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REVIEW ARTICLE

Physical and chemical characteristics and analysis of plant substrate

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Abstract

Cultivation in protected environments and containers culminated in the need of the use substrates with specific chemical and physical characteristics; assuming that a fundamental role in cultivation of horticultural plants. In this way, the objective was to describe the main physical and chemical characteristics of substrates, as well as the main methodologies for analysis. As physical characteristics we can refer as examples: density on a wet and dry basis, total porosity, air space and water retention (easily available, buffering capacity and remaining water). The most important chemical characteristics in substrates include pH, electrical conductivity and available nutrient content. These characteristics are responsible for all the nutritional dynamics and the availability of water and air in the culture medium, so they must be known, tested and managed during cultivation. Thus, it is possible to establish parameters for plant cultivation in containers, being also possible to correlate its influence on plant development for scientific research.
Keywords: container production, greenhouse cultivation, growing media, plant substrate, soilless culture.

Resumo

Características fisico-químicas e análise de substrato para plantas

O cultivo em ambiente protegido e recipiente culminou com a necessidade da utilização de substratos com características fisico-químicas específicas; assumindo um papel fundamental no cultivo de plantas hortícolas. Assim, o objetivo foi descrever as principais característica fisico-químicas de substratos e as principais metodologias para a sua análise. Quanto às características físicas, podendo-se referir a densidade em base úmida e seca, porosidade total, espaço aeração e retenção de água (água facilmente disponível, água tamponante e água remanescente). As características químicas mais importantes em substratos incluem pH, condutividade elétrica e teor de nutrientes disponíveis. Estas características são responsáveis por toda a dinâmica nutricional e de disponibilidade de água e ar no meio de cultivo, desta forma devem ser conhecidas, testadas e manejadas durante o cultivo. Assim é possível estabelecer parâmetros para o cultivo de plantas em recipientes e também correlacionar sua influência no desenvolvimento das plantas na pesquisa científica.
Palavras-chave: ambiente protegido, cultivo em recipientes, cultivo sem solo, meio de cultivo, substrato para plantas.

Introduction

Over the years, the increasing of the human population combined with the climate change has intensified the process of searching for more sustainable food production systems, especially when using non-renewable resources, such as water (Rosa-Rodriguez, 2020). This process resulted in an increase in the cultivated areas under a protected environment, since it has advantages, such as better control of climatic conditions, resulting in plants with superior development (Raviv and Lieth, 2008) when compared to open field conditions for cultivations.

Associated with the use of protected environments is the cultivation in containers and, consequently, in substrates (Raviv, 2017). There are several concepts of substrates for plants, developed by different authors, as mentioned by Fonteno (1996) who considers that any material placed in a container becomes a substrate for plants, or Kämpf (2005), who affirms that "growing media" are the environment where the roots of plants grow in soilless culture. Vence (2008), in his bibliographic review, brings together several concepts and summarizes them as: "substrate for plants can be conceptualized as any porous material, used pure or in mixture, which, when placed in a container, provides anchorage and sufficient water besides oxygen levels for optimal plant development". In Brazil, the term was proposed less than 20 years ago, being officially recognized by the Ministry of Agriculture in 2004, referring to it as: "product used as mean of growing a plant".

The appropriate conditions for the correct development of plants in containers are different from those observed in the open field, mainly due to the space restriction for root

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development, gas exchange and water dynamics in these containers. The main functions of a plant substrate are to provide support for roots, retain and make water available, have air space even in a state of water saturation, have structural stability, adsorption capacity, buffering capacity against pH changes, predictable nutrient dynamics and electrical conductivity, present behavior similar to the same management, few biological activity, absence of diseases and substances that can reduce or damage the development of plants, good rehydration capacity after drying and that allow storage.

The main properties of substrates refer to physical, chemical and biological characteristics, and among these, the physical and chemical characteristics play an important role (Schafer et al., 2015). As the physical characteristics go, which are considered the most important because of their inability to be changed after the crop is established, we can mention the density on a wet and dry basis, the total porosity, the aeration space and the water retention at low tensions of moisture. The most important chemical characteristics in the substrates include pH value, electrical conductivity and/or total content of soluble salts and levels of available nutrients.

The correct choice and management of the substrate is important for the success of a cropping system. We mustn't forget that this success depends on the interaction between factors, thus, in substrates, this is related to the interaction between the substrate, the recipients and the specific characteristics of each species/cultivar, which will determinate the management that will be adopted. It is difficult to find a plant substrate with raw materials fulfilling all the desirable characteristics, so it is common to use mixtures (basic materials, complements and additives), in variable proportions, in order to achieve the desirable physical, chemical and biological properties (Schafer, 2022). The main materials used in substrates, as basic and or in complements in world is the peat, coconut coir, wood fiber, bark, vermiculite, perlite and expanded clay. In Brazil, mostly due to regional availability, the main material used are coconut fiber, composted pine and eucalyptus bark, peat, carbonized rice husk, vermiculite, perlite and expanded clay. In some seedling production systems, such as the maintenance of clonal gardens, sand is used alone or in mixtures on a smaller scale. In low tech production systems, soil is also used, mainly due to its availability and easy acquisition, however it is not recommended because it negatively modifies the characteristics of a substrate and it is a potential inoculator of pathogens and invasive plants in the cultivation system (Avrella et al., 2021). There are also studies using regional materials such as pine needles (Ceccagno et al., 2019), residues of Brazil nut shell, acerola pit, assai pit and cupuassu peel (Araujo et al., 2020), babassu fiber (Nascimento et al., 2018) and coffee parchment biochar (Carnier, 2021).

