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Research Note

Substrates, containers, and nutritional management in fruit nursery tree production: a review

Substratos, recipientes e manejo nutricional na produção de mudas frutíferas em viveiro: uma revisão

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ABSTRACT

The global increase in high-quality fruit production in recent decades has led to a growing demand for seedlings with superior quality standards to support orchard expansion and renewal. In this context, the adoption of modern production systems and the implementation of precise nutritional management during the nursery phase are essential to produce seedlings with desirable morphological traits and added value. In Brazil, some nursery tree production systems are conducted in protected environments, either due to phytosanitary regulations or to optimize space, nursery operations, and marketing. These systems require the use of appropriate containers and substrates that provide suitable chemical, physical, and biological conditions for plant development. However, many substrates have low nutrient content, which is rapidly depleted, thus requiring fertilization to support adequate seedling growth. Understanding the nutritional requirements of fruit species and their adaptability to different substrates and containers enables the optimization of production processes, cost reduction, and improvements in seedling quality. This review aims to summarize and discuss the most relevant findings on substrate use, container types, and nutritional management strategies for fruit nursery tree production under protected conditions, with the goal of improving both morphological and phytosanitary quality standards.

KEYWORDS: Controlled-release fertilizers. Fertigation. Propagation of fruit trees. Nurseries.

RESUMO

O aumento global na produção de frutas de alta qualidade nas últimas décadas tem gerado uma demanda crescente por mudas com elevados padrões de qualidade, a fim de viabilizar a expansão e a renovação dos pomares comerciais. Nesse contexto, a adoção de sistemas modernos de produção e a implementação de um manejo nutricional preciso durante a fase de viveiro são essenciais para a formação de mudas com características morfológicas desejáveis e maior valor agregado. No Brasil, alguns sistemas de produção de mudas frutíferas são conduzidos em ambientes protegidos, seja em função de exigências fitossanitárias ou com o objetivo de otimizar o uso do espaço, as operações do viveiro e a comercialização. Esses sistemas demandam o uso de recipientes e substratos adequados, que proporcionem condições químicas, físicas e biológicas favoráveis ao desenvolvimento das plantas. No entanto, muitos substratos apresentam baixo teor de nutrientes, os quais se esgotam rapidamente, exigindo suplementação com fertilizantes para garantir o crescimento adequado das mudas. A compreensão das exigências nutricionais das espécies frutíferas e de sua adaptabilidade a diferentes substratos e recipientes permite otimizar o processo produtivo, reduzir custos e melhorar a qualidade final das mudas. Esta revisão tem como objetivo reunir e discutir as informações mais relevantes sobre o uso de substratos, tipos de recipientes e estratégias de manejo nutricional na produção de mudas frutíferas em ambiente protegido, com vistas à melhoria dos padrões morfológicos e fitossanitários das mudas.

PALAVRAS-CHAVE: Fertilizantes de liberação controlada. Fertirrigação. Propagação de plantas frutíferas. Viveiros.

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INTRODUCTION

The promotion of fruit consumption, associated with healthier eating habits, has led to a considerable increase in fruit growing activity over the last decades, both in terms of production and cultivated area. In the early 1960s, global fruit production was 199.8 million tons across a cultivated area of 27.2 million hectares, expanding to 909.6 million tons produced in 66.4 million hectares in 2022.

This represents an increase of 355% in fruit production and 144% in cultivated area. In this scenario, the production of oil palm, banana, watermelon, apple, orange, grape, coconut, mango, tangerine, pineapple, melon, peach, pear, olive and papaya stands out (FAO 2024). Apple, orange, grape, tangerine, peach, pear and plum trees are woody fruit crops in which commercial orchards are established with grafted seedlings, using scion/rootstock combinations and, in some cases, scion/interstock/rootstock combinations.

In these species, seedling production systems are usually carried out either in open field conditions (bare root seedlings) or in protected nurseries (containerized seedlings), with some variations depending mainly on phytosanitary issues, economic importance of the crop, and the need to optimize area and labor.

The expansion of cultivated areas and the renewal of commercial orchards require the annual production of millions of fruit seedlings worldwide (NATALE et al. 2018), which must meet genetic, morphological, and phytosanitary quality standards for commercialization. The adoption of appropriate phytosanitary, water, and nutritional management practices is essential during the propagation and early growth phases in the nursery, demanding technical knowledge of production factors to optimize production costs and seedling quality, especially through the rational and proper use of inputs (ALMEIDA et al. 2019).

In the past, a large portion of fruit nursery tree production in Brazil was carried out in open-air nurseries using beds or containers filled with soil (NATALE et al. 2018). As a result, soil-borne pests and pathogens began to spread from nurseries to commercial orchards, leading to productivity decline in several areas and even making production unfeasible in extreme cases.

An example is the infestation of *Meloidogyne enterolobii* in guava orchards in the Sub-Middle São Francisco Valley region, which caused more than a 70% reduction in guava production between 2000 and 2007 (FREITAS et al. 2015). Another important example was the spread of huanglongbing (HLB) or greening disease through the use of seedlings infected with *Candidatus Liberibacter asiaticus* in citrus orchards in the state of São Paulo, around 2004 (DADAZIO et al. 2018).

In response to this issue, laws and regulations were implemented to govern the production and commercialization of fruit seedlings in Brazil, which began to require compliance with minimum phytosanitary quality standards set by regulatory agencies. In Brazil, Law No. 10,711, enacted on August 5th, 2003, was established to regulate the National System of Seeds and Seedlings, aiming to ensure the identity and quality of plant propagation and reproduction materials produced, marketed, and used nationwide (BRASIL 2003).

