAK Unlimited Inc., Cornelia, GA, USA) either under intermittent mist or subirrigation (AmHydro propagation system, Arcata, CA, USA) with

opaque humidity domes (Bootstrap Farmer, Downingtown, PA). During propagation, plants from both intermittent mist and subirrigation environments were irrigated overhead with municipal water daily to ensure that the substrate stayed moist. Leaf greenness data was collected on days 1, 7, 14, 21, 28, and 36; all other data was collected on days 37 and 38 after sticking cuttings.

Expt. 2. Only terminal cuttings of the three hemp cultivars ‘Otto II Stout’, ‘Cherry HD’, and ‘AST 530’ were used. Three soluble fertilizer treatments of 0, 50, and 200 mg N/L from 20-10-20 Peter’s Professional General Purpose fertilizer (ICL Specialty Fertilizers, St. Louis, MO) were applied weekly beginning 18 days after sticking cuttings. Cuttings were rooted under intermittent mist (averages of 27.2 and 24.6 °C day and night temperature, respectively; 100% relative humidity) and subirrigation with a humidity dome (averages of 23.2 and 21.2 °C day and night temperature, respectively; 88.2% relative humidity). The experimental design was completely random with four replications and four cuttings per e.u. for a total of 96 cuttings per cultivar (24 e.u.) and 144 cuttings under each of mist and subirrigation (36 e.u.).

Stock plants were produced from feminized seed sown in Dec 2023. Thirty stock plants of each cultivar were produced and cuttings for the experiment were taken and stuck on 19 Feb 2024. Terminal cuttings of four nodes were collected from stock plants and the basal 1 cm of each was dipped in 0.1% K-IBA as in Expt. 1, trimmed, and then stuck into 1 in rockwool cubes (Grodan, Milton, Ontario). Cuttings were rooted and grown on in a glass-glazed greenhouse of TPSC under either intermittent mist or subirrigation as described for Expt. 1. During propagation, plants were irrigated overhead with municipal water daily until soluble fertilizer treatment applications began. Soluble fertilization with 20-10-20 fertilizer (Peter’s Professional General Purpose) was applied at rates of 0, 50, and 200 mg N/liter. Experimental units of respective fertilizer treatments were set in trays and fertilizer solutions were supplied for 30 minutes, allowing the rockwool substrate to become fully saturated. Leaf greenness data was collected every seven days; foliage rating, root rating, and rooting percentage was collected on day 38 after sticking cuttings.

Expt. 3. Terminal stem cuttings of three *Cannabis* cultivars with three pre-plant incorporated fertilizer treatments of Osmocote Plus 15-9-12 (3 to 4 month release, ICL Fertilizers, St. Louis, MO, USA) at rates of control (no fertilizer), low ($1.8 \text{ g}\cdot\text{L}^{-1}$), and high ($7.1 \text{ g}\cdot\text{L}^{-1}$), and a fourth fertilizer treatment of 200 ppm liquid nitrogen (Jack’s 20-10-20, JR Peters, Allentown, PA) applied once per week were rooted under intermittent mist. The experimental design was a randomized complete block with five cuttings per e.u. and four blocks for a total of 80 cuttings per cultivar and a total of 240 cuttings.

Stock plants were produced from feminized seed sown in Dec 2023. Twenty stock plants of each cultivar were produced in 3 gal nursery containers filled with a soilless substrate (MetroMix Sungro, Agawam, MA), amended with 10.7 Kg/m³ Osmocote Plus 15-9-12 (8-9 mo.) and 0.6 Kg/m³ dolomitic lime. Terminal stem cuttings, 10 to 15 cm in length, were taken on 21 April 2024. The cut was made immediately below a node, and the basal 1 cm of each was dipped in 0.1% K-IBA and inserted in Anderson Bands (Stuewe & Sons, Tangent, OR) filled with a 3 perlite : 1 peatmoss (vol/vol) substrate. Bands were placed in flats and flats were arranged on a raised bench in a polycarbonate glazed greenhouse under intermittent mist that operated for 6 sec. every 8 min during daylight hours. Rooting substrate was maintained at 21 C using heat mats (Redi-Heat, Phytotronics, Earth City, MO). Greenhouse temperature set points were maintained at 24 C (day) and 18 C (night). Controlled-release fertilizer (CRF) treatments were incorporated into the rooting substrate prior to filling the bands and inserting cuttings. Liquid fertilizer was mixed and applied 1x per week via an aluminum watering can. Leaf greenness data was collected weekly from 21 April to 19 May; all other data was collected on day 36 after sticking cuttings.

