

**T.C.**  
**GEBZE TECHNICAL UNIVERSITY**  
**GRADUATE SCHOOL**

**PRODUCTION AND CHARACTERIZATION OF FULLY  
BIODEGRADABLE BIOCOMPOSITE PLANT GROW PLUG  
ALTERNATIVES FOR SOILLESS AGRICULTURE**

**ABDULLAH HİLMİ COŞAR**

**A THESIS OF MASTER OF SCIENCE  
DEPARTMENT OF MATERIALS SCIENCE AND  
ENGINEERING**

**ADVISOR: ASSIST. PROF. DR. MERVE MOCAN**

**JANUARY 2026**

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**ABDULLAH HİLMİ COŞAR**

**YÜKSEK LİSANS TEZİ**  
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*In the name of Allah,  
the creator of the earth  
and the heavens.*

## ABSTRACT

Soilless agriculture, or hydroponics, is a plant growth method that provides sufficient mineral and nutrient resources to the plant in water without using soil. The importance and need for soilless agriculture, seedling farming and personalized home-type smart soilless farming systems will increase in the future agriculture with the increasing population and decreasing land area, especially in big cities. However, plant grow plugs, the substrates that house the seeds, are currently imported, driving up costs and expanding their carbon footprint. Moreover, their exact composition is often undisclosed, and insufficient toxicity testing is being performed on these plugs, suggesting that they are most likely non-biodegradable and may even contain toxic additives. For truly sustainable cultivation, locally manufactured plant grow plugs made from fully known and eco-friendly ingredients is required.

This study aims to develop two types of plant grow plugs that are dimensionally stable and composed of non-toxic, eco-friendly and fully biodegradable materials, designed to support healthy plant growth in soilless agriculture and seedling applications. In this way, an agricultural residue is also valorized and thus contributes to increasing sustainable agricultural production through effective waste management. The agricultural residue used in this study is cocopeat, derived from ground coconut shells, which exhibits a highly hydrophobic character.

The first plant grow plug consists of materials fungal mycelium and cocopeat, where mycelium acts as the matrix and cocopeat serves as the reinforcing phase of the biocomposite. Mushroom mycelium is the root system of fungi in fiber-like form which develops with appropriate nutrients and moisture. As mycelium grows, it forms a binding network with cocopeat within a mold, forming the plug's intended size and shape. Mycelium is mixed with sterilized and appropriately moistened cocopeat in molds and incubated under controlled conditions for a defined period. After the desired degree of binding network between the mycelium and cocopeat is obtained, the mycelium is deactivated and its growth is stopped. Deactivated products are ready for use. This plant grow plug is entirely natural, organically recyclable and eco-friendly with properties that promote healthy plant growth.

The second plant grow plug contains poly(butylene adipate-co-terephthalate) (PBAT), a biodegradable polymer and cocopeat fiber. PBAT granules, dissolved in a suitable solvent, are precipitated in a non-solvent to form fibers that physically bind within the cocopeat and hold it together. This semi-finished product is then molded into final plug form using suitable molds under controlled temperature and pressure. This grow plug, is organically recyclable, also home compostable, therefore, eco-friendly.

Both plug samples produced were subjected to material characterization processes using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA). Also, water absorption test and compression tests were performed on both plug samples, while plant growth and development tests were conducted on home-use smart garden plant growing devices. These results were compared with those of the reference plug. Overall, all plant growth plugs produced yielded comparable performance, with some showing superior results relative to the reference capsule, indicating their high potential as environmentally friendly and sustainable alternatives.

**Keywords: Soilless Agriculture, Plant Grow Plug, Mycelium, Cocopeat, PBAT.**

## ÖZET

Topraksız tarım yani hidroponik, toprak kullanmadan su içinde bitkiye yeterli mineral ve besin kaynaklarını sağlayan bir bitki yetiştirme yöntemidir. Artan nüfus ve özellikle büyük şehirlerde tarım alanların azalması ile geleceğin tarımında topraksız tarımın, öneminin ve ihtiyacının artacağı aşîkardır. Ancak, tohumlara yatak vazifesi gören substratlar olan bitki büyütme kapsülleri şu anda ithal ediliyor, bu da maliyetleri ve karbon ayak izlerini artırmaktadır. Dahası, tam bileşimleri genellikle açıklanmıyor olduğu için toksik katkı maddeleri içerebilmekte ve büyük olasılıkla biyobozunur özellik sergilememektedir. Gerçekten sürdürülebilir bir üretim için, içeriğı tamamen bilinen ve çevre dostu bileşenlerden yapılmış yerel olarak üretilen bitki büyütme kapsülleri gereklidir.

Bu çalışmada, topraksız tarım ve fidecilik sektörüne yönelik boyutsal olarak kararlı, toksik olmayan, çevre dostu ve tamamen biyolojik olarak parçalanabilen malzemelerden oluşan, iki adet bitki büyütme kapsülü prototipi geliştirilmesi hedeflenmektedir. Bu sayede, tarımsal bir atığın katma değerli bir ürünün bileşimi haline getirilmesi ve böylece etkili atık yönetimi ile sürdürülebilir tarımsal üretimin artırılması hedeflenmektedir. Bu çalışmada kullanılan tarımsal atık, öğütölmüş hindistan cevizi kabuğundan elde edilen ve yüksek derecede hidrofobik özellik gösteren kokopittir.

İlk bitki büyütme kapsülü çalışmamız kokopit malzemesin ve mantar miselyumundan oluşur. Mantar miselyumları mantarların kök sistemleridir. Miselyumlar uygun besin ve nem içeren her ortamda sarma, büyüme ve gelişme eğilimdedir. Miselyum büyüdükçe, bir kalıp içinde kokopitle bir bağlayıcı ağ yani sarım oluşturarak kapsülün son şeklini almasını sağlar. Miselyum, kalıplarda sterilize edilmiş ve uygun miktarda nemlendirilmiş kokopitle karıştırılır ve belirli bir süre boyunca kontrollü koşullar altında inkübe edilir. Miselyum ve kokopit arasında istenen sarım derecesi elde edildikten sonra miselyum deaktive edilir ve büyümesi durdurulur. Deaktive edilmiş ürünler kullanıma hazırdır. Bu bitki büyütme kapsülleri tamamen doğal, organik olarak geri dönüştürülebilir ve sağlıklı bitki büyümesini destekleyen özelliklere sahip çevre dostu kapsüllerdir.

İkinci bitki büyütme kapsülü, biyolojik olarak parçalanabilir bir polimer olan poli(bütölen adipat-ko-tereftalat) (PBAT) ve kokopit içerir. Uygun bir çözöcöde çözölen PBAT granöller, kokopit ile fiziksel olarak bağlanan ve onu bir arada tutan lifler oluşturmak için çözöcü olmayan bir maddede çökeltir. Bu yarı mamul ürün daha sonra kontrollü sıcaklık ve basınç altında uygun kalıplar kullanılarak son kapsöl formuna getirilir. Bu bitki büyütme kapsölü, organik olarak geri dönüştürülebilir, ayrıca ev kompostlanma şartlarında kompostlanabilir, dolayısıyla çevre dostudur.

Üretilen her iki kapsöl örneklerine referans olarak seçilmiş kapsöllerin sonuçlarıyla karşılaştırmalı olarak Taramalı Elektron Mikroskopisi (SEM), Enerji Dağılımlı X-Işını Spektroskopisi (EDS), Fourier Dönüşömlü Kızılötesi Spektroskopisi (FTIR), Termogravimetrik Analiz (TGA), su emme testi ve basma testleri ile malzeme karakterizasyon işlemleri yapılmış, ev tipi akıllı bahçe bitki büyütme cihazlarında ise bitki büyüme ve gelişme testleri yapılmıştır. Sonuçlara göre üretilen bitki büyütme kapsöller, referans kapsülle yarışabilir sonuçlar vermiş, çevreci ve sürdürülebilir bir ürün olarak iyi bir alternatif sunmuştur.

**Anahtar Kelimeler:** Topraksız Tarım, Bitki Büyütme Kapsölü, Miselyum, Kokopit, PBAT.

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## LIST OF SYMBOLS AND ABBREVIATIONS

|             |                                                   |
|-------------|---------------------------------------------------|
| <b>NFT</b>  | : Nutrient Film Technique                         |
| <b>DFT</b>  | : Deep Flow Technique                             |
| <b>DWC</b>  | : Deep Water Culture                              |
| <b>°C</b>   | : Degree Celsius                                  |
| <b>atm</b>  | : The standard atmospheric pressure               |
| <b>AVG</b>  | : Average                                         |
| <b>S.D.</b> | : Standard Deviation                              |
| <b>m</b>    | : Mass                                            |
| <b>MPa</b>  | : MegaPascal                                      |
| <b>PBAT</b> | : Polybutylene adipate co-terephthalate           |
| <b>BDO</b>  | : 1,4-butanediol                                  |
| <b>PTA</b>  | : Terephthalic acid                               |
| <b>DMT</b>  | : Dimethyl terephthalate                          |
| <b>AA</b>   | : Adipic acid                                     |
| <b>LDPE</b> | : Low density polyethylene                        |
| <b>PLA</b>  | : Polylactic acid                                 |
| <b>PHA</b>  | : Polyhydroxyalkanoate                            |
| <b>PS</b>   | : Polystyrene                                     |
| <b>PP</b>   | : Polypropylene                                   |
| <b>PE</b>   | : Polyethylene                                    |
| <b>FTIR</b> | : Fourier Transform Infrared Spectroscopy         |
| <b>TGA</b>  | : Thermogravimetric Analysis                      |
| <b>SEM</b>  | : Scanning Electron Microscopy                    |
| <b>EDS</b>  | : Energy Dispersive Spectroscopy                  |
| <b>XRD</b>  | : X-ray Diffraction Spectroscopy                  |
| <b>JCP</b>  | : Joint Committee on Powder Diffraction Standards |

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# 1. INTRODUCTION

According to a study of European Commission, the global population is expected to reach approximately 8 billion by 2025 and nearly 10 billion by 2050 (**Figure 1.1**) [1]. This rapid population growth requires radical transformations in the agricultural sector to ensure sustainability, enhance efficiency, and increase production capacity. Soilless agriculture methods (hydroponic, aeroponic and aquaponic etc.) eliminate the need for soil, providing savings in water and space. Studies indicate advantages such as a 50-90% reduction in water use and 2-15 times increase in yield [2].

The substrate material in these systems such as rock wool, glass wool, foam cube and perlite, are not biodegradable and cause environmental pollution [3]. On the other hand, the fact that these substrates are produced with huge economic burden and imported from other countries which increase production costs.

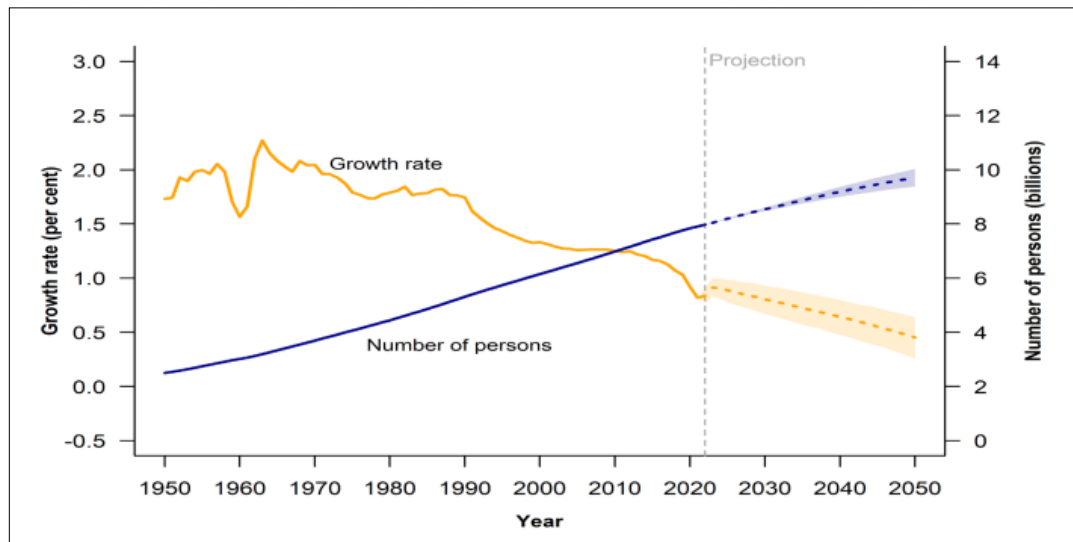


**Figure 1.1:** Global population size and annual growth rate: estimates, 1950-2022 and medium scenario with 95 percent prediction intervals, 2022-2050 [4].