Later, on March 16th, 2016, Normative Instruction No. 5 came into effect to set standards related to definitions, classification, specifications and guarantees,

tolerances, registration, packaging, labeling, and advertising of remineralizers and substrates for agricultural use (BRASIL 2016).

However, national legislation concerning substrate composition for fruit nursery tree production in containers is still insufficient, since the use of soil in substrate composition is prohibited by Normative Instruction No. 48, dated September 24th, 2013, only when intended for citrus seedling production in containers (BRASIL 2013).

Nevertheless, the use of soil in substrate composition has been declining due to discussions regarding its environmental impact from extraction in agricultural areas, its high weight and handling/transport cost, water retention issues, and its role in pest and disease dissemination. Moreover, due to its variability, many soils do not possess suitable physical, chemical, and/or biological characteristics for use in containers and packages (FERMINO 2014).

Among the problems associated with the use of soil, whether alone or as a component of substrates, the high potential for disseminating plant-parasitic nematodes from nurseries to commercial orchards stands out. These nematodes, also known as phytoparasitic nematodes, represent a diverse group of worms that feed on plants and cause significant economic losses in various crops, especially fruit species (KESHARI & MALLIKARJUN 2022). Infestation causes lesions on the root system, depending on the pest's feeding strategy. With impaired root functionality, there are reductions in yield, fruit weight and quality, as well as orchard plant density (GOMES et al. 2019). Roots damaged by nematodes become entry points for pathogenic fungi and bacteria, further deteriorating the root system (KESHARI & MALLIKARJUN 2022).

Among economically important fruit crops affected by plant-parasitic nematodes are pineapple, blackberry, persimmon, citrus, fig, guava, kiwifruit, apple, pear, papaya, strawberry, peach, nectarine, plum, and grapevine (ARIEIRA et al. 2008, CHITAMBAR et al. 2018, GOMES et al. 2019). Managing nematode-infested orchards typically involves high costs and the use of specialized chemicals with elevated toxicological classifications, or costly and often inefficient cultural practices to reduce nematode populations (KARURI 2022). Despite their damage and economic impact on many fruit crops, chemical nematicides are not yet registered in Brazil for most fruit species (AGROFIT 2024).

Some biological-based inputs available in the Brazilian market have shown satisfactory effectiveness against several nematode species (MACHADO 2022). In addition to their applicability in reducing nematode populations in infested fields, these products have been used in seedling production substrates due to their growth-promoting effects on the root system (STEWART & HILL 2014, ORTEGA-GARCÍA et al. 2015, HASHEM et al. 2019, NGALIMAT et al. 2021, LOU et al. 2022, YADAV et al. 2023).

Various reasons may justify the production of fruit tree seedlings in containers, such as: easier handling in the nursery (ergonomics for workers; easier weed control, irrigation, fertilization, packaging, and shipment for commercialization); optimization of physical space and internal logistics in nurseries; the need to produce seedlings free of soil-borne fungal diseases (VENTURA et al. 2019); the need to produce seedlings in screened environments to avoid insect vectors of diseases, as is the case for citrus seedling production in the State of São Paulo (CARVALHO et al. 2019) and passion

fruit in the State of Santa Catarina (PETRY et al. 2022); the need to produce seedlings free of nematodes due to the absence of registered chemical nematicides for various fruit species (AGROFIT 2024); the extension of the planting window in orchards (MAYER et al. 2022); convenience in meeting the retail seedling market; and the prolonged shelf life of seedlings.

Among the main changes adopted by nurserymen are the use of commercial substrates or substrate mixtures and the use of plastic containers of different sizes and shapes. Thus, substrates began to be widely used, particularly in the floriculture, landscaping, citrus, guava, and other fruit seedling sectors, with the primary function of providing adequate nutritional and structural conditions for the growth and development of seedlings (GONZAGA et al. 2016, SOUZA et al. 2018, MENEGATTI & BIANCHI 2019).

According to SCHAFER (2022), the term “plant substrate” has been adopted since the mid-20th century by the International Society for Horticultural Science (ISHS). Since then, various definitions have referred to any porous material, used alone or in mixtures, that, when placed in containers, provides anchorage and sufficient levels of water and oxygen for optimal plant development (VENCE 2008). In Brazil, the term “plant substrate” is relatively recent and was officially recognized by the Ministry of Agriculture in 2004, referring to products used as a growing medium for plants (SCHAFER 2022, SCHAFER & LERNER 2022). Driven by the importance of substrates for horticulture and forest seedling production, and by the need for an entity to promote and disseminate technical and scientific knowledge on plant substrates, as well as their production, marketing, and legislation, the National Association of Substrates for Plants (ANSUB) was created on February 3rd, 2021 (ANSUB 2024).

There are no official estimates of plant substrate usage in Brazil. However, according to the Brazilian Association of Industries in Plant Nutrition Technology (Abisolo), which includes major companies in the sector, about 624 thousand cubic meters of plant substrates were sold in 2022, generating revenue of approximately 362 million Brazilian Reais (ABISOLO 2024). According to SCHAFER & LERNER (2022), if the volume of substrate produced for internal consumption or by companies not affiliated with ABISOLO were included, those figures could be up to three times higher.

Finding a single plant substrate that satisfies all desirable characteristics is a challenging task. Therefore, it is common to use mixtures composed of various raw materials (basic materials, complementary materials, and additives) in variable proportions to achieve the desired physical, chemical, and biological properties (SCHAFER 2022). Substrates are usually made up of up to 60% basic materials (coconut fiber, pine bark, peat, etc.), which provide structure, and up to 40% complementary materials (vermiculite, perlite, carbonized rice husk, etc.), which improve water retention or drainage, increase porosity, and promote better root aggregation (SCHAFER et al. 2015). Finally, small amounts of additives may be used to control or improve the chemical and/or biological characteristics of the substrate (fertilizers, growth-promoting microorganisms, biocontrol agents, etc.) (SCHAFER 2022).