Results

Cutting type. In Expt. 1, terminal cuttings outperformed subterminal cuttings based on root ratings, rooting percentage, and foliage rating; there was no difference based on root length (Table 2). Therefore, use of terminal cuttings only is recommended, and only terminal cuttings were used in Expts. 2 and 3.

Rooting environment. Intermittent mist resulted in superior root length, rating, and rooting percentage in Expt. 1 (Table 2) and root rating in Expt. 2; rooting percentage was not different between environments in Expt. 2 (Table 3; Figure 2). However, leaf quality measured as lighter green color was generally worse under intermittent mist. Though foliage rating was not statistically different between environments (Table 2), on day 20 of rooting in Expt. 1, SPAD was lower under mist compared to subirrigation (Figure 3a). Similarly, foliage rating was worse under intermittent mist compared to subirrigation in Expt. 2 (Table 3), and on day 17, SPAD was lower under mist compared to subirrigation (Figure 4a).

Cultivar. In Expt. 2, foliage of 'Cherry HD' was more yellow than other cultivars (Figure 4b) though it did not have a different foliage rating (Table 3). In Expt. 3, after propagation began, 'Cherry' remained greener than 'Otto Stout II' and 'Cherry HD' at 15 days (Prob > F = 0.001) and at 22 days (Prob > F = 0.002). By Day 29, the three cultivars were different from each other with 'Cherry' greenest at 48.4, followed by 'Otto II Stout' at 42.7, and 'Cherry HD' at 35.5 SPAD units, respectively.

In Expt. 2, 'AST 530' had better root rating, though not different rooting percentage, compared to 'Cherry HD' and 'Otto II Stout' (Table 3). In Expt. 3, root number and rooting percentage were similar across cultivars (Tables 4 and 5).

Fertilizer. In Expts. 1 and 2, neither slow-release (Expt. 1) nor liquid (Expt. 2) fertilizer treatments had an effect on foliage rating (Tables 2 and 3). In Expts. 1 and 3, leaf greenness generally declined over time and was not different regardless of fertilizer treatment until day 29 in only Expt. 3 (Figures 3b and 5).

In Expts. 1 and 2, fertilization did not impact root rating or rooting percentage (Tables 2 and 3). In Expt. 1, the 4.7 g·L⁻¹ SRF treatment resulted in greater root length than the higher rate (Table 2). In Expt. 3, soluble fertilization with 200 ppm N may have slightly improved root quality and rooting percentage, but in inconsistent ways (Tables 4 and 5).

Discussion

The propagation environment influenced the quality of rooted cuttings more than fertilization across all experiments. Rooting percentage did not differ between intermittent mist and subirrigation environments, indicating that both environments maintained hydration and supported adventitious root formation. Similar findings in hemp and other species show that high-humidity environments, including intermittent mist and enclosed systems like humidity domes, result in comparable rooting percentages (McLeod et al., 2022). These results suggest that when relative humidity is maintained, propagation environment does not limit rooting success.

Despite similar rooting percentages, cutting quality differed between environments. Intermittent mist produced higher root ratings, while subirrigation resulted in improved foliage quality and reduced chlorosis. Previous research shows intermittent mist enhances rooting by lowering leaf temperature and vapor pressure deficit, limiting transpiration stress during propagation (McLeod et al., 2022). However, mist systems are linked to foliar nutrient leaching and chlorosis (Zhang & Graves, 1995), which is consistent with the reduced foliage quality observed in this research. Similarly, cuttings under humidity domes had less chlorosis and higher shoot quality than those under mist, despite similar rooting success (McLeod et al., 2022).

Subirrigation likely improved foliage quality by maintaining moisture availability at the root zone while minimizing foliar wetting and nutrient loss. In non-cannabis species, subirrigation has been shown to reduce nutrient leaching and improve plant quality compared to mist systems (Zhang & Graves, 1995). The improved foliage greenness observed in the present study suggests that subirrigation better preserves chlorophyll

during propagation, which helps maintain photosynthetic capacity and supports growth after transplant.