The use of substrate for plants occurs in several areas of agricultural production. Ornamental horticulture is the third area that most consumes this input, being surpassed by horticulture and production of tree seedlings. It is used for seedling production (propagation), potted flowers and foliage crops and annual and perennial plants and, in less quantity, in the production of garden plants and cut flowers.

There are no official estimates of the use of substrate for plants in Brazil, but according to the Brazilian Association of Technology Industries in Vegetal Nutrition (Abisolo), which brings together the main companies of the sector, in 2020, sales of substrates for plants nationwide had a volume of 605 thousand cubic meters (Abisolo, 2021). If we count the volume of substrate produced for our own consumption and for companies that are not connected to Abisolo, we can reach two or three times this value.

Given the importance of this topic for plant cultivation using containers, the objective of this literature review is to present the main physical and chemical characteristics of substrates for plants and how their analysis can be carried out.

Physical characteristics of plants substrates

Due to the use of containers, there is a confinement of the rooting system and this, in comparison with the production in the soil, becomes denser in order to satisfy the relationship with the aerial part, thus presenting a greater demand for oxygen. Likewise, water must be available at low tensions, establishing one of the most important functions of a substrate, which is to provide a sufficient amount of water and air. At this point, the physical characteristics most commonly evaluated in the substrates and which directly influence the development of plants are mainly based on the density and water retention curve, which seeks an approximation of the water and air availability for the plants development in a certain substrate.

Density, which expresses the relationship between the mass and volume of the substrate, presents significant importance, as it allows the conversion of moisture values into a volume basis. When working with density, we can relate it in three different ways, that is, the main one as the wet or current density, dry density and the packing density. Wet or current density is the ratio of mass to volume based on the moisture present in the substrate at the time the analysis was done. Dry density is the mass to volume ratio minus any moisture present. The packing density is the relation between the mass and the volume actually observed in the container at a given moment and can be influenced by the filling of the container and the cultural treatments. High-density substrates can limit plant growth and make it difficult to transport containers. Therefore, for each size of container a recommendation has been established regarding the most suitable density. Thus, cells and trays from 100 to 300 kg m^{-3}, for pots up to 0.15 m height, from 200 to 400 kg m^{-3}, for pots from 0.20 to 0.30 m height, densities from 300 to 500 kg m^{-3} and for larger pots up to 800 kg m^{-3}, considering the density on a dry basis (Kämpf, 2005).

The substrate density can be modified depending on the different managements applied to it. Consequently, all other physical properties of the substrate can also be changed, for example, the pressure applied when filling the containers, since when the substrate is compressed, there is an increase in the proportion of micropores, thus reducing the aeration space and increasing water retention.

The other characteristics refer to the porosity of the substrate, thus determining its retention of air and water. These refer to total porosity, aeration space, easily available water, buffering water and remaining water. Total porosity (TP) is the difference between the total volume and the volume occupied by solids in a sample, which can be filled by air and water. As for the size of the pores, these are classified as macro and micropores. In saturation condition, the macropores are filled with air and their volume is called aeration space, while the micropores are occupied by water, and their volume corresponds to the water retention capacity. The ideal range for TP is from 75% to 90% (Kämpf, 2005), whereas for De Boodt and Verdonck (1972), the ideal TP for horticultural substrates is 85%. In this way, it can be noted that the substrates, in general, have greater porosity compared to the soil, since most of the materials used have internal pores in addition to the external ones, formed between the particles, with a higher percentage of larger pores.

The aeration space (AS) is the volume of air present in the substrate after natural water drainage. According to De Boodt and Verdonck (1972) the adequate AS is 20% to 30%, while Penningsfeld (1978) classifies an ideal aeration space between 30% to 40%. In the laboratory, it can be determined by submitting the sample to the suction of a tension of 10 hPa.

The substrate can provide a volume of water in different tensions for the plants. The available water (AW - volume of water released between 10 hPa and 100 hPa of tension), is the one available in the medium for the plant development. It can be divided into easily available water (EAW - volume of water released between 10 hPa and 50 hPa of tension) and buffering water (BW - volume of water released between 50 hPa and 100 hPa tension). Remaining water (RW - volume of water that remains in the substrate after a tension of 100 hPa is applied) is the volume that is not available for the plant to absorb. According to Schmitz (2002), the ideal range for EAW is 20% to 30%, BW is 4% to 10% and RW is 25% to 30%.