Most substrates used contain low concentrations of nutrients and are generally insufficient to meet the nutritional demand required for proper plant growth during the

nursery phase (NATALE et al. 2018, ALMEIDA et al. 2019, MENEGATTI & BIANCHI 2019), necessitating nutritional supplementation to promote vigorous plant formation and reduce the time required to obtain market-ready seedlings (MENEGATTI et al. 2020a). However, the adopted nutritional management must consider irrigation frequency and rate, as poorly managed irrigation may enhance nutrient depletion from substrates due to leaching (SOUZA et al. 2018).

Given the great socioeconomic importance of the seedling production sector, organizations such as the European Nurserystock Association (ENA) and AmericanHort were established to represent common interests of seedling producers and traders, as well as to define national and international production and marketing standards. Accordingly, since 1990, the ENA has defined a series of European technical and quality standards for nursery stock, which have undergone several updates, with the most recent version from 2010 (ENA 2010). Similarly, the American Standard for Nursery Stock (ANSI Z60.1) defines guidelines for the production, identification, and marketing of nursery stock in the United States, including specific sections on container-grown plants (AMERICANHORT 2014).

Prior knowledge of the nutritional and water demands, as well as the adaptability of fruit species to different substrates and containers, allows nurserymen to optimize the seedling production process. However, the development of standards for seedling production, identification, and commercialization in Brazil is essential to boost the nursery sector and enhance national fruit production through improved genetic, morphological, and sanitary quality of seedlings. Therefore, the aim of this literature review was to summarize and discuss the main information regarding the use and recommendation of substrates, container types, and fertilizers in the production of fruit seedlings in protected environments, aiming to assist in the production of seedlings with improved morphological and phytosanitary standards.

DEVELOPMENT

Advances in the use of substrates

The production of fruit seedlings in containers demands greater investments in infrastructure, inputs, and labor training when compared to the production of bare-root seedlings under open-field nursery conditions. However, production costs tend to be offset by higher labor productivity, greater seedling output per unit area, earlier development, morphological uniformity, and overall quality of seedlings, resulting in added value to the final product (SCHMITZ et al. 2014).

The containerized seedling production system is highly dependent on the use of substrates, whether commercial or mixtures prepared within the nursery itself. In this context, variations in chemical, physical, and biological attributes, in addition to water retention and drainage capacity, are common due to the organic and inorganic materials used in substrate composition (KIM et al. 2021).

The growth of the root system of plants cultivated in containers is considered the central element of performance, regardless of the production stage (propagation, production, and post-production) (JUDD et al. 2015). The substrate used must provide favorable nutritional and structural conditions for the initial development of the root system and the shoot (MENEGATTI & BIANCHI 2019), as well as adequate water

retention capacity and freedom from weeds, pests, and pathogens (GONZAGA et al. 2016, SOUZA et al. 2018).

Sphagnum peat moss has been used in horticulture as one of the main components of substrates, mainly because it is relatively resistant to decomposition and possesses excellent chemical, physical, and biological properties, in addition to high water retention and cation exchange capacity (BEAULIEU et al. 2022). Alternative materials with similar characteristics and more attractive costs have been adopted by nurserymen in order to reduce production costs, such as coconut fiber and ground pine bark, which have become important substrate components.

As a renewable material with physical characteristics similar to those of peat, coconut fiber has been used in combination with other substrates to increase water retention capacity and porosity in the final mix (KINGSTON et al. 2017). Pine bark has been widely used in substrate mixtures in nurseries in Mexico and the United States, mainly due to its high porosity, good drainage capacity, and low acquisition cost (STEWART et al. 2019, MADRID-AISPURO et al. 2020, SILVA et al. 2020).

Studies conducted on "biochars" have highlighted this material as a possible partial substitute in the formulation of substrates commonly used in containerized seedling production (such as peat, vermiculite, perlite, coconut fiber, pine bark, etc.), offering improvements in water retention and physical-chemical properties of the substrate, with positive effects on plant growth under certain conditions (NIETO et al. 2016, MÉNDEZ et al. 2017, HUANG & GU 2019). Biochar is a carbon-rich solid material obtained through the thermal decomposition of biomass under limited or no oxygen supply. According to HUANG & GU (2019), there are three main processes for producing biochar: pyrolysis, gasification, and hydrothermal carbonization, which directly influence the physical and chemical characteristics of the final product.

In addition to production conditions, the raw material also determines variations in the physicochemical properties of biochars. Among the raw materials used are rice husk (LOCKE et al. 2013), wheat straw (VAUGHN et al. 2013), conifer wood (DISPENZA et al. 2017), forest residues (FORNES & BELDA 2018), and sugarcane bagasse (WEBBER et al. 2018), among others. Incorporating biochar into the substrate can affect cation exchange capacity (CEC) and nutrient availability due to the inherent properties of the biochar itself (HUANG & GU 2019). Thus, some biochars can partially meet plant nutritional demands for certain nutrients, such as phosphorus (P) and potassium (K) (ALTLAND & LOCKE 2012, 2013; LOCKE et al. 2013). Furthermore, biochar use can increase substrate pH, as it often has a neutral to basic pH range (ZHANG et al. 2014, DISPENZA et al. 2017, DUNLOP et al. 2015). However, acidic biochars can also be found, since pH is influenced by both raw material and production temperature (HUANG & GU 2019).