The purpose of this study is to develop alternative plant growth plug prototypes for soilless agriculture, composed of dimensionally stable, non-toxic, environmentally friendly and

fully biodegradable materials such as agricultural wastes. In this way an agricultural waste, cocopeat, is transformed into a valuable component of a product, contributing to effective waste management and supporting sustainable agricultural production. This approach aims to produce sustainable, independent and competitive solutions in soilless farming systems under the pressure of the rapidly growing global population.

## **1.1. Soilless Agriculture**

Soilless agriculture is an alternative farming method to conventional soil-based farming. In this method soil is eliminated or replaced with an alternative substrate and plants receive nutrients through water or by substrate [5]. In soil-based agriculture, soil provides water, minerals and nutrients. But in soilless farming, these are provided through directly controlled environments [6]. This allows for a higher degree of control [7]. Thus, it becomes possible to produce crops year-round, independently of climatic conditions [8]. Soilless agriculture is divided into four categories: hydroponic, aeroponic, aquaponic and aggregate culture systems [5]. Each of these systems is based on different principles regarding nutrient supply and growth media for plants [9].

## **1.2. Hydroponic Systems**

Hydroponic systems are a system which plant roots are in direct contact with a nutrient solution in water. It allows them to absorb minerals and nutrients from water. In these systems (**Figure 1.2**), plants are typically grown in inert media such as perlite, vermiculite, or cocopeat (**Figure 1.3**) and nutrients are absorbed by the roots through the water. Hydroponic systems consume 70–90% less water compared to traditional methods in terms of water use efficiency [10]. Additionally, since nutrients can be recycled, waste production is minimized and effective sustainable production is achieved [11]. By growth plants at specific and controlled pH and electrical conductivity (EC) levels, optimal development can be achieved [12]. Among various hydroponic system types, Nutrient Film Technique (NFT), Deep Flow Technique (DFT) and Deep Water Culture (DWC) are commonly used (**Figure 1.2**) [5].

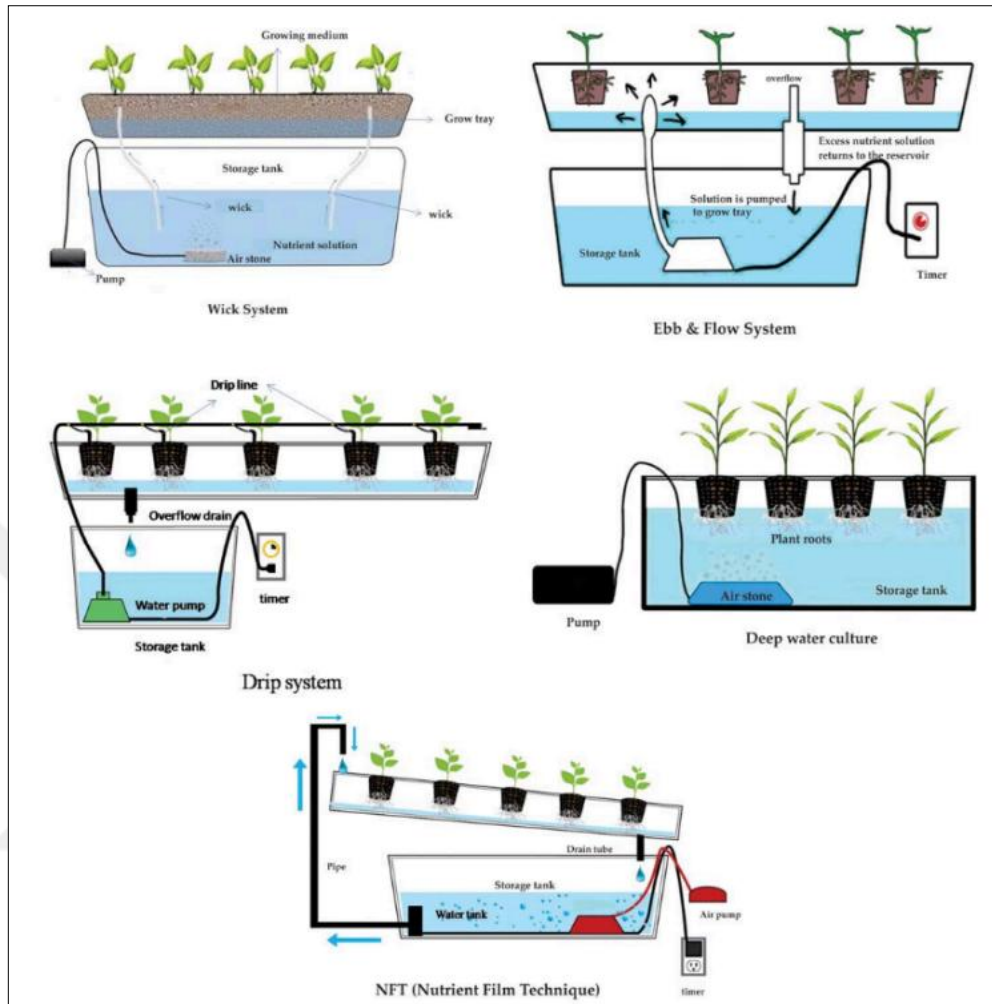


**Figure 1.2:** Types of hydroponic systems [8].



**Figure 1.3:** Some used growing mediums for hydroponic systems [13].

## Aeroponic Systems

In aeroponic systems (**Figure 1.4**), plant roots remain suspended in air and do not meet water. Nutrients are supplied to roots by absorbing and because the roots are in an open-air environment, growth rate increases [14]. NASA scientists consider these systems ideal for farming in space, as they provide excellent water conservation and their compact structure makes them ideal for use in limited spaces [15]. Moreover, illness control is easier since there is no soil or similar medium that could harbor pathogens [16]. Since the roots are open to air, leafy vegetables for example lettuce, basil and spinach show high biomass production [17].

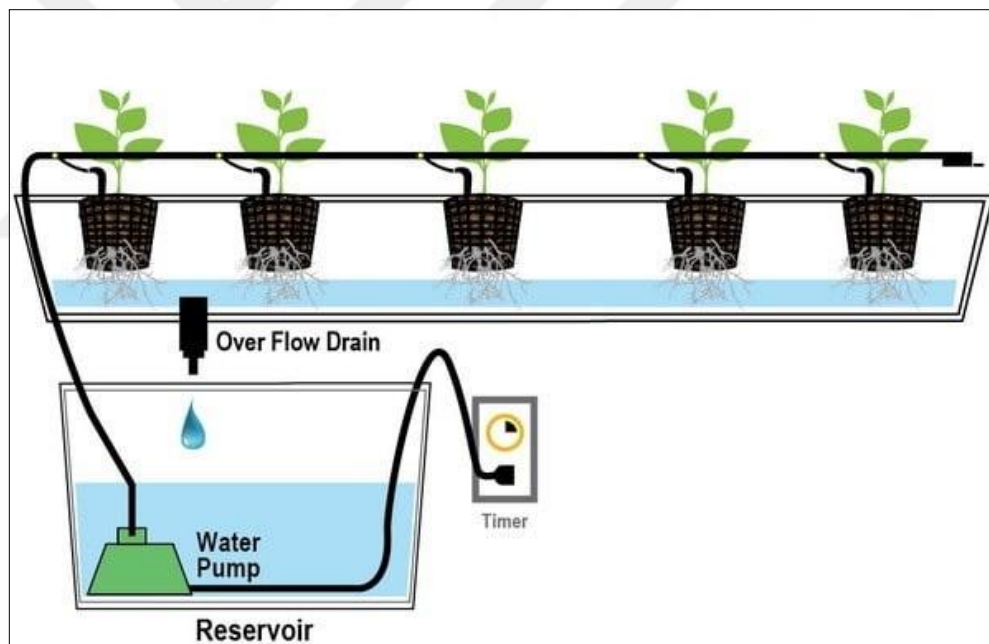


**Figure 1.4:** Aeroponic system scheme [18].

## Aquaponic Systems

Aquaponics system is a system (**Figure 1.5**) that integrates hydroponics with aquaculture (a fish farming method) [19]. In this system, fish waste is converted by bacterial processes into nitrates which serve as natural fertilizer for plants [20]. Plants filter these wastes, thus

establishing a sustainable cycle. These systems provide dual benefits for food security by producing both plant and animal products [21]. Species like carp or catfish are preferred for these kinds of systems. However, simulation models show that the nitrogen amount and its cycle must be well coordinated [22].

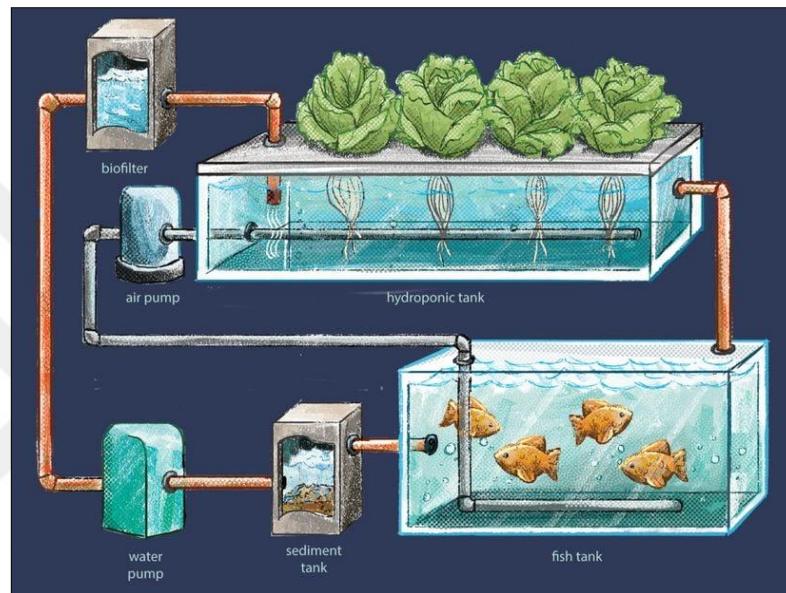


**Figure 1.5:** Aquaponic system [23].

### Aggregate Culture Systems

In aggregate culture systems (**Figure 1.6**), plants are grown not in soil but in substrates such as rock wool, perlite, cocopeat, sawdust, or sand [24]. Unlike hydroponic systems, nutrient solutions are not given directly to water but to these substrates and excess solution is drained [25].

Aggregate culture systems are commonly used in greenhouse conditions and have proven to be effective for fruit vegetables such as tomatoes and peppers. The substrate is selected with a porous structure to facilitate drainage of excess water and, by helping to anchor the roots, provides mechanical stability [26].

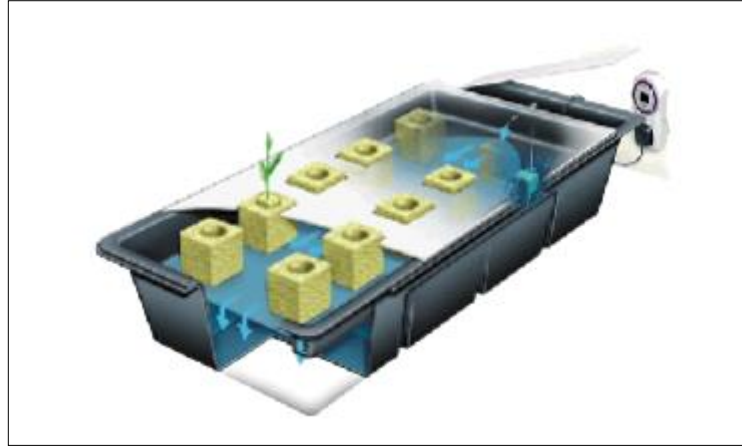


**Figure 1.6:** An aggregate system [27].

### **Economic and Environmental Aspects of Soilless Agriculture**

Soilless agriculture increases efficient food production by higher plant yields per unit area compared to the traditional ones. Their market size is increasing year by year (**Figure 1.7**). In addition, it facilitates urban agriculture by its different systems, limited areas can be used for plant production [28]. These soilless agricultural systems are ideal for regions that not enough water like Africa. The water loop system integrated, can save about %90 water [29]. Moreover, with known ingredients and pesticide ratio, system can get healthier plants and reduced environmental pollution [8]. Although the first substructure costs are high compared to conventional ones, reduced labor requirement and higher crop yield turn it into an advantage after extended period [5].