In the literature, it is common for authors to report "*ideal*" values referring to the air and water retention curve in a substrate. As previously reported, and making a compilation of this information, the following parameters can be used for interpretation: TP of 80%-90%, AS of 20%-30%, EAW of 20%-30%, BW of 4%-5% and RW of 20%-30% (De Boodt and Verdonck, 1972; Penningsfeld, 1978; Kämpf, 2005; Schafer et al., 2015). However, these values should serve as a basis for the production of substrates and, as mentioned in the introduction, we must consider the specificities of each plant. As an example, we can cite Kämpf (2005), who reports that for ornamental plants we can use AS of 2%-5% (eg, Ivy), 5%-10% (eg, Lily), 10%-20% (eg, Begonia) and 20%-30% (eg, Rhododendron).

Monteiro et al., (2020) while studying the production of seedlings of lettuce (*Lactuca sativa* L.) and black wattle (*Acacia decurrens* Wild), in different substrates, reinforces the necessity for a study regarding each species and/or variety, given that the results obtained in his studies were different for each plant. In addition, the generic "*ideal*" values for the physical and chemical characteristics of substrates are questioned. In another work, Monteiro et al. (2021) even proposes recommended ranges for physical-hydraulic and chemical parameters for the cultivation of black wattle (*Acacia mearnsii*) grown in substrates.

Chemical properties

The most used chemical properties for evaluating the quality of growing media are potential of hydrogen (pH), electrical conductivity (EC) or total soluble salts (TSS) - as forms of measuring salinity -, and cation exchange capacity (CEC). In addition to these properties, it is possible to find articles and recommendations about nutrient specific concentrations, which is basically determined by the amount of certain nutrients in the growing media.

Potential of hydrogen (pH)

The potential of hydrogen (pH) is the most relevant chemical propriety, since it directly interferes on the availability of nutrients in the growing media (GM), especially micronutrients (Savvas and Gruda, 2018). The pH value is defined as the activity of the hydrogen ion, which is expressed by the negative logarithm of the concentration of this ion. This propriety determines the relative acidity or alkalinity of a material. If the pH is in the range of 5.0 to 6.0, most of the nutrients will be easily assimilated by the plant, but the sensibility to an acid or alkaline environmental is going to varies according to the plant species. When it comes to growing media, pH values between 5.5 and 6.5 (pH in H_2O) are considered optimal (Fermino, 2014). For organic materials, values between 5.2 and 5.5 are the most indicated (Kämpf, 2005).

The buffering capacity of each material that are constituents of the growing media will influence the final pH value. Therefore, when using different materials in the mixture of GM, there are, as a consequence, variations in pH. More acidic GM (pH < 5.0) tend to have an increase in Al and Mn concentrations to toxic levels for plants, as well as causing damage to root membranes (Silber and Bar-tal, 2008; Fermino, 2014). Also, the deficiency of nutrients such as N, P, K and Mg can be observed (Kennard et al., 2020).

In cases where pH values are considered high (pH > 6.5), it might have a predisposition of problems with the availability of P, since in an alkaline medium there is a change in the proportions of $H_2PO_4^-$ and HPO_4^{2-}, then with the HPO_4^2 in higher concentration, which is less available to plants (Silber and Bar-tal, 2008). In addition to this, micronutrients such as Fe, Mn, Zn and Cu may also be unavailable (Kämpf, 2005). In a study performed by Chrysargyris et al. (2019), while evaluating GM with mixtures of peat, perlite and paper waste, the authors observed that as pH increased (from 4.5 to 5.6), the availability of Ca, Fe, Zn and Cu also increased. raised. However, when the pH reached values above 6.3, the availability of P, Fe, Zn and Cu was reduced, resulting in a lower performance of *Calendula officinalis* L., *Petunia×hybrida* L. and *Matthiola incana* L. Thus, depending on the type of cultivation and the materials used as GM, the pH will need a correction, either to raise or lower it. Such management can be carried out through inputs such as limestone and basic fertilizers (carbonates) for GM with acidic pH or elemental sulfur and acid fertilizers (phosphoric acid or nitric acid) for GM with alkaline pH.

During three years, a survey analyzing GM chemical properties was carried out by Schäfer et al. (2015) at the Laboratory of Substrates for Plants of the Department of Horticulture and Silviculture of the Faculty of Agronomy at Universidade Federal do Rio Grande do Sul (UFRGS). The results showed that there was a greater tendency of the use of substrates with pH values over the recommended in the literature, with an average of 6.2. If the range of values described by Cavins et al. (2000) is adopted, indicating that values between 5 and 6.5 are recommended, only 10.4% of the samples had an acidic pH. Likewise, adopting the range established by Kämpf (2005), 18.6% of the samples presented a pH considered low. However, when adding up all samples with pH > 6.5 (Cavins et al., 2000), a value of 45.7% of samples with high pH was founded. When using the parameters mentioned by Kämpf (2005), the authors found that 66.4% of the samples with pH above the recommended. These results showed that there is a tendency among the producers in using GW with high pH values, above the ranges established in the literature, especially when using materials such as organic compounds, known for having a high pH (Massa et al., 2018).