Fertilization during propagation did not affect root quality or rooting percentage in any experiment. These findings are consistent with propagation recommendations emphasizing minimal nutrient inputs during early root initiation. Rooting of stem cuttings depends mainly on endogenous carbohydrate reserves, hormonal balance, and cutting physiology rather than external nutrients (Caplan, 2018). Previous work shows factors like leaf number, cutting maturity, and auxin application influence rooting success more than fertilization (Caplan, 2018). Although some commercial studies report increased rooting speed or biomass with proprietary nutrient formulations (Howard et al., 2022), responses are inconsistent and depend on specific production systems and treatment combinations. Foliage quality was generally not influenced by the rates and timing of fertilizer used in this research. In only Expt. 3, after a month of rooting, did increased fertilizer rate result in greener foliage (Fig. 5).

The lack of response to fertilization may be due to sufficient nutrient availability within cutting tissue during propagation. These results suggest supplemental fertilization during propagation is unnecessary for producing high-quality rooted hemp cuttings in controlled environments.

Variability in rooting and cutting quality among cultivars reports suggest that genotype influences propagation outcomes (Cockson et al., 2019), and we observed some minor differences in leaf greenness across cultivars. Differences in cutting morphology and physiology, such as leaf area and carbohydrate availability, may also affect rooting performance (Caplan, 2018). However, overall environmental effects were consistent across cultivars, suggesting propagation environment may apply broadly across genetic backgrounds.

These findings have practical implications for commercial hemp propagation. Intermittent mist may be advantageous when maximizing root development is the primary objective, whereas subirrigation may be preferred to maintain foliage quality and reduce chlorosis. Both systems achieved high rooting percentages, so growers can choose methods based on desired plant quality and operational needs. Subirrigation may also offer benefits like reduced water use, better sanitation, and simpler management compared to mist systems (Zhang & Graves, 1995). Rooting outcomes may also be improved with other environmental modifications, such as root zone heating (Cockson et al., 2019).

Overall, these results show propagation environment is a key factor in rooted cutting quality in hemp, while fertilization during propagation offers little benefit under the conditions that we tested. Optimizing environmental conditions may be more important than changing nutrient inputs to improve cutting quality and consistency in controlled environment production systems.

Conclusions

Terminal cuttings demonstrated superior performance. Although rooting percentages were similar between environments, mist treatments produced poorer foliage but higher root ratings compared to subirrigation. Neither CRF nor soluble fertilizer improved foliage quality. While intermittent mist produced high rooting quality and percentage, subirrigation resulted in superior foliage quality with comparable rooting outcomes to the mist environment.

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Table 1. Treatment summary of the three hemp propagation experiments.

	Expt. 1	Expt. 2	Expt. 3
Lead student	Hishaw	Gross	Griffin
Cultivar(s)	'Cherry'	'Otto II Stout' 'Cherry HD' 'AST 530'	'Cherry' 'Otto II Stout' 'Cherry HD'
Cutting type(s)	Terminal Subterminal	Terminal	Terminal
Production environment(s)	Mist Subirrigation	Mist Subirrigation	Mist
Fertilizer, controlled-release (CRF)	0 g/L 1.8 g/L 4.7 g/L 7.1 g/L	N/A	0 g/L 1.8 g/L 7.1 g/L
Fertilizer, soluble	N/A	0 50 ppm N 200 ppm N	200 ppm N
Substrate	3 perlite : 2 peatmoss	1-in rockwool cubes	3 perlite : 1 peatmoss

Table 2. Results of main effects of cutting type, slow release fertilizer rate, and environment on foliage rating, root rating, root length, and rooting percentage on industrial hemp terminal and subterminal cuttings (Expt. 1).

Cutting type	Foliage rating	Root rating	Root length (cm)	Rooting percentage
Terminal (n=32)	2.6 a	1.6 a	8.0	57.4 a
Subterminal (n=16)	2.0 b	1.4 b	9.0	56.0 b
Prob > F	*	**	NS	*
Slow-release fertilizer (n=12)				
Control (0 g·L ⁻¹)	2.3	1.5	5.7 ab	53.3
Low (1.9 g·L ⁻¹)	2.4	1.6	5.8 ab	59.7
Medium (4.7 g·L ⁻¹)	2.6	1.9	6.9 a	61.1
High (7.1 g·L ⁻¹)	2.3	1.4	4.8 b	57.3
Prob > F	NS	NS	*	NS
Environment				
Mist (n=32)	2.3	1.9 a	10.1 a	66.9 a
Subirrigation (n=16)	2.6	0.8 b	4.3 b	36.1 b
Prob > F	NS	***	***	***
² Values within a column followed by the same letter are not different at P=0.05.				