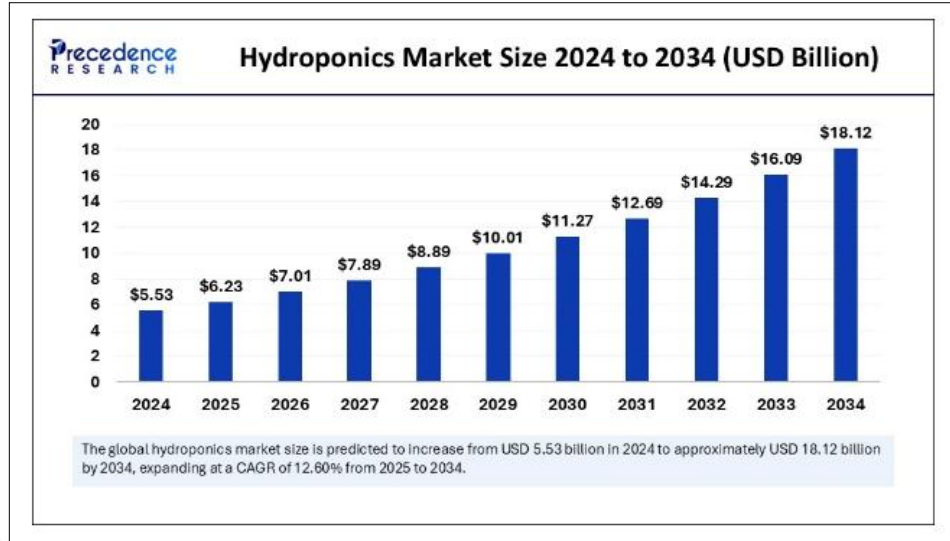


**Figure 1.7:** Hydroponic current market size future expectation [5].

### 1.3. Plant Growth Plugs

In soilless agriculture, plant growth plugs are designed to fulfill multiple functions such as acting as a substrate for roots, having a specific shape, water retention capacity, water absorption through cohesion and adhesion force and capillary effect (**Figure 1.8**) and providing sufficient space for air circulation [5]. The plugs used in these systems are made from polymer-based, organic-based, or biocomposite materials combining both [29].

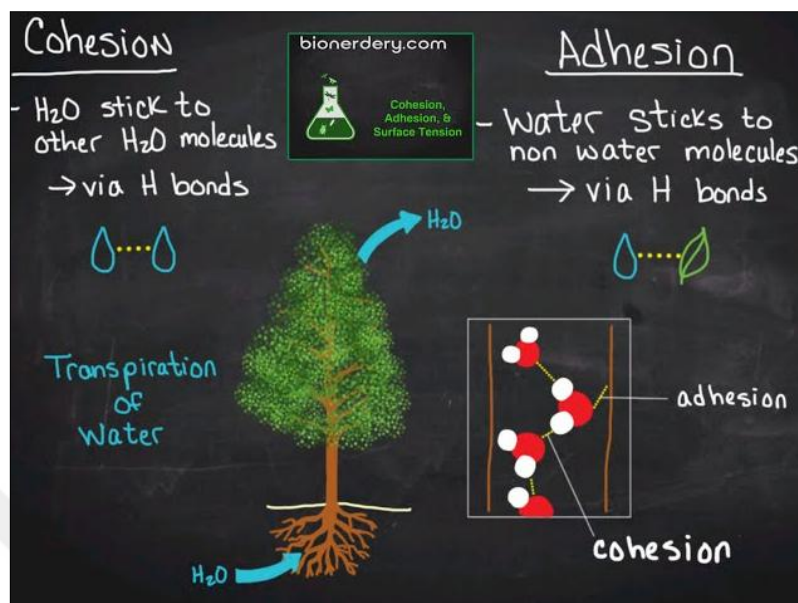


**Figure 1.8:** Cohesion and adhesion principle in plants [30].

The fact that these plant growth plugs have a specific shape and a porous structure facilitates oxygen uptake by the roots and also allows the nutrient solution to be absorbed and evenly distributed within the plug [31]. For example, polyurethane foams are widely used in these systems as they are lightweight, porous (**Figure 1.9**) and easily moldable [32].

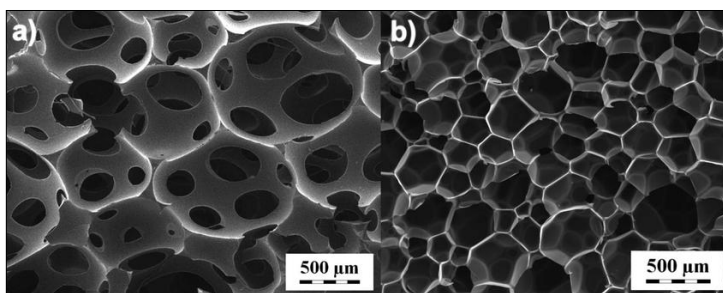


**Figure 1.9:** SEM images of open cell polyurethane foam (a) and closed cell polyurethane foam (b) [33].

However, the biodegradability of polyurethane foams is remarkably low [33]. Therefore, in recent years, biodegradable alternatives have been explored by scientists, especially

compostable polyesters such as polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT) have gained importance [34]. PBAT and PLA-based plugs form a porous microstructure that mimics soil and they are biologically degradable (**Figure 1.10**) and compostable. Moreover, they are compatible with root cells and can function as a substrate, thus supporting root growth without mechanical restriction.

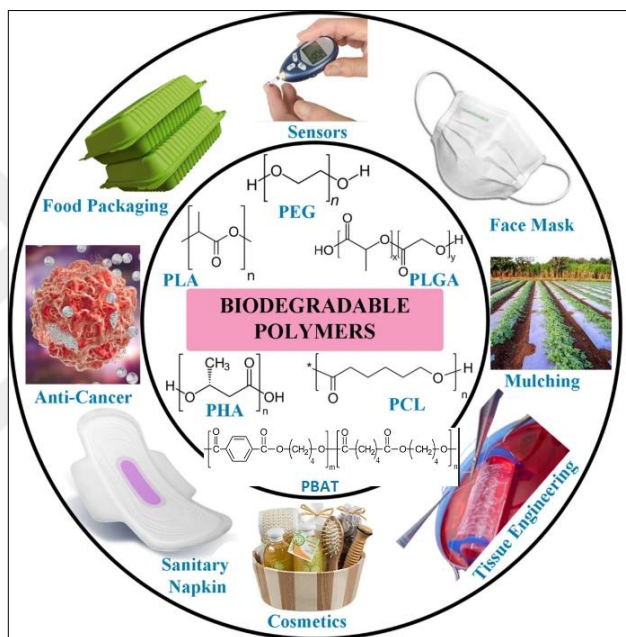


**Figure 1.10:** Some biodegradable polymers and their application areas. Adapted from:[35].

During material selection, properties such as mechanical strength, chemical stability, toxicity, water absorption and water retention should be considered. Additionally, the pH stability, ion exchange capacity and resistance to microbial colonization of the plug directly affect agricultural performance [36]. Mycelium biocomposite (**Figure 1.11**) materials produced with fungal mycelium are also considered an ecologically sustainable alternative [37]. Mycelium-based plugs are fully biodegradable in natural environments and can also interact symbiotically with roots. These fully biodegradable plugs can be

coated with agricultural residues such as cocopeat, straw, corn stover (**Figure 1.11**) and tea waste, forming a plug structure through physical bonding [38].

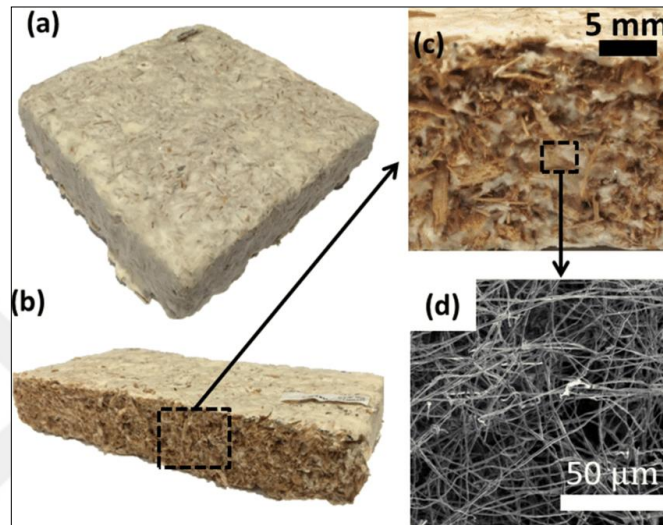


**Figure 1.11:** A sample of mycelium-corn stover bio-composite (a-b-c): macroscale, (d): microscale [39].

From materials perspective, with this type of material, porosity is 50–80%, so maximizing water/oxygen transfer [39][40]. The plant growth plug’s properties are extremely critical. It should be evaluated not only for plant growth and development performance but also strategically in terms of production process, waste management and environmental impact in alignment with the EU Sustainable Development Goals (**Figure 1.12**). Although conventional foams are effective in the short term, options made from biodegradable, environmentally friendly, reusable and organic materials are key to long-term sustainable agriculture [40].



**Figure 1.12:** The content of 12<sup>th</sup> Sustainable Development Goal [41].

### Fungal Mycelium

Mycelium is the vegetative root system of fungi. It develops underground and consists of thin and branched networks of hyphae (**Figure 1.13**). Hyphae are typically tubular structures with a diameter of several micrometers (**Figure 1.13**, **Figure 1.14**) and enable fungi to absorb water and nutrients from the environment. Mycelium plays a key role in the soil as they decompose organic matter, improve soil ecology and establish symbiotic relationships with plants [42].

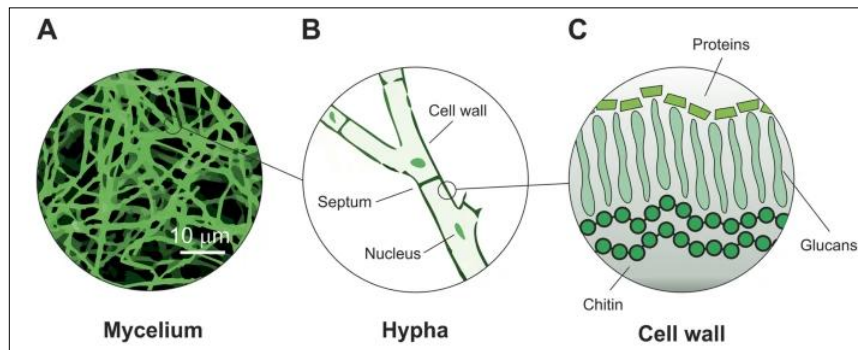


**Figure 1.13:** The structure of mycelium and its branched hyphae; a) optical microscopy image of mycelium and shows the diameters of hyphae, b) the biological structure of hypha, c) cell wall structure of hypha [43].

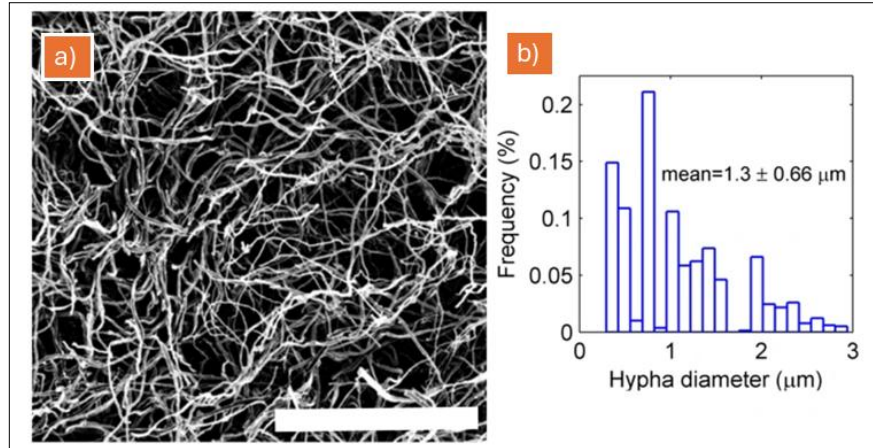


**Figure 1.14:** (a) SEM image of a mycelium bio composite (b) distribution chart of hyphae diameters [39].

The mycelium structures of different fungal species (**Figure 1.15**) also develop differently depending on environmental conditions. For example, the *Pleurotus ostreatus* (oyster mushroom) grows fast, edible and abundant in nature, their mycelium networks effectively degrade cellulose etc. The physical properties of mycelium are related to the type of substrate (e.g., straw, tea waste (**Figure 1.16**), cocopeat) and environmental conditions (temperature, humidity, pH) [39].



**Figure 1.15:** Some different mushrooms [44].



**Figure 1.16:** Mycelium hyphae on tea waste [45].

Mycelium consists of many cells and contains multi-nucleated structures within its hyphae. The growth and development of hyphae occur through apical extension at the tips, enabling fungi to spread over wide areas by wrapping around the substrate (**Figure 1.16**) [46].