This data reveals the problem of lowering pH of GM when presenting high values. In these cases, management is more expensive and difficult, in comparison with reduced pH values (Schäfer et al., 2015). As pointed out by Boaro et al. (2014), although there is knowledge on this subject, the methods used are still incipient, requiring more research, regarding elemental sulfur, for instance.

Elemental sulfur is a reducing agent, whose oxidation by microorganisms generates sulfuric acid and, later, the release of hydrogen ions in the solution, producing an acidifying effect (Heydarnezhad et al., 2012). In 2004, Roig et al. tested the addition of 0.5% of elemental sulfur in an organic compound (olive mill residues and sheep litter) with 40% moisture. Sulfur was able to reduce the pH from 8.8 to 7.5 in two weeks, without an exacerbated increase in electrical conductivity, which tends to be common due to the increase of H_2SO_4 caused by S oxidation. Thus, elemental sulfur could be used as an alternative to lower pH by adding it directly in the composting process, including on an industrial scale, without affecting the final product.

Particularly, for GM, satisfactory lowering pH results were reported from the addition of 0.5 g L^{-1} of sulfur to the mixture of coconut fiber + expanded clay (1:2, volume), without affecting the EC (Kämp et al., 2009). Using a GM based on composted eucalyptus bark, with a pH of 7.8, the dose of 16 g L^{-1} of elemental sulfur was able to decrease the pH to 5.42, after 80 days, but it significantly increased the EC (Boaro et al., 2014). Reactions like these indicate that there is variation in the dose of how much elemental sulfur is required, which depends on the material used as GM. Although more studies are required, especially for specific materials, the use of this agent is promising, since it is able, in certain cases, to solve the problem of high pH in organic residues used as substrate. However, in the absence of sulfur, utilizing residues with a high pH value tends to be common, and its consequences will be addressed in the following topic.

The increase in pH caused by organic composts may be related to a greater mineralization of organic matter, with consequent production of OH^- ions, as well as the introduction of basic cations (K^+, Ca_2^+ and Mg_2^+). Sousa et al. (2021) studying the use of salvinia-based organic compost for the production of *Trema micrantha* L., seedlings corroborate this data.

However, the influence of high pH levels varies according to the crop and for how long it is exposure to the alkaline GM. This fact can be observed in studies in which treatments with superior performance have pH higher than the values recommended by the literature. These effects are mainly noticed in GM designed for organic systems, since the use of organic compounds is usual, because its nutrient content, like for the production of vegetable seedlings (Lerner et al., 2021), in which it is not possible to use water-soluble fertilizers (Brazil, 2021).

Other materials, despite their high pH, are also commonly used as GM, such as carbonized rice husk (CRH). This is a well-established material for use as a substrate, mainly in the South region of Brazil, due to its physical properties (Kaushal and Kumari, 2020). For the production of lettuce seedlings in organic system, mixtures containing earthworm humus (EWH) and CRH in the proportions of 60% EWH + 40% CRH and 80% EWH + 20% CRH can be used, obtaining satisfactory results, despite the pH value of 7.1 obtained in both treatments (Watthier et al., 2019). In a conventional production system, a significant linear increase ($R^2 = 0.95$) of pH was identified as increasing proportions of CRH (0 to 100%) were added to commercial GM, with the pH ranging from 5.8 to 6.8, respectively. In this case, increasing participation of CRH in the substrate mixtures harmed the development of the seedlings, affecting their quality (Freitas et al., 2013). Therefore, is indicated the participation of 50% or less of CRH in mixtures.

The diversity of materials available and their respective pH values implies on a high complexity on management these inputs, so it is extremely important to know and choose the GM with adequate pH for use in association with the desired crop. When it comes to the cultivation of ornamental plants in pots, the appropriate pH value enhances the increase in buds formation, as well as promotes the synthesis of plant pigments. The cultivar 'KORcrisett' of *Rosa×hybrida* when cultivated in three GM with different pH values (3.3, 4.7 and 7.3), suffered a reduction on its flower production in the acidic pH (3.3) and in the alkaline pH (7.3). It reached its higher production (13.5 flowers $plant^{-1}$) in the pH of 4.7. However, the content of phenolic compounds was lower in this treatment (pH of 4.7). On the other hand, plants grown in acidic or alkaline GM developed fewer flowers, but contained significantly more phenolic compounds, which are essential for the higher quality and coloration of flower buds (Schmitzer and Stampar, 2010).

Salinity - Electrical Conductivity (EC)

The soluble salt contents of a GM can be measured by the total soluble solids (TSS) or electrical conductivity (EC). Throughout these measurements the amount of dissolved ions (salts) present in the medium is expressed. Nowadays, the EC is the most used form worldwide. The knowledge that when dissolved in water, ions conduct electric current in the direct proportion to their concentration, with the exception of urea, so, in this way the EC can estimate the content of soluble salts present in a GM (Fermino, 2014).

It should be noted that materials with organic origins, like animal manure, when in a GM, have to be done with precaution due to their high concentration of salts. Given this, Schäfer et al. (2015) recommend the use of these organic materials in small proportions, since in the analysis performed, the highest EC values were obtained in samples of GM that contained poultry litter, animal manure and domestic compounds.