The use of specific proportions of vermiculite and perlite as substrate components typically provides advantages to the nurseryman. In the case of vermiculite, noteworthy properties include high water retention capacity, cation exchange capacity that allows retention and release of mineral ions in the substrate solution, lightweight properties, and its role in substrate temperature regulation. The use of perlite improves drainage, facilitates the balance between air and water in the root zone, and supports root growth (KIM et al. 2021).

In general, substrates composed of multiple material mixtures have shown a greater capacity to meet the chemical and physical needs of plants. As such, substrates used for containerized fruit nursery tree production are typically composed of decomposed organic matter and peat (main components), mixed with vermiculite, carbonized rice husk, coconut fiber, and/or perlite (secondary components), among others (GASPARIN et al. 2014) (Figure 1).



Figure 1. Substrates used in the production of fruit seedlings in containers, namely: a) Carbonized rice husk; b) Medium-grade expanded vermiculite; c) *Sphagnum* peat moss; d) Black peat. Photos: Paulo Luiz Lanzetta Aguiar.

Currently, there is a wide range of commercial substrates available in the Brazilian market, with different compositions and nutrient levels depending on the availability of materials in each production region. Nurserymen have opted to use commercial substrates for large-scale fruit nursery tree production (MENEGATTI & BIANCHI 2019), mainly because they meet recommended structural standards, are free of pests and pathogens, and contain certain amounts of essential nutrients for plants. Nevertheless, nutritional supplementation remains a common practice among nurserymen, using both chemical fertilizers and organic materials available on farms (GASPARIN et al. 2014, SOUZA et al. 2018, MENEGATTI & BIANCHI 2019, GOMES et al. 2020, MENEGATTI et al. 2020a).

Advances in the development and use of containers

According to HAASE et al. (2021), seedling quality is primarily determined by the production system and cultivation techniques adopted during the nursery phase, which must meet the minimum standards for each species in terms of genetic, physiological, and morphological attributes. The quality of container-grown seedlings is also related to the type of container used. Currently, the market offers numerous models and brands of seedling containers, varying in volume, dimensions, shape, rigidity, raw material, the position and number of drainage holes, and the presence or absence of internal ridges. These features affect their arrangement in the nursery, irrigation management, and seedling growth (LANDIS et al. 2014).

Several decades ago, a variety of containers were used to produce vegetable, ornamental, forest, and fruit seedlings. In Brazil, for instance, the *xaxim* container, turned from the stem of the tree fern *Dicksonia sellowiana*, was widely used. However, due to overexploitation for gardening and floriculture purposes, *xaxim* has been included on the national list of endangered plant species. As a result, its extraction, processing, and commercialization are prohibited by law, in accordance with CONAMA Resolution No. 278, dated May 24th, 2001 (CONAMA 2001).

Additionally, several Brazilian states, such as Rio Grande do Sul, Minas Gerais, and São Paulo, have adopted their own measures to prohibit its processing and commercialization. As an alternative, Embrapa Agrobiologia developed the "Agroecological *Xaxim*," which is produced from the plant fiber of fast-growing species, such as pearl millet (*Pennisetum glaucum*), coated with a wax layer to provide rigidity and waterproofing to the container, thereby extending its useful life (LEAL 2013).

Widely used during the 1950s and 1960s for forest seedling production, especially for *Eucalyptus* species (AGUIAR 1973), the "*Torrão paulista*" consisted of an individual package made from a mixture, equal parts by volume, of red soil or clayey soil, sandy soil, and animal manure. Once homogenized, the mixture was moistened to the appropriate point and pressed in special machines capable of producing hexagonal blocks, generally measuring 6.5 cm in diameter and 13.0 cm in height when dry (GUIMARÃES et al. 1959). According to STURION (1981), in addition to the aforementioned containers, there are records of the use of unglazed clay pots, bamboo tubes, tar-paper tubes, wood laminates, and plastic materials.

Currently, a large number of nurseries still use flexible polyethylene containers (plastic bags, non-returnable and disposable), mainly because they are inexpensive, lightweight, foldable, and available in various sizes (Figure 2). However, in recent years these packages have been gradually replaced by rigid or semi-flexible polyethylene containers, which are more durable and can be reused by nurserymen, provided they are properly sanitized.



Figure 2. Flexible polyethylene bags of various sizes used for seedling production. Photos: Paulo Luiz Lanzetta Aguiar.

According to HAASE et al. (2021), the use of such containers allows for the production of higher-quality seedlings, especially regarding root system formation, due to the internal characteristics and design of the containers, which prevent root coiling. Despite some advantages of plastic bags for seedling production, their use may result in problems for the buyer. Because the surface of these containers is smooth, roots tend to grow in a spiral toward the bottom of the container, which can lead to root system deformation if planting in the field is delayed (CEDAMON et al. 2005, TAKOUTSING et al. 2014).

In addition to root coiling, a low production of secondary roots is often observed, resulting in a reduced overall root volume (DUMROESE & WENNY 1997). As a consequence, plant anchorage, as well as water and nutrient absorption capacity after transplanting, may be impaired, reducing the plant's tolerance to stress and potentially shortening its lifespan (HAASE et al. 2021). In an attempt to mitigate these issues, some manufacturers have offered copper-coated container options to reduce root deformation through chemical root pruning (DUMROESE & WENNY 1997, ALDRETE et al. 2002).