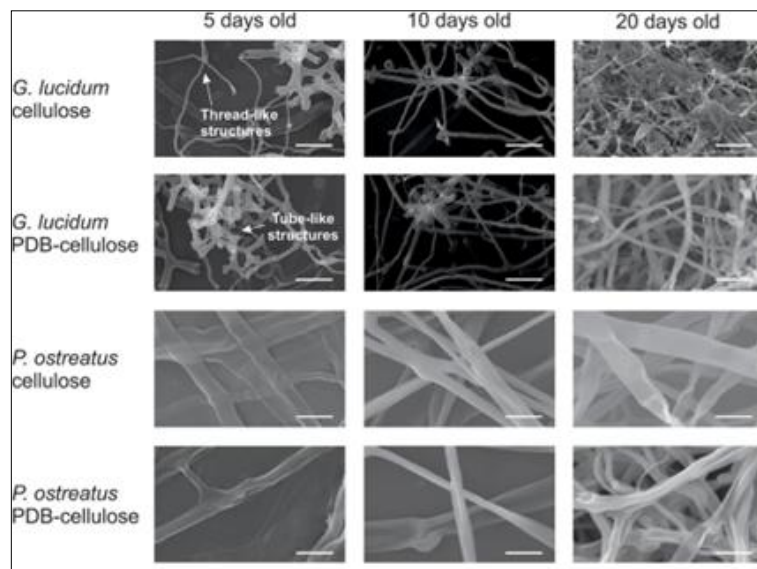


**Figure 1.17:** An example of mycelium hyphae growing and spreading process. Adapted from:[43].

Mycelium is considered an alternative material in sustainable material production. It is especially cultivated and structured over agricultural waste materials (e.g., cocopeat, corn cob, straw, tea waste), acting as a natural binder to form structurally cohesive materials [47]. These biocomposite materials are economical, biodegradable and organically recyclable, thus environmentally friendly. Mycelium biocomposites are used as insulation panels, packaging products, household items, plant grow plugs, vegan imitation leather and even construction materials (**Figure 1.18**).



**Figure 1.18:** Some applications of mycelium biocomposites. In a) insulation, b) packaging, c) furniture, d) vegan artificial leather, (e) the pattern of this leather) f) lighting. Adapted from: [45], [48].

The microstructures of mycelium-based materials exhibit high porosity and low density due to their naturally occurring fibrous hyphal network (**Figure 1.17**) [49]. Owing to this structure-property relationship, they can demonstrate performance like conventional polymeric foams (**Figure 1.19**) in terms of sound and thermal insulation (**Figure 1.18-a**) and lightweight characteristics. Furthermore, the mechanical properties of mycelium vary according to the nutrient source and cultivation conditions, providing an advantage to produce customized biocomposites.

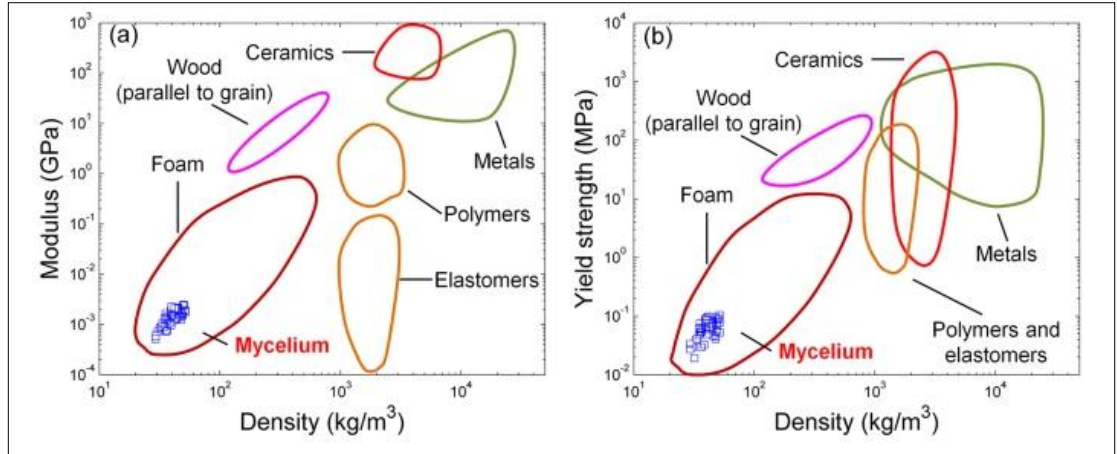


**Figure 1.19:** Young modulus (a) and yield strength (b) of mycelium, foam and other materials as a function of density [39].

Mycelium-based materials and products, being organic, can be easily decomposed in nature by microorganisms (**Figure 1.20**). This offers some advantages compared to conventional polymers and foams. Mycelium can degrade in a few months and not leave any toxic and harmful residues to nature [50]. Moreover, mycelium production does not need any elevated temperature and heavy machines, therefore lowers the carbon footprint.

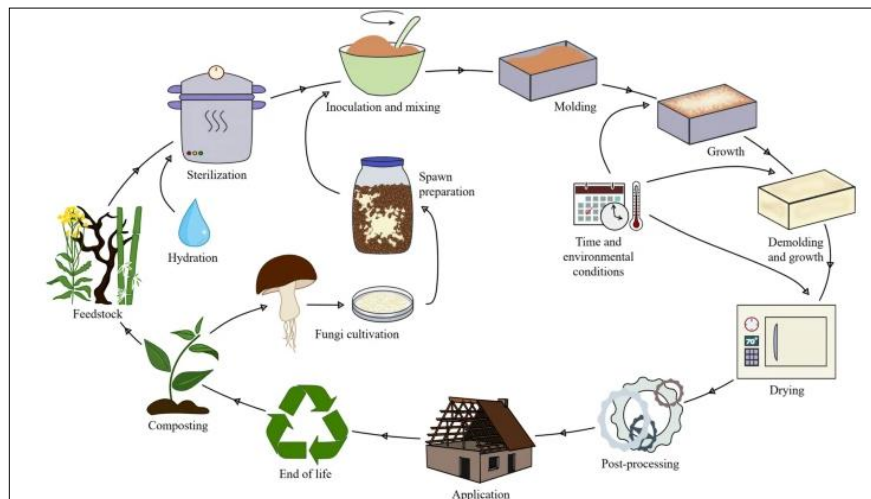
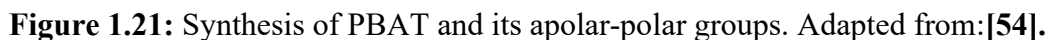


**Figure 1.20:** Production procedure and sustainable recycle loop of mycelium [51].

Poly(butylene adipate-co-terephthalate) (PBAT) is an aliphatic-aromatic copolyester with a random block content, obtained through the polycondensation of 1,4-butanediol (BDO), adipic acid (AA) and terephthalic acid (TPA or PTA) or dimethyl terephthalate (DMT). **(Figure 1.21) [52]**. In production, first, an aliphatic polyester is synthesized using adipic acid and 1,4-butanediol, followed by the synthesis of an aromatic polyester using dimethyl terephthalate. Then, these two polyesters are copolymerized via transesterification using catalysts such as zinc and titanium **[53]**. During production, the temperatures are above 190 °C, under vacuum and the process takes approximately 19 hours. This process results in a structure containing random blocks (e.g., ABAAB), which makes PBAT both flexible and tough.



16

strength to the structure, while also imparting apolar characteristics to the molecule. Due to this aromatic structure, PBAT has properties such as low water permeability [55].

PBAT has aliphatic ester bonds and this structure gives it open to enzymatic degradation [56]. When composting PBAT (with temperature and humidity), surface degradation and disintegration occurs in 48–72 hours by ad hydrolase enzyme such as *TfCut* (**Figure 1.22**) [57]. Unlike polymers such as PLA that can only be industrially compostable at high temperatures ( $58\pm 2^{\circ}\text{C}$ , 50% humidity: ASTM D6400), PBAT polymer is also compostable even under home composting conditions ( $20\text{--}30^{\circ}\text{C}$ , %50-60 humidity) [58].

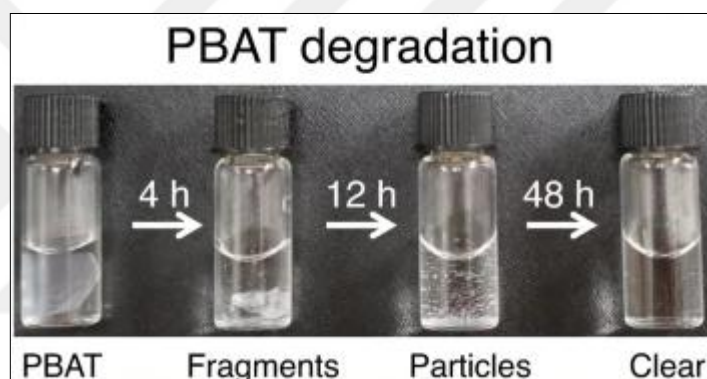


**Figure 1.22:** PBAT degradation by a hydrolase enzyme *TfCut* at  $70^{\circ}\text{C}$  in 2 days, adapted from [57].

PBAT offers rather high elongation at break (500-670%) and good tensile strength properties ( $\sigma$ :15-35 MPa). This makes it ideal for applications such as films and packaging (**Figure 1.23**) [59]. The aromatic blocks give rigidity, while the aliphatic blocks are flexible. In the start of 2020, the PBAT global capacity is increased to 465,000 tons. This rise in production is linked to environmental demands and its eco-friendly properties [55].



**Figure 1.23:** Some applications of PBAT as packaging [60].

In recent times, PBAT has begun to be preferred polymer instead of a non-biodegradable low-density polyethylene (LDPE) due to its biodegradable, compostable and flexible properties for film production and compatibility with food contact. In addition, by blending with other biodegradable polymers such as PLA and polyhydroxyalkanoate (PHA), improvements can be made in mechanical and other properties (**Figure 1.24**). Replacing conventional polymers with biodegradable polymers has begun in applications such as packaging, disposable cups and plant growth plugs.

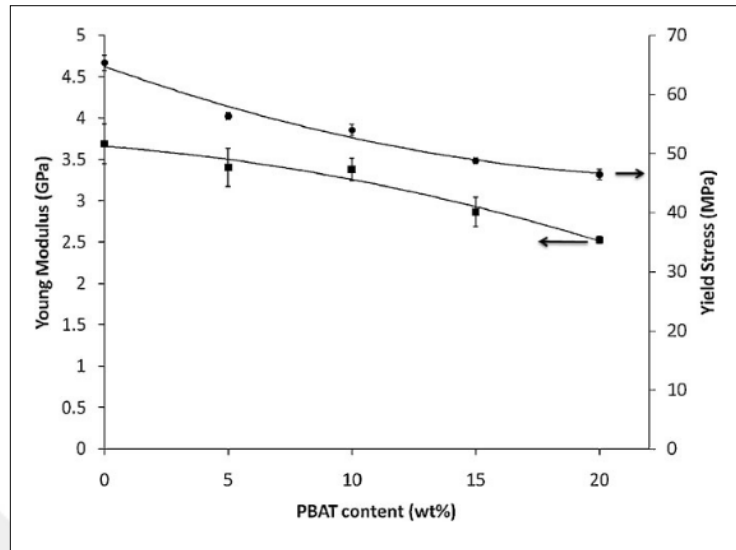


**Figure 1.24:** A graph of young modulus and yield stress curves for a PBAT/PLA blend [61].

PBAT has been present in the polymer market since 1998. Its market size is increasing and is expected to continue growing year by year. (**Figure 1.25**). This growth is associated with efforts to reduce plastic usage and pollution, promote compostable packaging, address concerns about microplastics and meet greenhouse gas emission reduction goals. Due to its properties that allow it to compete with conventional polymers and its biodegradability, it has been supported by institutions that produce environmental legislation, such as the European Union Commission [55].

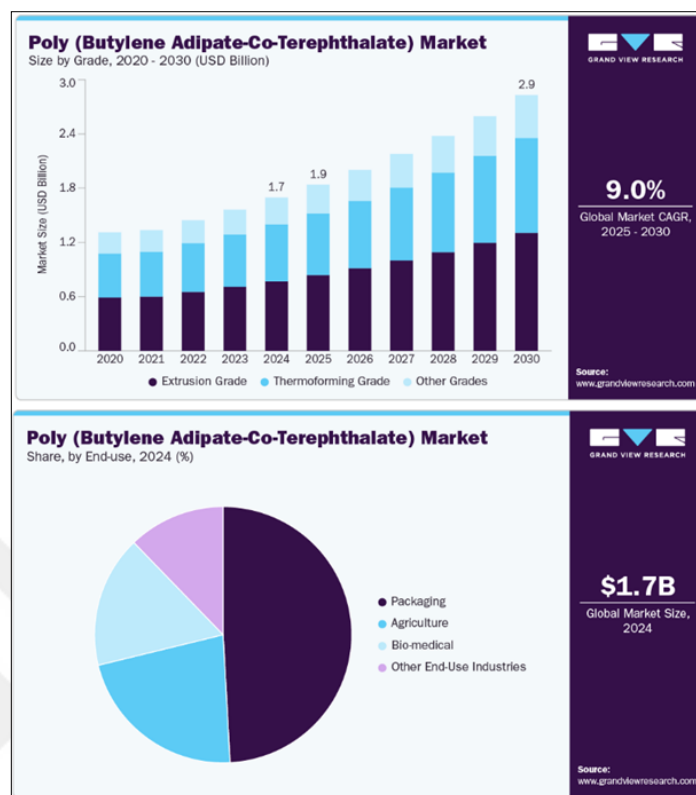


**Figure 1.25:** A report on PBAT market size. Adapted from:[62].

### Solvent precipitation of PBAT

In this work, the solvent precipitation method in polymers is used as a technique to produce growth plugs. The method is based on dissolving the polymer in a suitable solvent and then precipitating it into a non-solvent (a liquid in which the solvent is miscible, but the polymer is not). This technique is frequently used to purify polymers and in the production of nanoparticles-microparticles and nanofibers-microfibers [63].