Table 3. Results of main effects of cultivar, liquid fertilizer rate, and environment on foliage rating, root rating, and rooting percentage of industrial hemp terminal cuttings (Expt. 2).

Cultivar (n=12)	Foliage Rating	Root Rating	Rooting Percentage
AST 530	2.9	4.0 a	100
Cherry HD	2.9	3.3 b	99.0
Otto II Stout	3.2	3.4 b	96.9
F-value	NS	0.002	NS
Liquid Fertilizer (n=12)			
0 ppm N	2.9	3.4	99.0
50 ppm N	2.9	3.6	97.9
250 ppm N	3.2	3.7	99.0
F-value	NS	NS	NS
Environment (n=24)			
Mist	2.1 b	3.9 a	97.2
Subirrigation	3.9 a	3.2 b	99.3
F-value	<0.0001	<0.0001	NS
² Values within a column followed by the same letter are not different at $P=0.05$.			

Table 4. Rooting percentage of industrial hemp terminal cuttings with incorporated controlled release fertilizer (CRF) or weekly liquid fertilizer drench (Expt. 3).

CRF (g·L ⁻¹)	Rooting (%)		
	Cherry	Cherry HD	Otto II Stout
0	35 b ^z	90 a	85 ab
1.8	80 a	85 a	75 b
7.1	35 b	75 a	75 b
Liquid (ppm N)			
200	85 a	100 a	100 a

^zValues within a column followed by the same letter are not statistically different at $P=0.05$.
n=20

Table 5. Number of roots per rooted cutting of industrial hemp stem cuttings with incorporated controlled release fertilizer (CRF) or weekly liquid fertilizer drench (Expt. 3).

CRF (g·L ⁻¹)	Root Number		
	Cherry	Cherry HD	Otto II Stout
0	3.6 b ^z	4.4 c	8.0 b
1.8	8.3 a	6.1 bc	12.9 a
7.1	3.9 b	8.5 ab	10.4 ab
Liquid (ppm N)			
200	8.1 a	9.3 ab	13.1 a

^zValues within a column followed by the same letter are not statistically different at $P=0.05$.
n=20

Figure 1. Ratings scales used to evaluate foliage (a) and rooting (b) quality of terminal cuttings in Expt. 2.