Plastic bags are frequently placed directly on the ground during the nursery period. As a result, roots may perforate the containers and penetrate the soil in search of more water and space for growth, which can lead to root damage or loss due to the need to remove the containers and prune the roots for transport and commercialization (HAASE et al. 2021). The combined effect of root system deformation, reduced root volume, and possible cutting of the taproot or damage to the root system during seedling handling in the nursery reduces the functional root area and causes imbalance between root and shoot systems.

Rigid or semi-flexible polyethylene containers are available on the market in different sizes, volumes, shapes, materials, and, naturally, prices (LANDIS et al. 2014) (Figure 3). The rigid inner surface typically includes ridges that direct root growth toward the bottom of the container, preventing spiraling and allowing the root system to form with adequate volume and architecture.

In addition, the bottom of these containers features holes that aid in excess water drainage and enable natural air pruning of roots, inhibiting root growth beyond the container. Although the acquisition cost of rigid containers is higher compared to plastic bags, they have greater longevity, can be sanitized, and reused for over 10 years, depending on the material and the number of nursery production cycles, while also providing better work efficiency, higher seedling quality, and superior post-nursery performance (HAASE et al. 2021), including faster growth and higher survival rates compared to seedlings produced in plastic bags (CEDAMON et al. 2005).

Plastic bags are frequently placed directly on the ground during the period in which the seedlings remain in the nursery, so that roots penetrate the containers and grow into the soil in search of more water and space for growth. This results in root damage or loss due to the need to remove the containers and prune the roots for transport and commercialization (HAASE et al. 2021). The combined effect of root system deformation, low root volume, and potential cutting of the taproot and damage to the root system during seedling handling in the nursery leads to a reduction in the functional root area and an imbalance between root and shoot systems.



Figure 3. Semi-flexible polyethylene containers of various sizes, volumes, and shapes used for seedling production. Photos: Paulo Luiz Lanzetta Aguiar.

The use of rigid or semi-flexible containers allows for the production of seedlings with more uniform growth, more vigorous root systems, and better shoot-to-root balance in a shorter period and with less substrate volume when compared to the use of plastic bags (ANNAPURNA et al. 2004), and especially to bare-root seedlings produced in the field (NICOLAO et al. 2023), provided that appropriate nutritional management is adopted.

Since both nursery time and container volume can be reduced, factors such as nursery infrastructure and labor can be optimized (HAASE et al. 2021), making it possible to reduce production costs. It is important to highlight that the adoption of seedling production systems based on the use of these containers and soil-free substrates requires more frequent irrigation to ensure proper plant water status, compared to seedlings produced in plastic bags with soil (HAASE et al. 2021) or even those produced under field conditions (NICOLAO et al. 2023). Daily monitoring of substrate moisture, alongside adjustments in nutritional management, irrigation schedule, time of year, and plant age, is essential to ensure the well-being and growth of seedlings in the nursery.

Regardless of the type of container used (flexible, semi-flexible, or rigid), once the seedlings are ready for planting, there is greater flexibility for field planting (HAASE et al. 2021) compared to bare-root seedlings produced in the field (SCHMITZ et al. 2014, NICOLAO et al. 2023). Even so, constant communication between nurserymen and buyers is important to avoid compromising production, commercialization, and planting schedules. It is essential that seedlings grown in containers be kept on benches or raised platforms in order to favor natural root pruning by air, facilitate

sanitary practices, improve worker ergonomics, extend the lifespan of containers, and prevent contamination by soil-borne pests and pathogens (EFROM & SOUZA 2018, FERMINO et al. 2021, HAASE et al. 2021).

In addition to these types of containers, during the nursery phase and until commercialization, flexible or rigid polyethylene multicellular trays and polystyrene multicellular trays can also be used for germination and early growth of fruit tree rootstocks, where the root system initially requires less space, thereby reducing substrate and nursery space requirements (EFROM & SOUZA 2018, MENEGATTI et al. 2020b). Many fruit and forest nurseries have adopted the use of rigid tubes, generally made of polyethylene in various sizes and shapes, with vertical internal ridges. In addition to traditional tubes, citropots are available on the market; these typically have greater volume capacity than tubes, may or may not include feet and stakes, and feature holes and internal ridges to aid substrate aeration and drainage, as well as root guidance (Figure 4).



Figure 4. Citropots with different shapes and features, made of rigid polyethylene, used for seedling production. Photos: Paulo Luiz Lanzetta Aguiar.

In general, the size and shape of the container to be used depend on the characteristics of the plants to be cultivated, the duration of the production period, whether grafting is required, and the standards demanded by the market for commercialization (EVANS et al. 2010). Due to their high durability and the possibility of manufacturing containers in various sizes, shapes, and colors, petroleum-based plastics (especially polyethylene) have become the preferred materials for producing seedling containers and for use in protected cultivation systems (FUENTES et al. 2021). However, due to environmental sustainability concerns, the production of plastic containers has undergone changes to meet the market demands of recent years, leading to an increase in the use of regionally sourced organic materials aimed at producing biodegradable containers or biocontainers (BARRET et al. 2016).

Biocontainers can be defined as containers made from renewable sources that degrade rapidly once planted in the field or that can be used in composting processes (EVANS et al. 2010). These containers may be classified as plantable, compostable, or recycled, depending on the raw materials used in their manufacturing, their physicochemical properties, and their degradation capacity after their useful life (EVANS et al. 2010, NAMBUTHIRI et al. 2015, HARRIS et al. 2020). Plantable biocontainers are designed to withstand irrigation and handling during the seedling production phase, while allowing the seedlings to be planted directly in the final location without the need to remove the container.