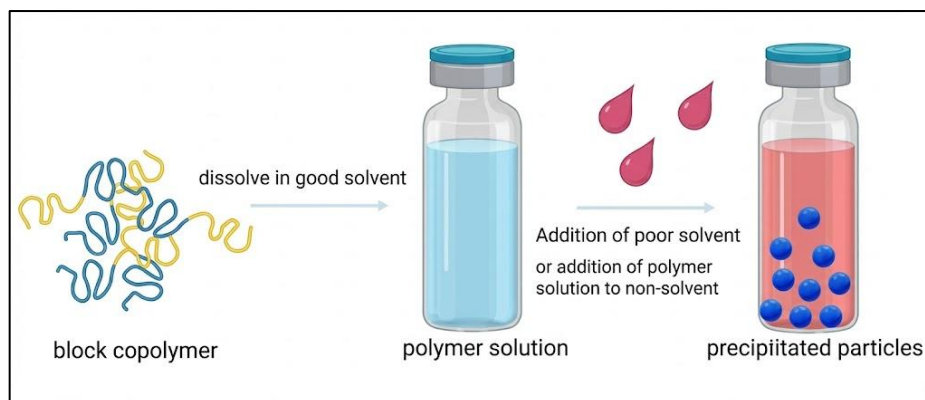


**Figure 1.26:** Schematic representation of solvent precipitation. Adapted from:[64].

During the precipitation process, the addition of the non-solvent decreases the solubility of the polymer, which terminates the dissolution and causes the polymer chains to aggregate and form particle-or fiber-like structures (**Figure 1.26**). The precipitation process is sensitive to solvent type and ratio, non-solvent type and ratio, temperature, polymer concentration and stirring rate [65].

For solvent precipitation, organic solvents such as chloroform, dichloromethane and tetrahydrofuran are used as solvents, while ethanol, methanol or water are commonly used as non-solvents [66]. The polarity difference between the solvent and non-solvent is the main precipitation factor affecting the precipitation rate and particle size. PBAT is a biodegradable, semi-crystalline, random copolymer and it is composed of aliphatic and aromatic blocks. Its hydrophobic structure comes from aromatic blocks (**Figure 1.21**) and needs careful selection of solvents. PBAT shows high solubility in chloroform and dichloromethane and low solubility in water, ethanol, methanol [67].

For PBAT, solvent precipitation process includes preparing a PBAT+chloroform solution and dripping the PBAT+chloroform solution into ethanol (preferably with an at least 10 times higher volume) for precipitation. If a stirrer such as a glass rod is used during this process, the precipitated PBAT wraps around the glass rod; if no stirrer is used, the dripped PBAT polymers form spherical particles upon precipitation (**Figure 1.26**). This method is used especially for drug delivery systems, encapsulation, biodegradable film and fiber

production [68]. Factors such as stirring speed, solvent/non-solvent type and ratio and precipitation temperature control particle size and distribution of precipitation.

## Cocopeat

Cocopeat is an agricultural waste material with organic content and high-water retention capacity, obtained by grinding the coconut husk. The name cocopeat is derived from the combination of coconut and peat, as it resembles peat in appearance. Comprising a mixture of powder and fiber-like material, this naturally derived by product is regarded as an environmentally friendly option [69]. The global use of cocopeat is increasing and it is gaining importance as an alternative to peat [70].



**Figure 1.27:** Dry and water absorbed state of 5kg bulk cocopeat. Adapted from:[71].

One of the most well-known features of cocopeat is its super water holding capacity. It can hold water about 6–8 times of its dry mass (**Figure 1.29**) [72] and up to 60-70% of its volume in water (**Figure 1.28**), making it especially valuable in water-based agricultural systems like soilless farming. In addition, it has high air porosity; it contains about 50–60% air space (**Figure 1.28**), which facilitates oxygen access to the roots [73]. The pH of cocopeat ranges between 5.5 and 6.8, making it ideal for the growth of most plants [74].

| Media components | Bulk Density (g/cc) | Particle Density (g/cc) | Porosity (%) | Moisture Content (%) | Water holding Capacity (%) |
|------------------|---------------------|-------------------------|--------------|----------------------|----------------------------|
| Coco peat        | 0.09                | 0.23                    | 60.91        | 37.36                | 65.49                      |
| Vermi compost    | 0.52                | 1.05                    | 50.78        | 34.05                | 44.53                      |
| Press mud        | 0.70                | 1.37                    | 48.77        | 31.06                | 39.01                      |
| Bio compost      | 0.75                | 1.42                    | 46.79        | 30.38                | 31.29                      |

**Figure 1.28:** Some growing media properties [73].

| Physical characteristic              | Method   | Units                                    | Coir pith |
|--------------------------------------|----------|------------------------------------------|-----------|
| Moisture content $W_m$               | EN 13040 | % (m/m)                                  | 60–75     |
| Dry matter $D_M$                     | EN 13040 | % (m/m)                                  | 25–40     |
| Organic matter $W_{om}$              | EN 13039 | % (m/m)                                  | 90–95     |
| Bulk density $D_B$                   | EN 12580 | $\text{g L}^{-1}$                        | 200–300   |
| Laboratory bulk density $L_D$        | EN 13040 | $\text{g L}^{-1}$                        | 250–350   |
| Bulk density <sub>dry</sub> $D_{BD}$ | EN 13041 | $\text{kg m}^{-3}$ ( $\text{g L}^{-1}$ ) | 60–90     |
| Water capacity                       | EN 13041 | $\text{g}/100\text{g DM}$                | 600–800   |
| Total pore space $P_s$               | EN 13041 | % (v/v)                                  | 85–95     |
| Water capacity $W_v$                 | EN 13041 | % (v/v)                                  | 60–70     |
| Air capacity $A_v$                   | EN 13041 | % (v/v)                                  | 15–35     |
| Shrinkage value                      | EN 13041 | %                                        | 15–25     |

**Figure 1.29:** Some properties of cocopeat (coir pith is cocopeat). Adapted from [72].

Cocopeat is used in many different fields, but its most common application is in agriculture and horticulture (**Figure 1.30**). It is widely preferred in potting mixes, seedling production, turf establishment, ornamental plant cultivation and soilless farming systems. Especially in seedling production, cocopeat is mixed with peat and perlite to optimize air-water balance. In terms of waste management, cocopeat provides a sustainable solution due to its biodegradability and the reuse of waste from the coconut industry [75].



**Figure 1.30:** Cocopeat application of some cocopeat production brands of different countries in soilless agriculture. Adapted from [76].

Being a natural product, cocopeat offers various environmental advantages compared to peat. It has a lower carbon footprint than peat, which is typically extracted from wetlands, while cocopeat is a by-product of the coconut industry and is derived from an already available raw material [72]. Additionally, due to its reusable and long-lasting structure, it also provides economic benefits.

### Plastic Pollution

Plastic materials have become the most using material of our life, with their increasing usage since the beginning of the 20th century. Today, over 400 million tons of plastics are produced in a year. And approximately 40% of this is single use plastics drinking and packaging [77]. This plastic pollution released into the environment and remains undegraded in nature, causing environmental pollution.

The impact of plastic waste on marine ecosystems is dramatic. According to a study in 2015, approximately 4–12 million tons of plastic waste throw the oceans each year and this amount of waste continues annually (**Figure 1.31**) (In Figure 1.31, the high, mid, and low scenarios represent the assumed ratios of mismanaged plastic waste, corresponding respectively to high ( $\approx 40\%$ ), medium ( $\approx 25\%$ ), and low ( $\approx 15\%$ ) leakage rates [78]. This pollution causes physical and chemical harm to marine organisms. Moreover, microplastics enter the food chain and potential risks occur to human health [79].

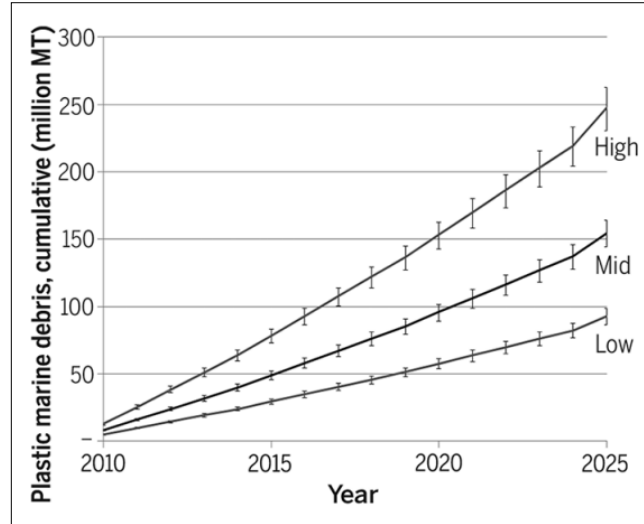


**Figure 1.31:** Plastic waste amount in marines [78].

The source-based classification of plastic waste gives some important information about which sectors contribute most pollution. According to a Europe Union plastic waste report in 2022, the plastic production of Europe is approximately 39% in packaging sectors, 23% in construction, 16% in other applications, 8% in the automotive industry and 6% in electronic products (**Figure 1.32**). The agriculture, farming and gardening sector consumes about 4% of total production of it [80]. The non-biodegradable polymers such as polyethylene and polypropylene results in long-lasting waste in nature when we think about the most using polymers in industries.

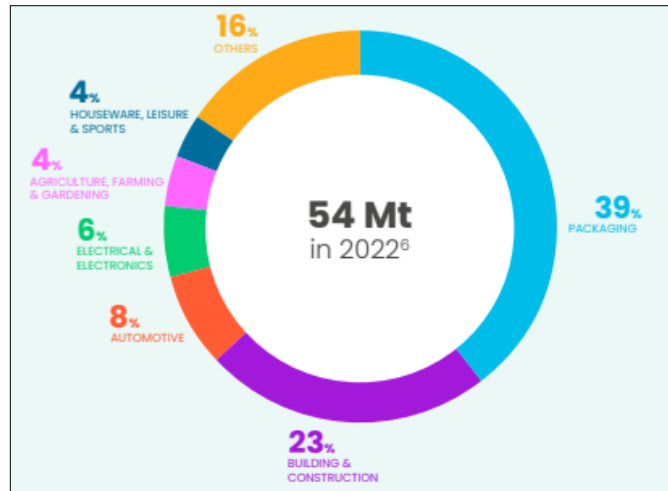


**Figure 1.32:** Plastic waste parts ratio by application [80].

Most plastics used in agriculture as covering materials, single use pots, drip irrigation systems, seedling trays, transport containers and substrates. However, due to the non-biodegradable nature of the polymers used, many of these products cannot be recycled; instead, they are mixing in soil, causing microplastic pollution [81]. The toxic substances released during the degradation of these plastics can be harmful for soil biota.

Soilless agriculture (hydroponics, aeroponics, aquaponics, etc.) is a modern production method where water or inert substrates are used instead of soil. Among the materials used in these systems, plastic-based products play a significant role. Polystyrene (PS) seedling plugs (**Figure 1.33**), polypropylene (PP) pots, polyethylene (PE) covers and transport containers are essential components [5]. However, most of these products are not biodegradable and become waste directly when removed from the system.

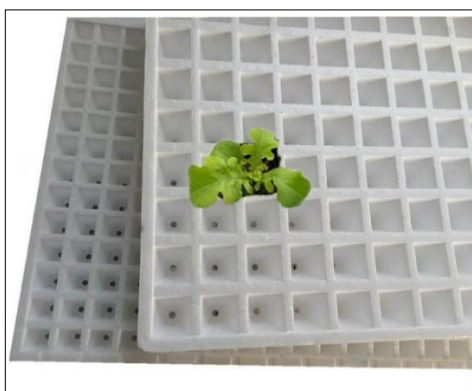


**Figure 1.33:** A polystyrene seedling tray [82].

## Biodegradation

Biodegradability is the process in which materials are broken down by microorganisms into water, carbon dioxide (or methane under anaerobic conditions), biomass and inorganic compounds (**Figure 1.34**). This process is particularly an important criterion in terms of the environmental sustainability of polymer materials. Biodegradable materials contribute to the reduction of waste by enabling natural recycling in the environment [83].