As for EC, a GM analysis, using the 1:5 - v:v extraction method, presented values between 0.36 and 0.65 mS cm^{-1} are considered normal, being within the standards for most of the crops (Cavins et al., 2000). It is also worth noting that the tolerance limit value, indicated by the authors for ornamental plants with high demand for fertilization, is 0.65 mS cm^{-1}. Therefore, it is necessary to know and monitor the EC of the medium to provide an adequate and balanced management of crops, since salinity can significantly affect their productivity.

A low EC value symbolizes a reduction of ions in the GM, which can imply a shortage of nutrients (Savvas and Gruda, 2018), indicating the need to add salts through nutrient solutions. Thus, a common practice used to increase the EC of a GM is to raise salts concentrations supplied in the fertigation.

On the other hand, when diagnosed an EC value above the recommended, solutions to its reduction must be done quickly, since high levels of salts can harm crops productions. Salt stress inhibits plant growth and development as it triggers ionic toxicity and osmotic stress. Therefore, the plant will have more difficulty in absorbing water, requiring more energy for this activity, resulting in a decrease in crop yield (Dias et al., 2019). In extreme cases, all production can be lost.

Some possibilities to overcome high EC of substrates are: reducing salts concentrations on nutrient solution, interrupting the fertigation for a few days or promoting leaching of the GM, with the application of a higher amount of water, the latter being generally the most suitable. However, this practice may prove to be inadequate, as it can lead to an increase in pH and nutritional imbalance in the GM (Savvas and Gruda, 2018), so it must be carefully done. Thus, it is recommended to constantly monitor chemical properties such as pH and EC to know and control their changes.

Schäfer et al. (2015) carried out a survey regarding the physical and chemical properties of substrates that were sent for analyzes at UFRGS. In this study, when analyzing EC, the researchers found that 56.4% of the samples showed values up to 0.65 mS cm^{-1}, which is considered, according to the classification by Cavins et al. (2000), with a 1:5 (v/v) methodology, as the limit value of EC for a GM to be considered normal. Approximately 110 samples were within the ideal range (considered normal), that is 0.36 to 0.65 mS cm^{-1} (Cavins et al., 2000), corresponding to only 23% of the samples. A high percentage (43.6%) of samples presented results with EC values above 1.1 mS cm^{-1}. These materials, with high EC, can be used, but in a restrictive way and they will probably need to have it salts leached. However, the recommendation is that they be avoided in stages such as sowing, rooting and establishment of crops (Schäfer et al., 2015), since these initial stages demand lower salts concentrations.

Regarding materials, seeking alternatives to the use of peat as a substrate for the production of ornamental plants in pots Fascella et al. (2018) analyzed the behavior of *Rosa rugosa* plants in GM with the addition of conifer wood biochar. Four substrate mixtures (v/v) were tested, being 100% peat (P), 75% P + 25% biochar (B), 50% P + 50% B and 25% P and 75% B. of the participation of biochar in the formulations, the authors observed an increase in electrical conductivity, with the highest values reached in the P25–BC75 treatment. The EC values obtained ranged from 2.1 to 14.6 dS m^{-1} (1:5, v/v).

Among the obtained results analyzing the EC of the GM, all exceeded the acceptable limit of 0.5 dS m^{-1} (1:5, v/v) for the medium to be considered ideal for cultivation in pots (Abad et al., 2001). These higher EC values may be related to the higher concentrations of potassium and sodium found in these GM. The substrates with the highest EC had the worst results in all variables analyzed, such as shoot height, number of leaves, leaf area, number of flowers, root length, fresh mass of shoot and root, which may be related the high salinity of these GM.

Finally, it is relevant to mention the potential of the *Pinus* sp. needle for use as a substrate conditioner for the production of citrus seedlings. Ceccagno et al. (2019) developed studies analyzing the mixture of this material with a commercial substrate and observed that it shows variation in EC values according to the granulometry used (3.5 and 8.0 mm for medium or coarse respectively), but always with low salt content, being less than 0.60 mS cm^{-1} (1:5, v/v method), when raw.

Also, the reduction of granulometry promoted greater release of ions to the solution, resulting in an increase in the EC. This fact was observed due to the difference between treatments composed 100% with needles, and in the granulometry of 3.5 mm, which had an EC corresponding to 0.6 mS cm^{-1}; and in the granulometry 8.0mm, 0.23 mS cm^{-1}. Therefore, the thinner the material - the greater the specific surface area of the material, the greater the release of salts, resulting in a higher EC.

Furthermore, it was found that as the proportion of needles increases in the GM, there is a reduction in EC, since the material contains a low amount of salts. Thus, there is a need for fertilization, with nutrient complementation through nutrient solution, which is an appropriate characteristic for a material to be used as a substrate, since it will allow the adjustment of the fertility of the medium according to the needs of the crop. Given its chemical and physical characteristics, with emphasis on pH and EC, *Pinus* sp needles has potential for use as a substrate and/or conditioner in substrate mixtures (Ceccagno et al., 2019).