Their manufacturing characteristics permit the plant root system to perforate the container walls and continue to grow normally, reducing potential transplant shock, examples include CoirPots®, CowPots®, EllePots®, FertilPots®, JiffyPots®, among others. Compostable biocontainers, on the other hand, do not allow root growth through their walls, as they degrade at a slower rate; therefore, they must be removed before planting the seedlings in the field. Nevertheless, they can decompose rapidly when subjected to composting processes (MOONEY 2009).

Lastly, recycled containers are made from recycled PET bottles, which are blended with biodegradable natural fibers such as cotton, plant fibers, or bamboo. When pressed at high temperatures, this mixture binds to form a fabric-like material, which is then sewn into container shapes, as in the case of RootPouch® containers. These containers are not biodegradable or compostable, but they are capable of slowly disintegrating to a certain extent, leaving fewer residues in the environment compared to traditional plastic containers.

Advances in seedling nutrition in containers

The use of substrates in the production of fruit seedlings in containers is a widely adopted practice today, primarily because it provides a growing medium suitable for root system development and offers high water-use efficiency. The quality of substrates varies according to the proportions of organic and inorganic materials in their composition, which influence their capacity to retain water and nutrients (KIM et al. 2021).

Most of the substrates used have low nutrient concentrations, especially when high proportions of inert materials such as vermiculite and perlite are employed (NATALE et al. 2018, REHMAN et al. 2020). Thus, if fertilization is not properly supplemented to meet the nutritional requirements of the target species, especially in

woody fruit species, the substrate nutrients are rapidly depleted, and plant demand is unmet, compromising growth (ALMEIDA et al. 2019, MENEGATTI & BIANCHI 2019, MADRID-AISPURO et al. 2020).

Proper nutritional adjustment of substrates is essential for large-scale seedling production, mainly because it promotes the development of more vigorous, uniform, and healthy plants (NATALE et al. 2018, MENEGATTI & BIANCHI 2019). In the nursery, well-nourished seedlings are less susceptible to pests and diseases and more tolerant to environmental stresses. For fruit species propagated by grafting, rootstocks cultivated under adequate nutritional conditions grow more rapidly and become suitable for grafting in a shorter period, which can reduce nursery time and production costs (NATALE et al. 2018, MENEGATTI et al. 2019).

Although the importance of nutrition for the production and quality of rootstocks and fruit tree seedlings is widely recognized, fertilization practices adopted in nurseries are often defined empirically. In general, this is due to inconsistencies in the literature regarding fertilizer management (NATALE et al. 2018), and to the scarcity of scientific information capable of assisting nurserymen in assessing the nutritional status of plants during the nursery phase (SOUZA et al. 2015).

According to NATALE et al. (2018), many studies still rely on fertilization recommendations proposed by MALAVOLTA (1980) for greenhouse experiments using soil, which consist of 300 mg dm^{-3} of nitrogen, 200 mg dm^{-3} of phosphorus, 150 mg dm^{-3} of potassium, 75 mg dm^{-3} of calcium, 15 mg dm^{-3} of magnesium, 50 mg dm^{-3} of sulfur, 0.5 mg dm^{-3} of boron, 1.5 mg dm^{-3} of copper, 0.1 mg dm^{-3} of molybdenum, 5 mg dm^{-3} of zinc, and 5 mg dm^{-3} of iron. In addition, the splitting of nitrogen and potassium applications into two or three doses is recommended, with the first applied at planting and the others as top-dressings during plant growth.

Ideally, nutrient supply to seedlings throughout their development should occur at appropriate times and doses, taking into account nutritional balance, which is influenced by the type of substrate, species, and cultivar (NATALE et al. 2018). Thus, knowledge of nutrient uptake and accumulation rates is essential for nurserymen. The nutrient uptake rate is considered an appropriate reference parameter for providing nutrients in adequate doses to optimize plant development (NATALE et al. 2018). This knowledge can assist in determining the composition of the substrate to be used, as well as in planning fertilization practices during the seedling formation period.

The nutrient uptake rate represents the amount of nutrients absorbed and accumulated in plant tissues throughout growth, that is, the amount of nutrients required by the plant during its development (NATALE et al. 2018). On the other hand, the quantity of nutrients supplied to the plant must take into account the nutrient use efficiency for each element, which varies depending on cultivation conditions (ROZANE et al. 2013), especially as a function of the species, cultivar, and rootstock used (FRANCO et al. 2008, AMIRI et al. 2014, HROTKÓ et al. 2014, MENEGATTI et al. 2019, 2020b, 2022). Consequently, variations in leaf nutrient concentrations are common, as the rates of nutrient uptake and translocation vary due to the root system's selective absorption capacity, as well as differential nutrient allocation, which may occur depending on the genotype (HROTKÓ et al. 2014, SOUZA et al. 2019, MENEGATTI et al. 2019, 2020b, 2022).

The nutrient uptake rate varies throughout plant growth; however, its pattern is similar among several fruit species and generally follows three phases: 1) an initial phase of slow growth; 2) a phase of intensified growth and nutrient accumulation until the maximum uptake rate is reached, and; 3) growth stabilization (FREITAS et al. 2011, NATALE et al. 2018, MENEGATTI et al. 2019, 2020b, 2022). With knowledge of the nutritional demands of the cultivated species, it is possible to optimize fertilization management during the nursery phase, promoting the formation of vigorous seedlings while reducing operational and input-related costs.

Nutrient supply to seedlings in the nursery has been carried out in three main ways: 1) incorporation of mineral fertilizers into the substrate (Figure 5a, 5b, 5c, and 5d); 2) incorporation of controlled-release fertilizers (CRF) into the substrate (Figure 5e and 5f); and 3) fertigation of seedlings throughout their time in the nursery (MADRID-AISPURO et al. 2020, SILVA et al. 2020). Organic fertilizers can also be used, but they generally do not fully meet the nutritional demand of the seedlings (OKUMURA et al. 2008, MACHADO et al. 2011), which require nutritional supplementation after a certain growth period.