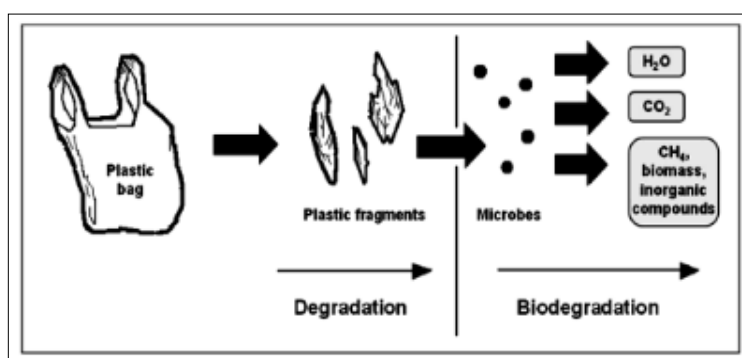


**Figure 1.34:** An example of the biodegradation process of a biodegradable plastic bag [84].

The topic of biodegradability of plastics is researching to reduce and amount the impact of microplastics released into nature. Especially the development of biodegradable alternatives to single use and packaging products (**Figure 1.35**) is being encouraged such as by European Green Deal [85].



**Figure 1.35:** Some biodegradable packaging products [86].

For a material to be considered biodegradable, it must degrade within a specific period under certain environmental conditions (e.g., temperature, humidity). These conditions are tested in laboratory simulations (laboratory scale) that attempt to mimic real-life environments. Biodegradability is not an absolute property. It depends on factors such as material type, chemical structure, environmental conditions and time [87].

Biodegradability is divided into three stages: biological degradation (decomposition of substances by microorganism), physical degradation “mineralization” (the disintegration of broken small parts and stabilizing in nature) and non-toxicity. Therefore, not only the disappearance of the material but also its harmlessness to the environment is an important criterion [88].

Composting is a process in which biodegradable organic waste is biologically decomposed under controlled conditions, mixed and stabilized in soil (**Figure 1.36**). Composting parameters such as temperature and humidity must be optimized. Compostable plastics should be biodegraded under these conditions. Composting is divided into home compost (low temperature) and industrial compost (high temperature

and controlled conditions) types. While home composting is carried out at 20–30 °C, industrial composting occurs at temperatures between 50–60 °C [89].



**Figure 1.36:** An example of composting a biopolymer and its final condition, adapted from: [90].

Compostable plastics should not produce toxic substances during and after composting and the remaining residues in the soil should be harmless. Therefore, for a material to be labeled as “compostable,” just biodegradability is not sufficient; it must also pass ecotoxicity tests for using it soilless agriculture application for example.

There are international standards that evaluate the concepts of biodegradability and compostability conditions. These standards determine biodegradation and composting phenomena under certain conditions. For example, the ISO 14855 standard defines ultimate aerobic biodegradability of plastics and the biodegradability test based on CO<sub>2</sub> production amount under controlled composting conditions [91].

Another important standard is ASTM D6400, which tests the sample in industrial composting conditions. As ASTM D6400 standard, it requires that 90% of the material become biodegradable within 180 days (**Figure 1.37**) [92].

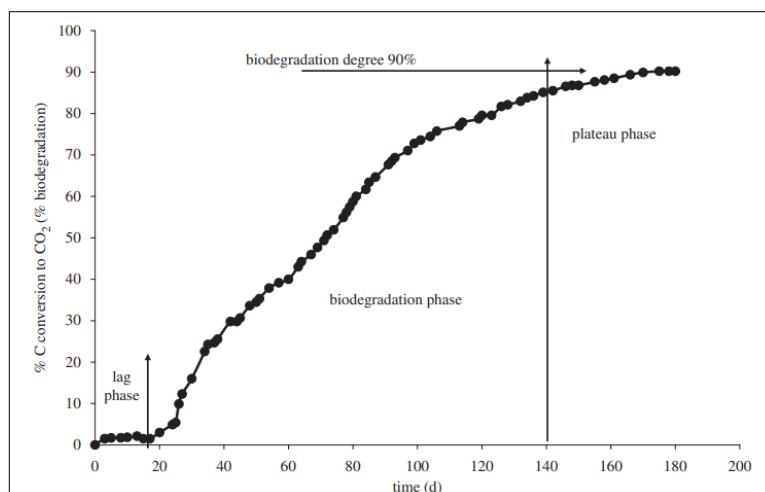


**Figure 1.37:** An example of industrial composting CO<sub>2</sub> release rate of a biodegradable polymer [93].

One of the most used standards in the European Union is EN 13432 and EN14046 standard. These standards combine biodegradability, disintegration (requirement of a specific particle size and stabilizing in nature as “mineralization”), maximum allowable heavy metal content and toxicity measures criteria for compostable plastic packaging in nature. According to European Standard EN 13432:2000 (**Table 1**), after exposing the plastic samples to industrial composting conditions for 12 weeks, 90% of the dry weight of the sample must pass through a 2-mm sieve and 90% of the carbon in the sample must be converted into carbon dioxide within 6 months. Plus, the EN 14995 (ISO 17088) test protocol is employed to quantify the CO<sub>2</sub> released during the biodegradation of plastic samples.

**Table 1.** Composting comparison and its standards. Adapted from:[93].

| <b>Criteria</b>       | <b>Industrial Composting (EN 13432)</b>                                                                                     | <b>Home Composting (Vincotte Certification)</b>                                                                                 |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| <b>Biodegradation</b> | Test at 58 °C for 180 days<br>Minimum 90% biodegradation                                                                    | Test at 20–30 °C for 365 days<br>Minimum 90% biodegradation                                                                     |
| <b>Disintegration</b> | Test at 58 °C for 90 days 2 mm mesh sieve<br>Disintegration >90%Max. 10% of dry weight allowed to be retained by 2 mm sieve | Test at 20–30 °C for 180 days 2 mm mesh sieve<br>Disintegration >90%Max. 10% of dry weight allowed to be retained by 2 mm sieve |
| <b>Certification</b>  | DIN Certco / OK Compost                                                                                                     | OK Home (Vincotte)                                                                                                              |

## 2. MATERIALS AND METHODOLOGY

### 2.1. Materials

The materials used for the fabrication of mycelium-cocopeat biocomposite plugs are listed in **Table 2**.

**Table 2.** Materials used in mycelium-cocopeat biocomposite plugs

| # | Materials                | State  | Form                                  | Bought/Used from                   |
|---|--------------------------|--------|---------------------------------------|------------------------------------|
| 1 | Cocopeat                 | Solid  | fibrous and particulated, brown color | Hateksan Company, Türkiye          |
| 2 | Distilled water          | Liquid | clear color                           | Sartorius Ultra-Pure Water System  |
| 3 | Oyster Mushroom Mycelium | Solid  | white color with barley particles     | Evde Mantar Misel Company, Türkiye |

The materials used for the fabrication of PBAT-cocopeat biocomposite plugs are listed in **Table 3**.

**Table 3.** Materials used in pbat-cocopeat biocomposite plugs

| # | Materials                                                                     | State  | Form                                  | Bought/Used from                     |
|---|-------------------------------------------------------------------------------|--------|---------------------------------------|--------------------------------------|
| 1 | PBAT                                                                          | Solid  | granule, white color                  | Ecoflex® F Blend C1200 BASF. Germany |
| 2 | Ethanol (technical grade, 96%)                                                | Liquid | clear color                           | AYSLAB, Türkiye                      |
| 3 | Chloroform (anhydrous, $\geq 99\%$ , contains 0.5-1.0% ethanol as stabilizer) | Liquid | clear color                           | Sigma Aldrich. Germany               |
| 4 | Cocopeat                                                                      | Solid  | fibrous and particulated, brown color | Hateksan Company, Türkiye            |

## 2.2. Characterization Methods

All characterization tests performed on plugs are listed in **Table 4** below with their names, device names, standards, and details.

**Table 4.** Characterization test details.

| # | Method             | Device Name                                               | Standard              | Process                                                                                                                                                                                                        |
|---|--------------------|-----------------------------------------------------------|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | FTIR               | Perkin Elmer Spectrum 100                                 | ASTM E168             | The vibrational and rotational motions of molecular bonds were investigated using infrared radiation in the wavenumber range of 500–4000 $\text{cm}^{-1}$ .                                                    |
| 2 | TGA                | Mettler Toledo TGA/SDTA 851e                              | ASTM E1131            | Thermal decomposition of the samples was studied at a heating rate of 10 $^{\circ}\text{C}/\text{min}$ over the temperature range of 25–800 $^{\circ}\text{C}$ under an $\text{N}_2$ atmosphere.               |
| 3 | SEM                | Phillips XL30 SFEG Scanning Electron Microscopy           | ASTM E2809            | All samples were coated with gold to prevent charging effect. An accelerating voltage of 15 kV was applied, and microstructural examination was carried out with Secondary Electron detector at micron levels. |
| 4 | EDS                | Phillips XL30 SFEG Scanning Electron Microscopy EDS Probe | ASTM E2809            | All samples were coated with gold to prevent charging effect. An accelerating voltage of 15 kV was applied, and elemental energy distribution examination was carried out with EDS detector at micron levels.  |
| 5 | XRD                | Bruker Advance D8 Diffractometer                          | DIN EN 13925-2        | Atomic structure and crystallography of the samples were examined between 5–70 $^{\circ}$ .                                                                                                                    |
| 6 | Compression Test   | Labomak Çeko                                              | ISO 844:2021          | A force-deformation analysis was performed and plotted as a stress-strain graph. More details are given below.                                                                                                 |
| 7 | Water Absorption   | -                                                         | ASTM D570             | Moisture was removed and water absorption tests were conducted after 2 hours and 24 hours. More details are given below.                                                                                       |
| 8 | Plant Growth Tests | Vahaa Home VSG001 Plant Growth Device                     | HYDROPONIC POT METHOD | A germination test and a 4-week plant growth test were conducted using basil and lettuce seeds. More details are given below.                                                                                  |

**Compression Test:** A compression load was applied using a 25 kg load cell at a crosshead speed of 2 mm/min, up to a maximum deformation of 50%. Samples had 20 mm in diameter and 10 mm in height. The samples were conditioned at room temperature for at least 2 days.

**Water Absorption Test:** The plugs were kept under 25°C and 7 mbar in vacuum oven for 48 hours to remove moisture. Then, three samples were weighed for each plug and soaked in distilled water in beakers. Their weights and weight gain ratios were weighed after 2 hours and 24 hours, then averaged and tabulated.

**Plant Growth Tests:** The plant growth tests were conducted in greenhouses affiliated with the KutmanLAB and Biotechnology Institute of Gebze Technical University. The plant growth performance of our plugs were tested in a home-use smart soilless gardening system (Vahaa Device - VSG001) on two different plans: green basil (first test), final test: green basil, red leaf lettuce, dill, purple basil, lettuce, red chard in comparison with a commercially imported reference plug. Each type of plug (mycelium and PBAT biocomposite plugs) was tested in triplicate in the units with 6 plugs. Drinking water was added to the maximum level inside the home-type smart soilless garden plant growth system, and two caps of commercially available, specially formulated nutrient A and two caps of nutrient B were added to the system. Plant seeds were placed in our plugs and reference plugs. Plant growth plugs containing seeds were placed in the home plant growth system baskets, and the germination caps were closed. The unit was set to germination mode, and germination was monitored at regular intervals. The device's light was then switched to the cultivation mode after germination. Two weeks after the plants began growing in the system, the nutrients were changed. Drinking water was added to the maximum level of the system, and 4 caps of nutrient A and 4 caps of nutrient B were added, and the system was connected to the power source. The water level in the system was checked at regular intervals. When the water level fell below half of the water tank, drinking water was added. The experiment was terminated when the plants reached 28 days in the system. During harvesting, the green parts of all plants were harvested separately, and their wet weights were weighed and tabulated.