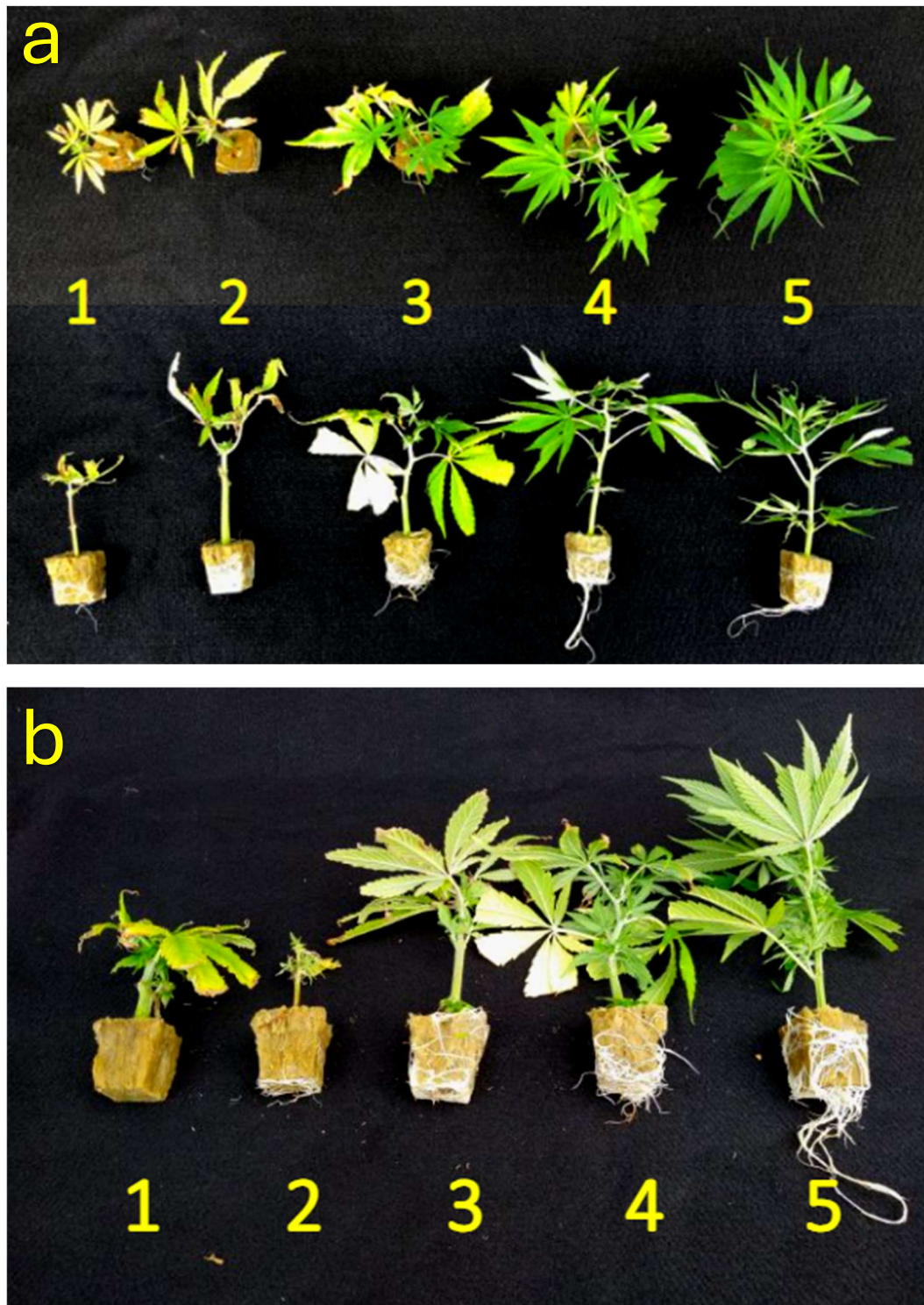


Figure 2. Comparison of a representative experimental unit of each treatment (environment x cultivar x fertilizer rate) evaluated in Expt. 2 at harvest

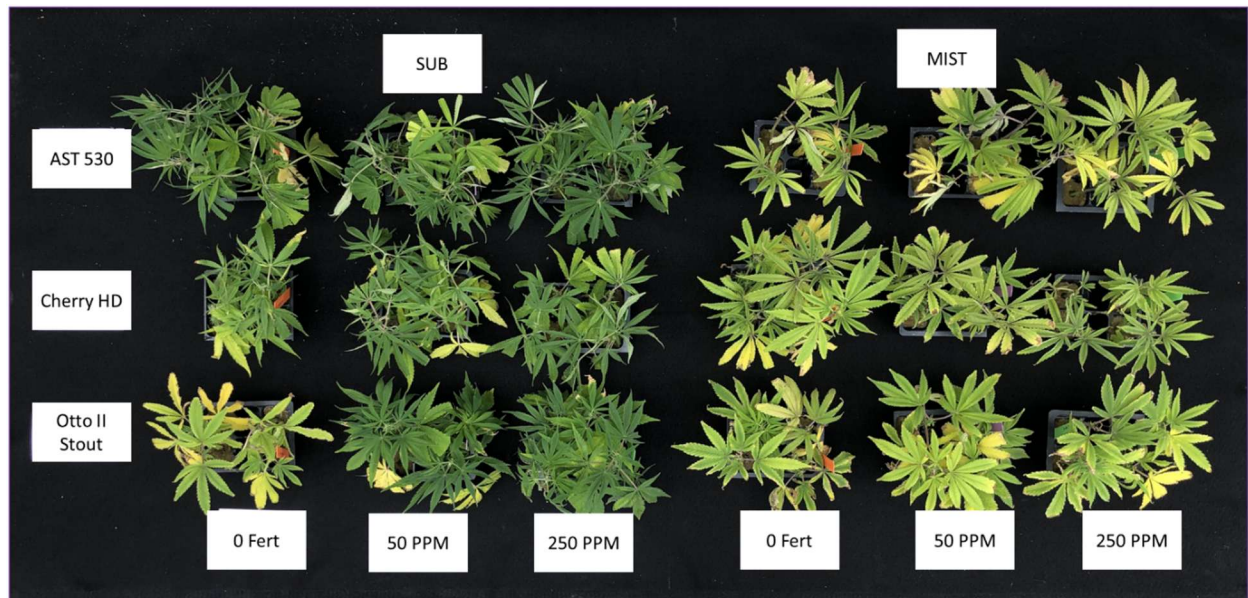


Figure 3. Weekly leaf greenness (SPAD) data for terminal cuttings only comparing main effects of environment (a) and fertilizer treatment (b) in Expt. 1. Statistics were run by date; NS = not statistically different, *** = different at <0.0001.