Figure 5. Examples of mineral and controlled-release fertilizers: a) urea; b) potassium chloride; c) commercial 5-20-20 (N-P-K) fertilizer; d) triple superphosphate; e) controlled-release fertilizer – 6 months; f) controlled-release fertilizer – 9 months. Photos: Paulo Luiz Lanzetta Aguiar.

The incorporation of mineral fertilizers into the cultivation substrate is a common practice in the fruit nursery tree production sector (GOMES et al. 2020). These fertilizers supply nutrients to plants immediately after application and can be rapidly absorbed by the root system. However, nutrient losses due to volatilization and leaching are greater with mineral fertilizers compared to other fertilization methods,

such as the incorporation of CRF into the substrate or fertigation (MENEGATTI & BIANCHI 2019).

Since the production period for grafted fruit tree seedlings is relatively long, substrate fertilization should preferably be carried out in split applications (GOMES et al. 2020) in order to reduce nutrient losses and ensure nutrient availability throughout plant growth. Although effective, this practice requires more time and labor, which increases production costs, especially in nurseries that do not have automatic fertigation systems (ALMEIDA et al. 2019, MENEGATTI & BIANCHI 2019).

In recent years, there has been a significant increase in the use of CRFs incorporated into substrates. This practice has proven highly advantageous, particularly because it helps reduce operational costs and optimize fertilization in container-grown fruit seedlings (AZEEM et al. 2014, ALMEIDA et al. 2019, MENEGATTI & BIANCHI 2019, GOMES et al. 2020, MENEGATTI et al. 2020a, SMIDERLE et al. 2022).

Controlled-release fertilizers are composed of granules containing a blend of nutrients (macronutrients or macro + micronutrients), coated with semipermeable polymers that promote gradual nutrient release into the growing medium, making them available throughout the seedling growth period (AZEEM et al. 2014, WANG et al. 2016, ALMEIDA et al. 2019, MENEGATTI & BIANCHI 2019, MENEGATTI et al. 2020a). This allows for the formation of vigorous seedlings in a shorter time frame (SMIDERLE et al. 2022), while also reducing the likelihood of nutritional deficiencies and minimizing fertilizer waste (ADAMS et al. 2013, ALMEIDA et al. 2019, GOMES et al. 2020, MADRID-AISPURO et al. 2020).

Currently, the Brazilian market offers a variety of CRFs. These fertilizers differ in nutrient composition and concentration, as well as in the time required for complete nutrient release (ranging from 2 to 15 months), which is mainly influenced by the composition and thickness of the semipermeable polymer coating the fertilizer granules, in addition to substrate temperature and moisture (ADAMS et al. 2013, ALMEIDA et al. 2019, MADRID-AISPURO et al. 2020).

The main objective of CRFs has not yet been fully achieved (ADAMS et al. 2013), as the ideal scenario would involve a constant nutrient release rate that matches plant demand, regardless of environmental conditions (WANG et al. 2016). Nevertheless, their efficiency in fruit nursery tree production has been well demonstrated, showing that fertilizer demand varies according to species, cultivar, plant age, and cultivation conditions. These parameters must be considered because, although CRFs are easy to apply, help reduce nutrient leaching, and provide adequate nutrition during the seedling phase, they have a significantly higher cost compared to conventional mineral fertilizers (MACHADO et al. 2011, ALMEIDA et al. 2019, MENEGATTI & BIANCHI 2019). The use of CRFs in nursery tree production is practical and effective for meeting initial nutritional demands; however, it is more expensive than other nutrient management practices, such as fertigation (SILVA et al. 2020).

Fertigation, in turn, is a technique that involves the simultaneous application of a fertilizer solution together with irrigation water, usually delivered via micro-sprinklers or drip irrigation systems (KADYAMPAKENI et al. 2015). This method is generally considered efficient in terms of both nutrient and water management throughout the

seedling production period, which can result in economic advantages (SOUZA et al. 2018, SILVA et al. 2020). Compared to other fertilization strategies, fertigation stands out by allowing greater efficiency in managing the supply of water and nutrients to plants, enhancing nutrient absorption at adequate levels during plant development, improving water use efficiency and nutrient residence time in the root zone, and reducing NO_3^- leaching when managed correctly (KADYAMPAKENI et al. 2015).

Additionally, fertigation helps reduce nursery operational costs, since fertilization can be incorporated into the routine irrigation schedule. However, some disadvantages hinder its broader adoption when compared to CRFs. These include the need for proper infrastructure and equipment to ensure uniform fertilizer distribution to the seedlings, the requirement for high-quality water and an efficient filtration system, the high cost of soluble fertilizers (some of which are regulated by the military and/or federal police), and the potential for clogging of the irrigation system caused by these products (KADYAMPAKENI et al. 2015, SILVA et al. 2020).

The use of CRFs and fertigation with nutrient solutions are both recommended technologies for the production of fruit seedlings in containers, with proven efficiency for various crops. However, studies comparing the efficiency and cost-benefit of these practices in fruit nursery tree production are still scarce in Brazil. In this context, SILVA et al. (2020) evaluated the efficiency and cost-effectiveness of different fertilization strategies for the production of yellow passion fruit (*Passiflora edulis*) seedlings.