### 2.3. Mycelium Biocomposite Plug Production Method

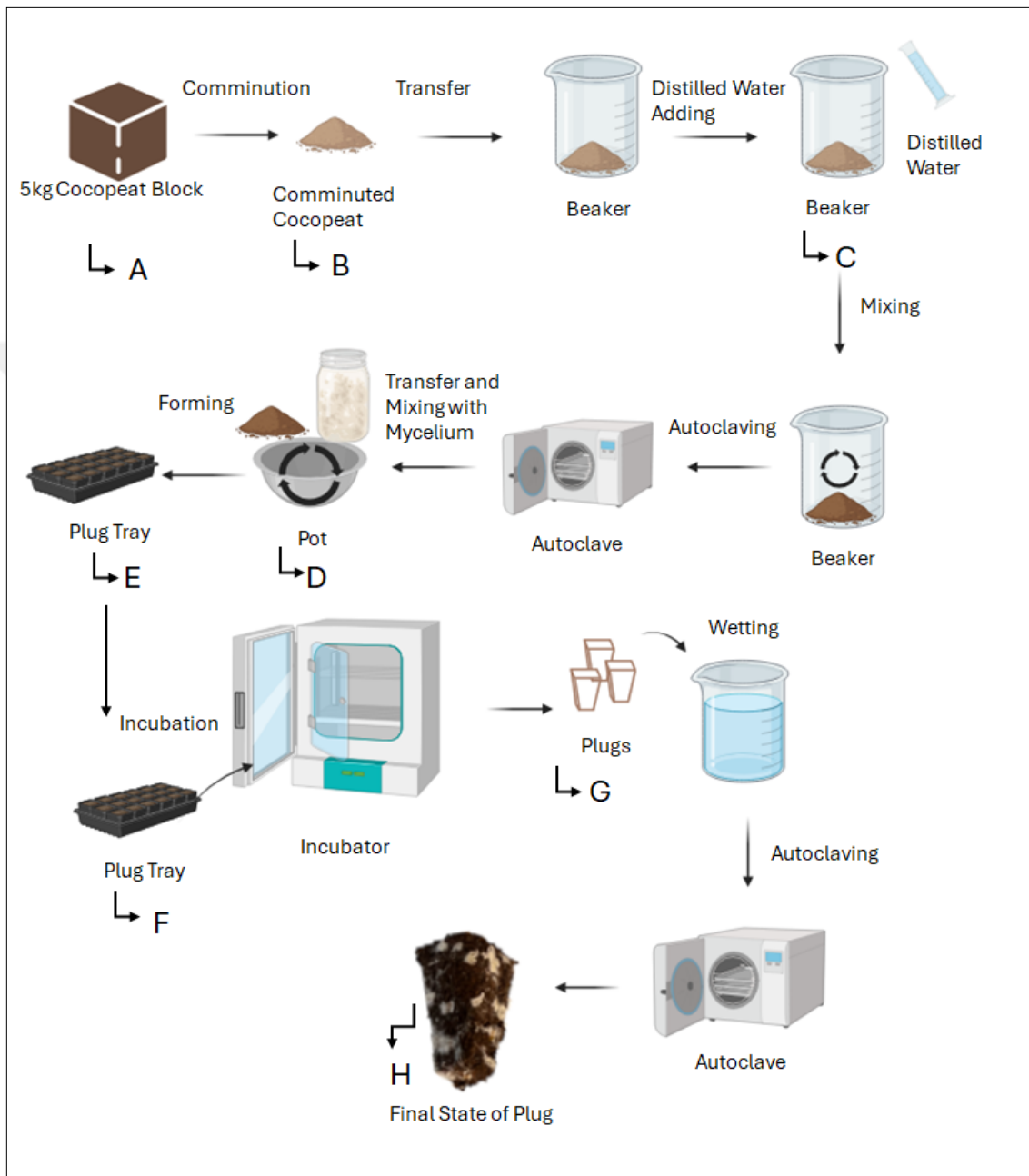


**Figure 2.1:** Production tree of mycelium biocomposite plug.

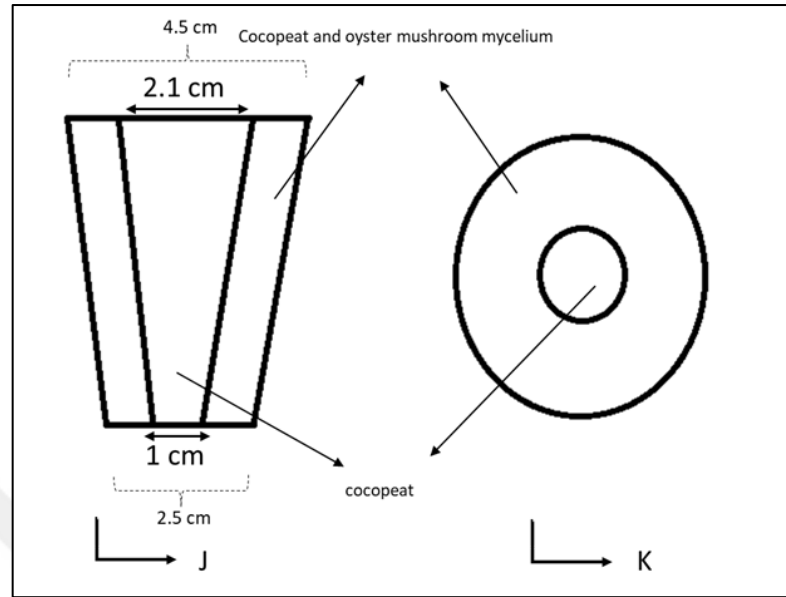


**Figure 2.2:** The design of mycelium biocomposite plugs.

Our mycelium biocomposite plug is based on the method of shaping cocopeat, an organic material, by allowing oyster mushroom mycelium to grow and wrap around it in suitable plug trays. The main matrix material of the plug is cocopeat. Cocopeat has EC: 0.8 mS/cm, pH: 6.38, Na: 1.83 mm/l, K: 3.96 mm/l, Ca: 0.17 mm/l. Cocopeat is obtained in 5 kg bulk block form (**Figure 2.1**, section: A). From this block, cocopeat is separated and crushed for use (**Figure 2.1**, section: B). The reinforced and distinctive material of the plug is oyster mushroom (*Pleurotus ostreatus*) mycelium. Grey oyster mushroom mycelium, produced from barley grains, were used as mycelium. Mushroom mycelium tends to colonize the area in which it is placed under the appropriate nutrient and moisture conditions [94]. The amount of moisture required by the mushroom mycelium in the plug tray is pre-added to the cocopeat (**Figure 2.1**, section: C). This moisture amount is approximately 275 ml of distilled water for every 100 g of cocopeat. The moistened cocopeat is then subjected to autoclaving at 121°C for 20 minutes to achieve solid culture sterilization. Afterwards, a portion of the sterilized cocopeat is set aside and the remaining cocopeat is mixed with oyster mushroom mycelium in a pot (**Figure 2.1**, section: D). In this mixture, approximately 0.65 g of mushroom mycelium is used per 1 g of cocopeat. This mixture is transferred into plug trays using the plug geometry shown in **Figure 2.1**.

As shown in sections J and K in **Figure 2.2**, the mixture of mushroom mycelium and cocopeat is placed around the edges of the mold, while the center is filled with the cocopeat only with the dimensions given in **Figure 2.2**. The aim here is to use the capillary action of the cocopeat in the center, which can carry water upward, more effectively. Since mushroom mycelium is a highly hydrophobic material, its capillary effect is weak or not observed at all [95]. The filled plug trays (**Figure 2.1**, section: E) are then incubated at 25°C for one part 4 days and the other part 10 days (**Figure 2.1**, section: F). During these 4 or 10 days, the mushroom mycelium surrounds and tries to consume cocopeats in the plug tray, enabling the cocopeat and mycelium to take the shape of the plug tray mold (**Figure 2.3**). Plugs with completed incubation (**Figure 2.1**, section: G) are removed from the plug tray and immersed in a beaker filled with water. The plugs are then subjected to an autoclave process. The purpose here is to deactivate the mushroom mycelium, terminating its growth and preventing mushroom formation during soilless agriculture applications. The reason for immersing in water before autoclaving is to enhance the penetration and effectiveness of the deactivation process. Plugs removed from the autoclave (**Figure 2.1**, section: H) are then left to dry in open air under room conditions for one day. Once dry, the plugs are ready for use. During our plug production process, problems such as failure to deactivate the mushroom, lack of capillary action preventing water absorption and unwanted mold formation were encountered. As described above, these problems were resolved through autoclave procedures and plug geometry optimization. And our mycelium-cocopeat biocomposite plugs are named as at **Table 5**.

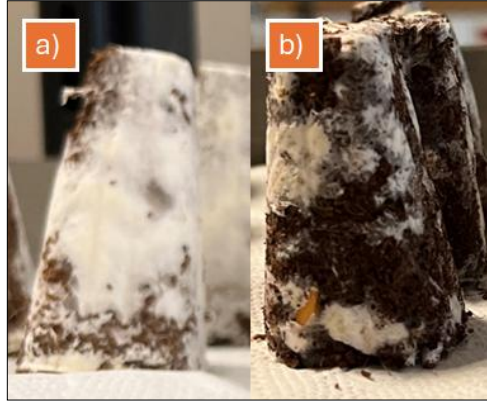


**Figure 2.3:** Mycelium-cocopeat plug incubated for 10 days (a) and 4 days (b).

### **2.3.1. Production Method of Mycelium Biocomposite Plugs Incorporating Biochar and Perlite:**

In addition to mycelium cocopeat biocomposite plugs, plugs containing biochar and perlite were produced (**Figure 2.4**). Following the plug design in **Figure 2.2**, only cocopeat was used in the middle. Perlite is a volcanic rock, a silicon-based rock used to regulate air space and air flow in in soilless agriculture substrates. The addition was made to consider whether increasing the porosity in the plugs could improve the plant grow quality of the plugs. Biochar used in this study was obtained by carbonizing (by pyrolysis) tomatoes grown in our university greenhouse at Institute of Biotechnology. Biochar is used in soilless agriculture as a supplement containing various minerals such as Mg and K that promote plant growth. The potential effects of these minerals on plant growth were investigated. Within this scope, plugs containing an additional 5% (w/w total weight) perlite, 5% biochar, 5% perlite + 5% biochar, and 10% biochar have been produced (**Table 5**).