Examining the data that was presented in this article, it is possible to observe the range of possibilities when using organic compounds, from different origins and in different percentage of participation, as a GM for containerized crops. It should be noted that, given the higher concentration of salts in organic compounds such as animal manure, earthworm humus (Alvarez et al., 2017) and green residues, these should be used as chemical complements in a substrate (Schafer, 2022). In addition, when aiming at a satisfactory development of plants in any substrate, EC must be monitored. In order to meet the nutritional demands of crops, additional management can be carried out with nutrient solutions to complement the requirements, aiming to adapt the GM for a superior cultivation (Xiong et al., 2017).

Cation exchange capacity (CEC)

Cation exchange capacity (CEC) is related to the sorption force and buffering ability of substrates for nutrients. So, a substrate with high CEC value is able to store more nutrients. Thus, it is a property of solid particles of the substrate to adsorb and exchange cations, and the greater the charge, the greater the affinity of the particles, which makes this property important for regulating the nutrition to be added to the GM. If not managed correctly, a GM with a high CEC value may lead to nutrient imbalance. However, using frequent fertigation is an option to reduce the potentials negative effects (Gruda et al., 2017).

A study was conducted by Kim et al. (2017) in order to examine the applicability of rice hull derived biochar as a part of a GM mixture. The biochar was incorporated into a commercial GM at 0, 1%, 2% and 5% (w/w). The results showed that the biochar increased the CEC from 82 $cmol_c$ kg^{-1} (0%) to 96 $cmol_c$ kg^{-1} (5%), this happened mainly because of the large surface area and high charge density of this material. This behavior tends to happen with organic materials.

Nutrient availability

The nutrient availability is basically determined by the amount of specific nutrients found in a GM. These analyzes are more specific and expensive, being used just in some cases to verify the nutritional balance of the substrate or nutrient solutions used in crops cultivation. These type of analyzes become important when there is a prior knowledge that the GM used is nutritionally unbalanced, which can be problematic given the possibility of antagonism between some nutrients, or even when it is known that a particular crop has higher requirements for a specific nutrient, that if its lacking, can cause physiological and phytosanitary problems. As an example, manganese plays a key role for ornamental plants, since its excess can cause toxicity. Symptoms cause damage in commercial plant structures, such as in gerbera leaves grown in GM, through the appearance of small dark and necrotic dots, with irregular size and distribution (Ludwig et al., 2014).

Physical and chemical characterization of plant substrates

Several methods are known for characterizing plant substrates. Regarding the physical characterization, this one is done by relating the water content and the water potential. First, it is necessary to determine the density on a wet basis or the current density using a methodology proposed by Hoffmann, (1970), called self-compacting method. Basically, to determine the water curve retention, the methodology described by De Boodt and Verdonck (1972) is used. The cited methodology was adapted from the classic soil water retention curve to be used in plant substrate, determining that the points which can better explain the dynamics of water and air retention are those of low tensions. In this way, to carry out the analysis, the methodology proposes the application of different tensions to determine the water retention curve (tensions of 0, 0.10, 0.50 and 1 m of water column or 0, 10, 50 and 100 hPa).

In order to determine the water retention curve, according to the methodology of De Boodt and Verdonck (1972), various equipment's can be used. The basic equipment used is composed of a porous ceramic plate that work at low tensions and let water pass through, but not allowing air. Normally, these plates are placed in glass Büchner funnels, with a system of communicating vessels, where cylinders are placed with substrate samples and the corresponding tension is applied (Figure 1.D). The tension table methodology can also be used, where the cylinders are placed to drain on a glass top covered with filter paper, or the sand beds methodology, where the cylinders with substrates are placed in a box filled with fine sand, both with an opening with a small central hole through, in which the water is drained (Figure 1). All these methodologies use the principle of communicating vessels where tensions of 10, 50 and 100 hPa are applied. Avrella et al. (2022) present a summary of the methodologies mentioned above.