The authors tested six treatments: a) control (no fertilization); b) standard fertilization [Ammonium sulfate (3 g L^{-1} of substrate) + Potassium chloride (2 g L^{-1} of substrate) + Magnesium thermophosphate (2 g L^{-1} of substrate) + Osmocote® Plus 15-09-12 (6 g L^{-1} of substrate) + Osmocote® Mini-Prill 19-06-10 (6 g L^{-1} of substrate)]; c) Osmocote® Plus 15-09-12 (6 g L^{-1} of substrate); d) Osmocote® Mini-Prill 19-06-10 (6 g L^{-1} of substrate); e) complete fertigation [Calcium nitrate (0.8 g L^{-1}) + Potassium nitrate (0.5 g L^{-1}) + Magnesium sulfate (0.35 g L^{-1}) + Monoammonium phosphate (0.1 g L^{-1}) + ConMicros® Standard (0.025 g L^{-1})]; f) fertigation with macronutrients [Calcium nitrate (0.8 g L^{-1}) + Potassium nitrate (0.5 g L^{-1}) + Magnesium sulfate (0.35 g L^{-1}) + Monoammonium phosphate (0.1 g L^{-1})]. It was found that the greatest biomass increase in seedlings occurred with Osmocote® Mini-Prill 19-06-10, which was 25% higher than that of fertigated seedlings, but at a cost three times higher than fertigation. Moreover, seedling growth was lower with both the standard fertilization and Osmocote® Plus 15-09-12, which were, respectively, 7 and 3 times more expensive than fertigation with macronutrients.

Since the morphological characteristics and Dickson Quality Index values were similar among fertigated seedlings, those fertilized with Osmocote®, and those subjected to standard fertilization, the authors emphasized that the cost-benefit of the chosen nutritional management strategy must be taken into account. Therefore, factors such as experience with fertigation, availability of trained labor, acquisition of specific equipment and inputs must all be considered when selecting the fertilization system to be adopted (ALMEIDA et al. 2019).

Regardless of the fertilization strategy used in the nursery, nutritional deficiencies or toxicities, resulting from the lack or excess of specific nutrients, may occur during the nursery phase. The nutritional status of plants can be monitored through periodic

leaf analysis, enabling nurserymen to make timely corrections based on foliar diagnosis. The diagnosis of the plant's nutritional status is performed by comparing nutrient concentrations in sampled tissues with reference values previously obtained from calibration experiments, typically conducted in greenhouses under controlled environmental and nutritional conditions (NATALE et al. 2018). Thus, foliar diagnosis has been considered the most reliable method for assessing plant nutritional status (ARROBAS et al. 2014).

However, even though foliar diagnosis is a proven tool for nutritional assessment in orchards, the technique remains underutilized by growers and nurserymen due to the lack of information regarding adequate nutritional standards for different plant growth stages, as well as the correct timing and method of leaf sampling for most fruit species (NATALE et al. 2018). Nutrient levels in plant tissues vary according to species (GALVEZ-SOLA et al. 2015), rootstock (AMIRI et al. 2014, HROTKÓ et al. 2014), scion cultivar, sampling time (CARVALHO et al. 2011, AMIRI et al. 2014, ARROBAS et al. 2014), leaf age, plant organ analyzed (ARROBAS et al. 2014), among other factors. Therefore, to obtain reliable nutritional diagnoses, it is essential that the sampled plant material, type and age of leaves, and sampling period be similar to those used to establish reference values for the species, rootstock, and/or cultivar of interest (NATALE et al. 2018).

CONCLUSION

The use of appropriate substrates is essential for the production of high-quality containerized fruit seedlings. The chemical and physical properties of the growing medium are affected by its composition; therefore, it is important to understand these properties to provide conditions that meet the specific requirements of each species or cultivar, particularly during the nursery phase. The development of technologies for containerized seedling production, such as protected nursery systems, substrates, containers, automated misting and fertigation systems, has contributed to improving seedling quality and labor efficiency.

Some fruit production chains have recognized and valued the efforts of research, education, and extension, which has encouraged knowledge exchange, resource mobilization, and continuity of research aimed at overcoming current challenges.

Proper nutritional management favors the production of seedlings with superior quality standards (healthy and uniform) enhancing their resistance to pests, diseases, and environmental stress. Therefore, it is crucial that nutrient supply occurs in adequate amounts and at appropriate times, considering the variation in nutrient uptake rates throughout plant growth (i.e., phases of slow growth, intensification, and stabilization). Understanding these demands enables more efficient fertilization management during the nursery period, resulting in higher quality seedlings, reduced costs, and decreased input losses to the environment.

The development of plant substrates from recyclable materials is a critical initiative in the current global context, where environmental sustainability and economic efficiency are top priorities. Using recyclable materials would not only reduce production costs, making substrates more accessible, but also alleviate environmental impact by reusing existing resources. The reuse of organic waste and recyclable

materials would reduce waste generation and minimize the environmental burden associated with conventional substrate production.

Furthermore, employing such materials promotes the circular economy by closing product life cycles and generating economic benefits for nurserymen, fruit growers, and consumers. Lastly, along with advances in nutritional management, investment in research and development in this area is vital to create more efficient substrates that meet the needs of plants, producers, and the environment.

NOTES

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, and formal analysis, JAP, MPM, NAM and VJB; investigation, JAP; writing-original draft preparation, JAP; writing-review and editing, MPM, NAM and VJB; supervision, NAM and VJB. All authors have read and agreed to the published version of the manuscript.

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INFORMED CONSENT STATEMENT

Not applicable because this study did not involve humans.

DATA AVAILABILITY STATEMENT

The data can be made available under request.

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CONFLICTS OF INTEREST

The authors declare no competing interests.

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