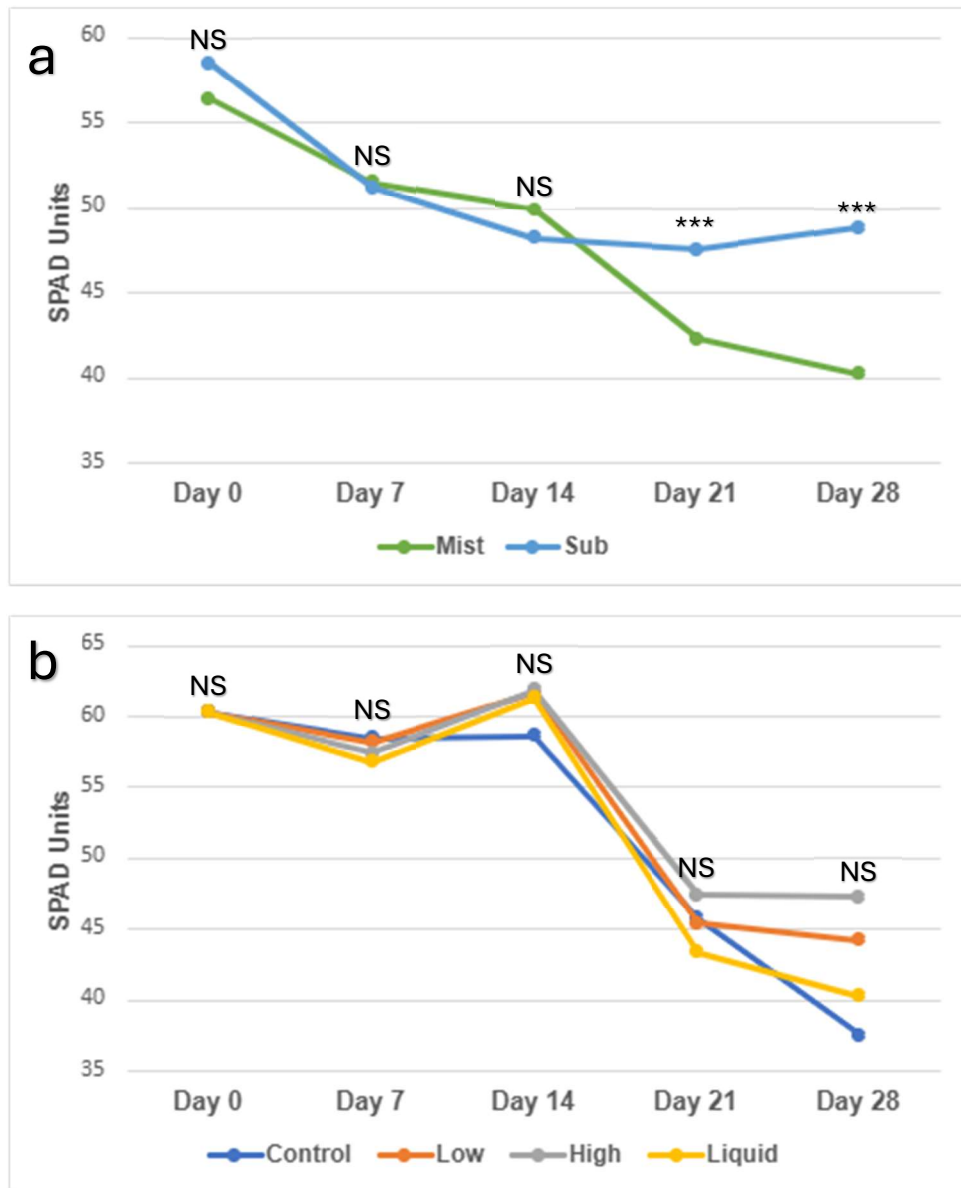


Figure 4. Weekly leaf greenness (SPAD) data comparing main effects of environment (a:** = significance at 0.001, *** = significance at <0.0001) and cultivars (b: on a day, the same letters indicate no difference in the means) in Expt. 2.