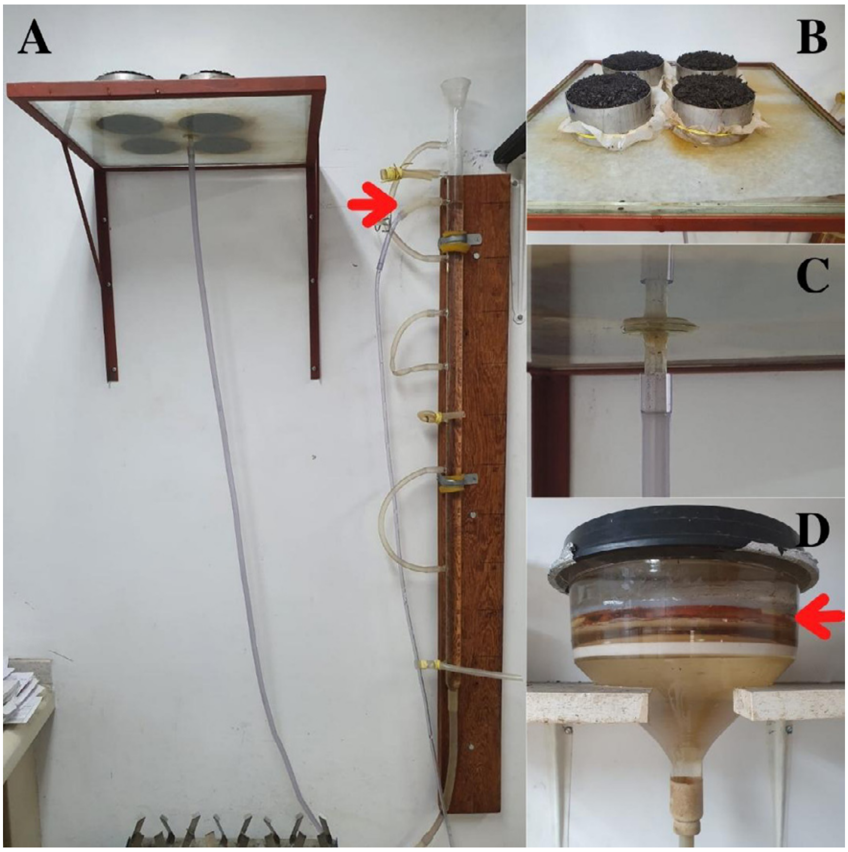

Figure 1. Details of the tension table and Büchner funnel equipment. A) Glass tension table with sample cylinders at the top, showing the details of the communicating vessels and indicating, in the red arrow, the tension of 10 hPa. B) Tension table top showing substrate-filled cylinders being placed on filter paper. C) Underside of the tension table showing the central hole for applying the curve tensions. D) Glass Büchner funnel with porous ceramic plate (arrow).

From the determination of the mass resulted from the referred pressures, the water retention curve can be calculated. Point 0 is considered as saturated substrate, thus without the presence of air. The difference between the saturated substrate and the one subjected to tension 10 hPa is the air space (AS), i.e. the space occupied by macropores. From point 10 to point 100 we have the available water for plants (AW), which can be divided into easy available water (10-50 hPa – EAW) and water buffering capacity (50-100 hPa – WBC). The remainder from 100 hPa to dry substrate (65 °C to constant weight) is considered the remaining water (RW). The sum of all these previous characteristics will give the total porosity (TP), with the rest being considered the solid part of a substrate. The calculation of the available water content (AWC) is given by all the water that the substrate is able to retain after free drainage, in this case the difference between point 10 and the dry substrate. An organization chart with the procedures for the determination of each point is presented in figure 2 and the calculation formulas are presented in table 1.

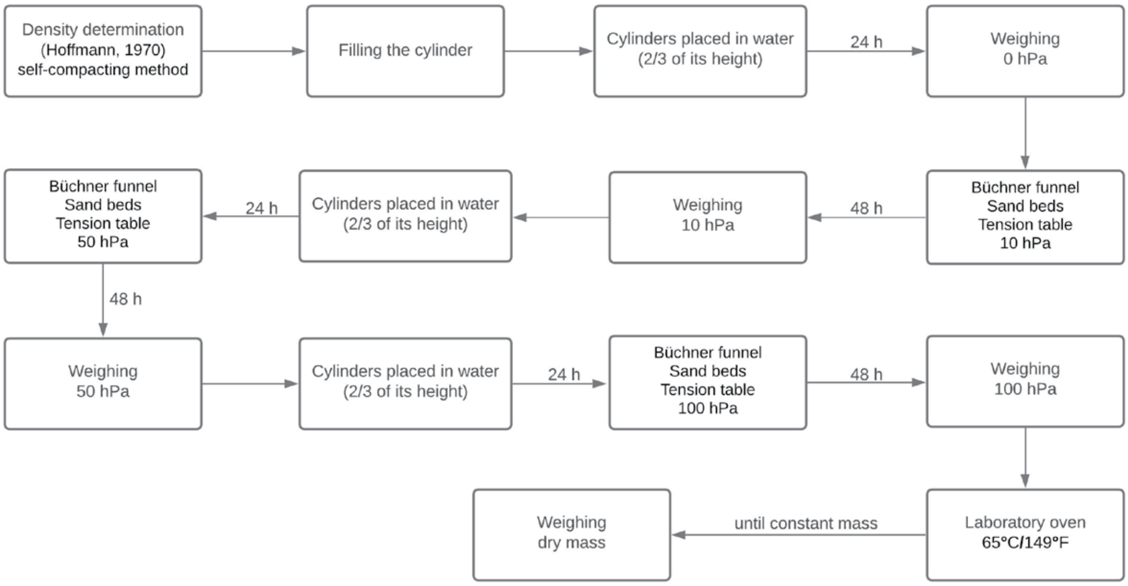

Figure 2. Flow-chart of the procedures to obtain the water content in the samples after 0, 10, 50, and 100 hPa tension. Adapted from Avrella et al. (2022).

Table 1. Formulas for calculating the density, substrate mass in the cylinder and water retention curve.