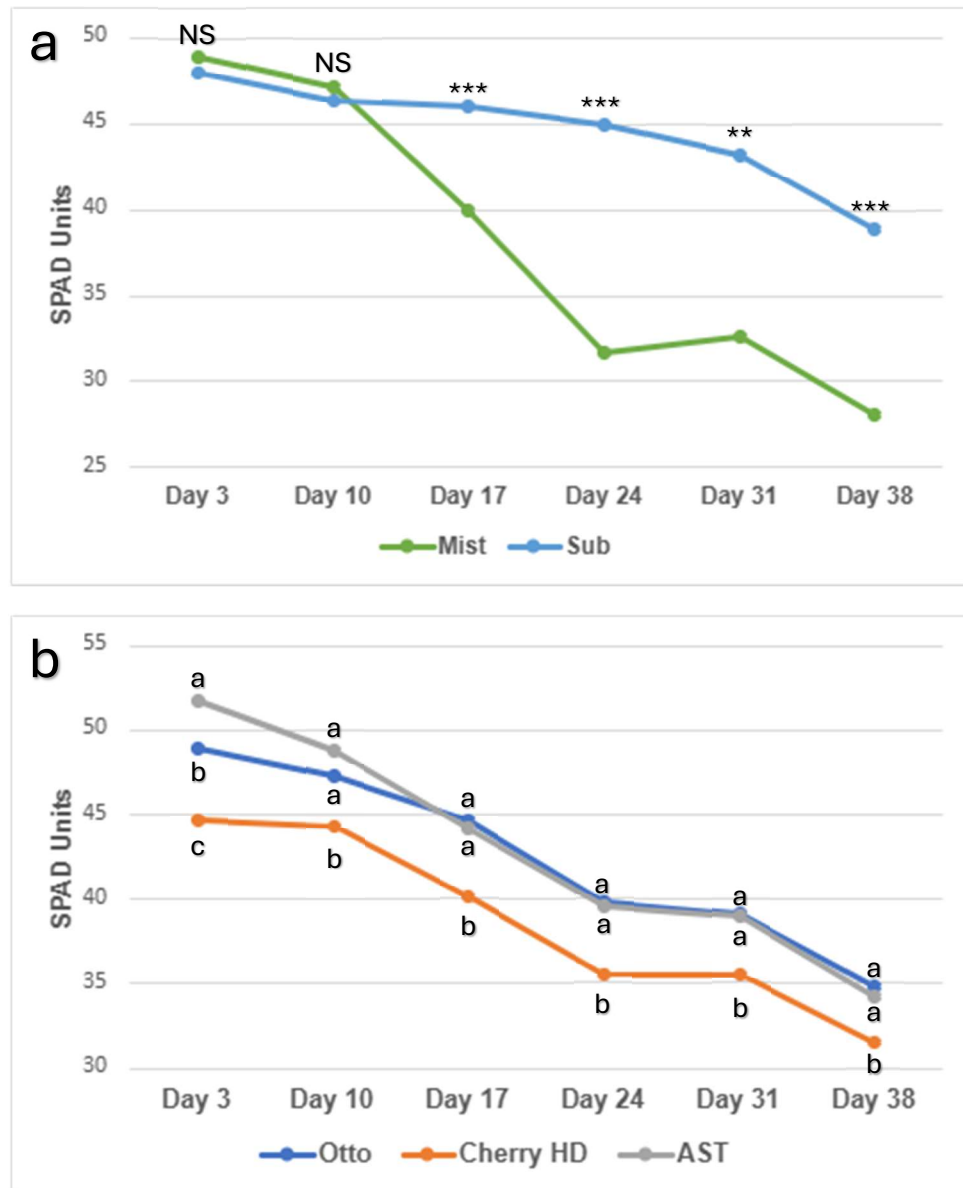


Figure 5. Weekly leaf greenness (SPAD) data comparing main effect of fertilizer treatments of none (control), liquid, low CRF, and high CRF averaged across cultivars in Expt. 3. Statistics were run by date; NS = not statistically different, *** = different at <0.0001.