Characteristic	Unit	Formula
Wet density or current density	Kg m^{-3}	$\frac{Wet\ mass\ (g)}{Volume\ (mL)}\ x\ 1000$
Substrate mass in the cylinder	g	$\frac{cylinder\ volume(mL)\ x\ wet\ density\ (gL^{-1})}{1000}$
Total porosity	%	$\frac{W.0hPa - dry\ mass}{cylinder\ volume}\ x\ 100$
Air space	%	$\frac{W.0hPa - W.10hPa}{cylinder\ volume}\ x\ 100$
Available water	%	$\frac{W.10hPa - W.100hPa}{cylinder\ volume}\ x\ 100$
Easy available water	%	$\frac{W.10hPa - W.50hPa}{cylinder\ volume}\ x\ 100$
Water buffering capacity	%	$\frac{W.50hPa - W.100hPa}{cylinder\ volume}\ x\ 100$
Remaining water	%	$\frac{W.50hPa - W.100hPa}{cylinder\ volume}\ x\ 100$
Available water content	%	$\frac{W.100hPa - dry\ mass}{cylinder\ volume}\ x\ 100$

W. = Weighing at correspondent tension (0, 10, 50 and 100 hPa) in grams. Dry mass in grams and cylinder volume in mL.

The proportional distribution of particle size is determined using 100 g samples of air-dried material for 24h, where the samples were subjected to a sieving system (3.35; 2.00; 1.40; 0.50 and 0.106 mm) under manual shaking for 5 min or until there is no more substrate passing through the sieves. The fractions retained in each sieve are weighed and the percentages calculated based on the total mass of samples.

Different methodologies can also be applied to determine the main chemical characteristics of a substrate. In regards to determining the pH, dilutions in water or calcium chloride can be used. In general, the methodology through dilutions with water is used because it is easier to be performed. Likewise, for the determination of electrical conductivity (EC) we have several methodologies, mostly with regard to its dilution. Mainly, dilution in water is used in different proportions (1:1, 1:2, 1:2.5, 1:5) or the saturated paste method. In Brazil, the methods most used by producers are the 1:2 method and, officially, the 1:5 method (Brasil, 2022). Care must be taken to always make comparisons of results with the same methodology.

The 1:5 methodology was mainly adopted because it is possible to determine EC and pH in the same sample. It consists on using one fraction of substrate to five fractions of deionized water. Based on the current density values, an aliquot of 60 mL of substrate is used and 300 mL of deionized water is added. Afterwards, the mixture is shaking for one hour at 40 rpm with a Wagner's shaker machine. Then, the pH of the sample can be read. After performing the pH reading, this sample is filtered, using quantitative filter papers, discarding the first 10mL. The electrical conductivity reading is performed one hour after the end of filtering (Brasil, 2022).

The methodologies presented above, for the determination of pH and EC, are used mainly before cultivation. For them to be used during cultivation would require the collection of a representative sample (the entire profile of the container) and in this way the collection would be considered destructive. Thus, a methodology called PourThru or Pour-throught leachate (PT) (Wright, 1986) is used for monitoring pH and EC during cultivation. PT is a quick and easy methodology to be performed and can provide important information on pH, EC and nutrient contents. The test runs as follows: a) Irrigate the crop one hour before testing (clear water). Make sure the substrate is saturated. b) After the container has drained for 30 to 60 minutes, place a plastic saucer under the containers to be sampled. c) Pour enough deionized or distilled water on the surface of the substrate to get 50 mL of leachate in the saucer. d) Test your samples for pH and EC. Test the leachate as soon as possible (Landaverde, 2020). The nutrient content can be analyzed directly from the water collected after filtration, using methodologies for the determination of nutrients in water, such as ion chromatography system (IC) (Landaverde, 2020). It is recommended to use representative samples of at least five individuals for each cultivation or phase, and monitoring must be constant over time.

Lastly, it should be noted that all methodologies presented above were developed and tested concerning the use in plant substrates. With that said, there are other methodologies and researchers in this area, such as the work developed by Avrella et al. (2022). Brazil has a Normative Instruction from the Ministry of Agriculture that describes the official analytical methods of substrate for plants (Brasil, 2022). Although this regulation does not cover all the characterization necessary for substrates, such as the complete water retention curve, it must be followed by the industry and researchers. It is a very common practice to publish articles in the area of plants substrate, with a methodology designed for soils, which is something that the authors consider inappropriate. As an example, we can mention the water retention curve in soils (Teixeira et al., 2017), where the determination of available water is carried out between tensions of 100 hPa and 15.000 hPa, which should not be used as a substrate for plants.

Conclusions

The physical and chemical characterization of plant substrates is a fundamental requirement to understand the growth processes of plants in containers. In scientific research, it consists in a basis for explaining these processes and the differences that occur in plants development.

The search for regional inputs for use as a substrate for plants should be pursued by researchers and producers, not only to replace soil or non-renewable natural resources, but also to lower the cost of production.

Author contribution

GS: Idea creation, research orientation, preparation of the manuscript, suggestions and review. **BLL**: Preparation of the manuscript, suggestions and review.

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