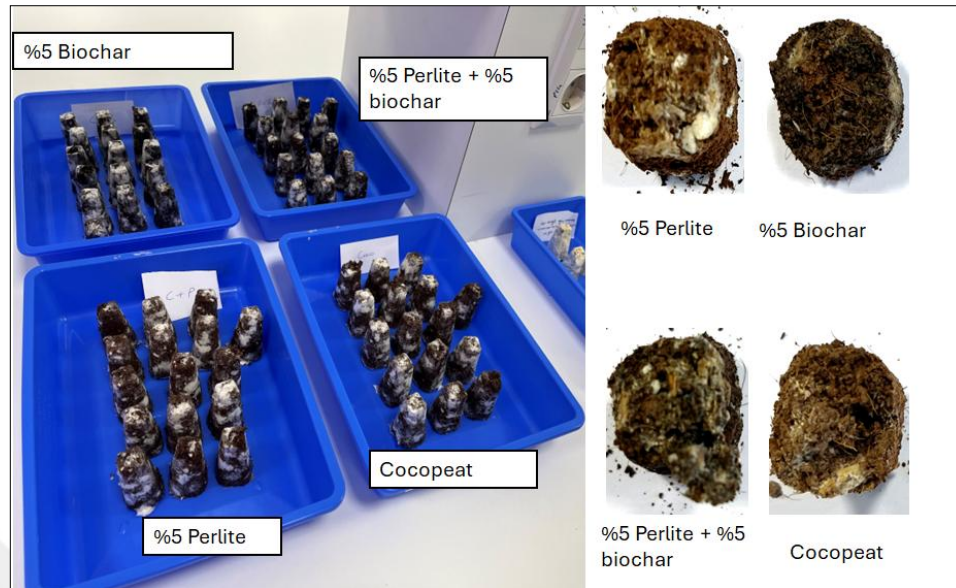


**Figure 2.4:** Biochar and perlite added plugs.

## 2.4. PBAT-Cocopeat Biocomposite Plugs Production Method

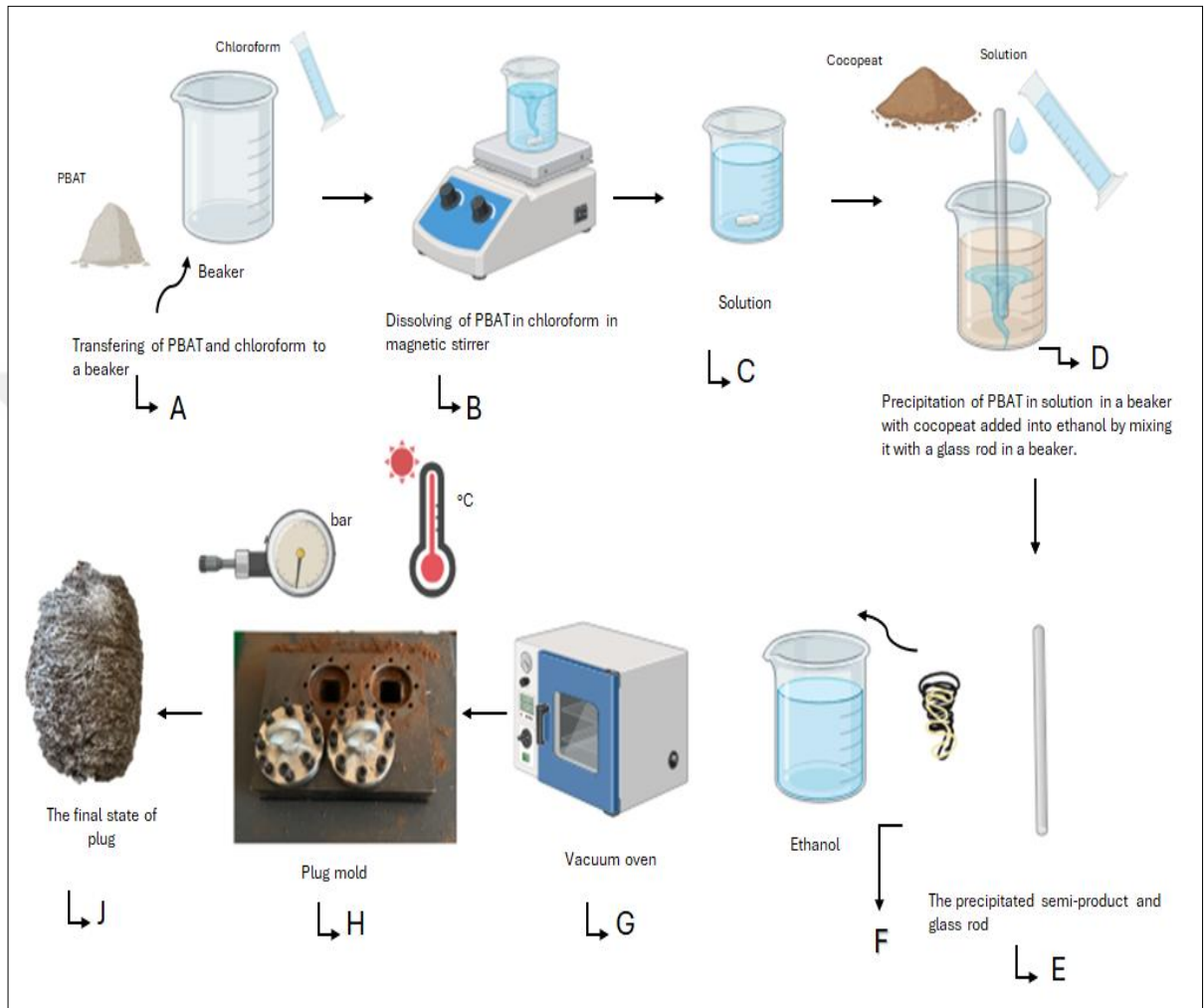


**Figure 2.5:** Production tree of PBAT plug.

Our PBAT plug is based on the method of wrapping precipitated PBAT polymer fibers around cocopeat. The main matrix material of the plug is cocopeat as in other mycelium-cocopeat plug. The reinforcing and distinctive component of the plug is the precipitated PBAT polymer fibers. Since PBAT is a hydrophobic polymer, a physical hydrophilic characteristic has been added to it through the precipitation method in fiber form [96]. The production begins with placing PBAT granules and chloroform into a beaker (**Figure 2.5**, Section: A). In the production process, 50 ml of chloroform is used for every 10 g of PBAT to be dissolved. Then, this mixture is stirred with a magnetic stirrer (**Figure 2.5**,

Section: B). PBAT can dissolve in chloroform at room temperature; it is stirred for approximately 30 minutes without heating. The stirring speed is determined according to the beaker and mixture volume. While a speed of 250–300 rpm is sufficient for a 100 ml beaker containing 50 ml of chloroform and 10 g of PBAT, a speed of 650–750 rpm is sufficient for a 250 ml beaker containing 125 ml of chloroform and 25 g of PBAT. After the PBAT is dissolved in chloroform, an appropriate amount of the PBAT-chloroform solution (**Figure 2.5**, Section: C) is transferred into a graduated cylinder and precipitated with cocopeat in ethanol (**Figure 2.5**, Section: D). For plug composition comparison, PBAT-cocopeat ratios of 25%-50%-75% by weight for PBAT polymer and 75%-50%-25% for cocopeat were applied, resulting in the production of three different polymer plugs (**Figure 2.6**, **Table 6**). For the 25% PBAT plug, 2.5 ml of solution is added to the graduated cylinder, containing 0.5 g PBAT and 1.5 g of cocopeat, is transferred into ethanol. While precipitating PBAT with cocopeat in ethanol, for a more homogeneous distribution, the solution and cocopeat must be added in 3–4 steps rather than all at once and stirred with a glass rod in ethanol. A glass rod (**Figure 2.5**, Section: E) was preferred for its corrosion resistance and consistency during the ethanol precipitation process. The precipitated precursor product wrapped around the glass rod (**Figure 2.5**, Section: F) is then placed into a beaker filled with ethanol and stirred to enhance the removal of chloroform. The precursor products are left in ethanol for 1 hour and then transferred into a vacuum oven (**Figure 2.5**, Section: G). In the vacuum oven, at 60°C and 7 mbar vacuum, the residual chloroform is removed for at least one day. The precursor products, purified from chloroform, are now ready for use (**Figure 2.5**, Section: J). During the plug production process, residual chloroform and sticking to the mold have been encountered as problems. These problems were resolved by soaking the plugs in ethanol and drying them in the vacuum oven and by coating the products to be molded with cocopeat powder.

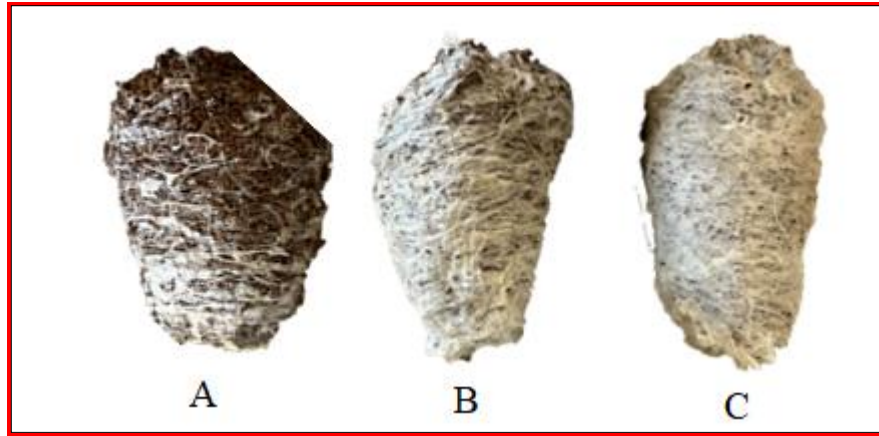


**Figure 2.6:** PBAT-cocopeat biocomposite plugs. (A:25%PBAT, B:50%PBAT, C:75%PBAT by weight).

**Table 5:** Nomenclature of mycelium-cocopeat biocomposite plugs.

| # | Name          | Incubation Period | Autoclave | Perlite Addition (%) | Biochar Addition (%) |
|---|---------------|-------------------|-----------|----------------------|----------------------|
| 1 | 4myce         | 4 days            | -         | 0                    | 0                    |
| 2 | 10myce        | 10 days           | -         | 0                    | 0                    |
| 3 | 4myce-o       | 4 days            | +         | 0                    | 0                    |
| 4 | 4myce-o-5p    | 4 days            | +         | 5                    | 0                    |
| 5 | 4myce-o-5b    | 4 days            | +         | 0                    | 5                    |
| 6 | 4myce-o-5p-5b | 4 days            | +         | 5                    | 5                    |
| 7 | 4myce-o-10b   | 4 days            | +         | 0                    | 10                   |

**Table 6:** Nomenclature of PBAT-cocopeat biocomposite plugs.

| # | Name   | PBAT (%) | Cocopeat (%) |
|---|--------|----------|--------------|
| 1 | 25PBAT | 25       | 75           |
| 2 | 50PBAT | 50       | 50           |
| 3 | 75PBAT | 75       | 25           |

### 3. RESULTS AND DISCUSSION

#### 3.1. Mycelium-Cocopeat Biocomposite Plugs

##### 3.1.1. FTIR

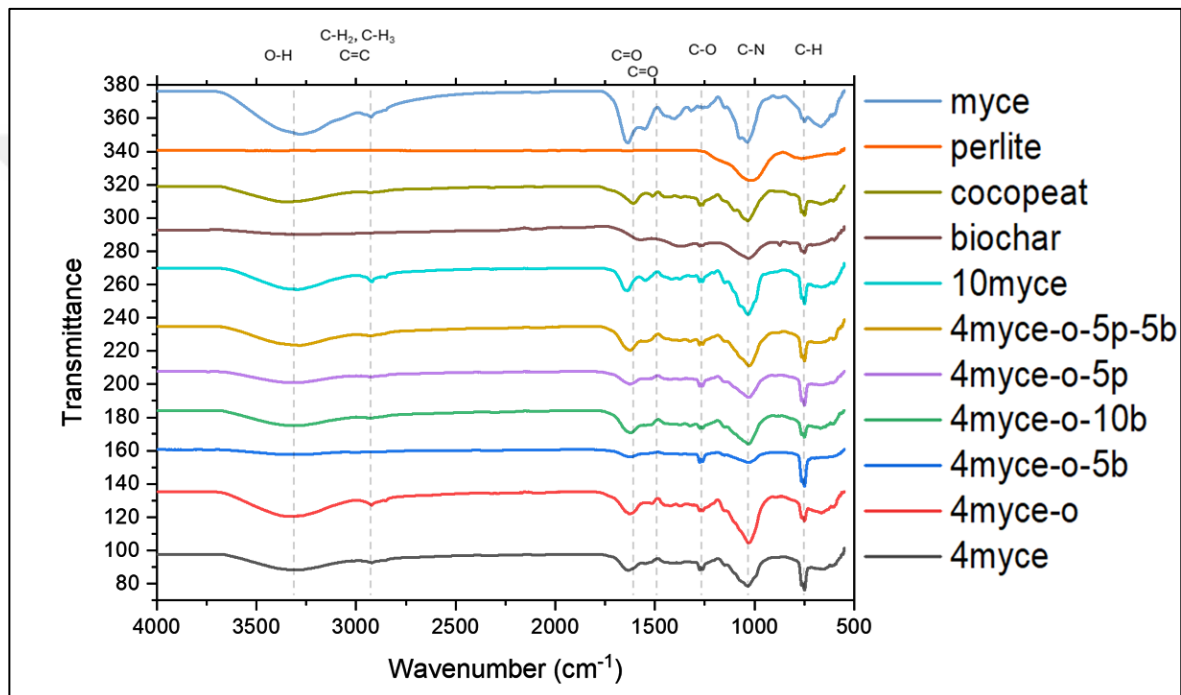


**Figure 3.1:** FTIR graph of mycelium biocomposite plugs.

**Figure 3.1** shows FTIR spectrum of mycelium-cocopeat biocomposite plugs. O-H bonds in the  $3600\text{--}3200\text{ cm}^{-1}$  region [97], which originate from the presence of water, cellulose, and lignin groups in our biocomposite plug. This region is prominent in all plugs, and the difference in peak intensity in the perlite sample is due to the presence of inorganic material. The reason it is not seen in perlite, which is an inorganic material, is that it does not contain O-H bonds in its structure [98]. A C-H stretching band was observed in the  $2950\text{--}2850\text{ cm}^{-1}$  region [97], [99], which is due to organic compounds of lipids, proteins, and lignin. Since mycelium is rich in lipids and proteins, it has characteristic C-H bands in this region and determines the peak intensity. A C=O stretching band was observed

between 1740-1630  $\text{cm}^{-1}$  [99], which is due to the structure of lignocellulosic materials of cocopeat and biochar. A critical region was observed in the 1500-500  $\text{cm}^{-1}$  region, including C-O at 1310-1250  $\text{cm}^{-1}$ , C-N at 1250-1020  $\text{cm}^{-1}$  [99], Si-O-Si at 1005-940  $\text{cm}^{-1}$  [98], and C-H bonds [97]. The main differences in the FTIR spectra of the samples are the C-N stretching from the presence of chitin in the mycelium, the Si-O-Si presence from inorganic structures such as perlite, and the C-O and aromatic ring vibrations from lignocellulosic materials of cocopeat [98], [99].

### 3.1.2. TGA

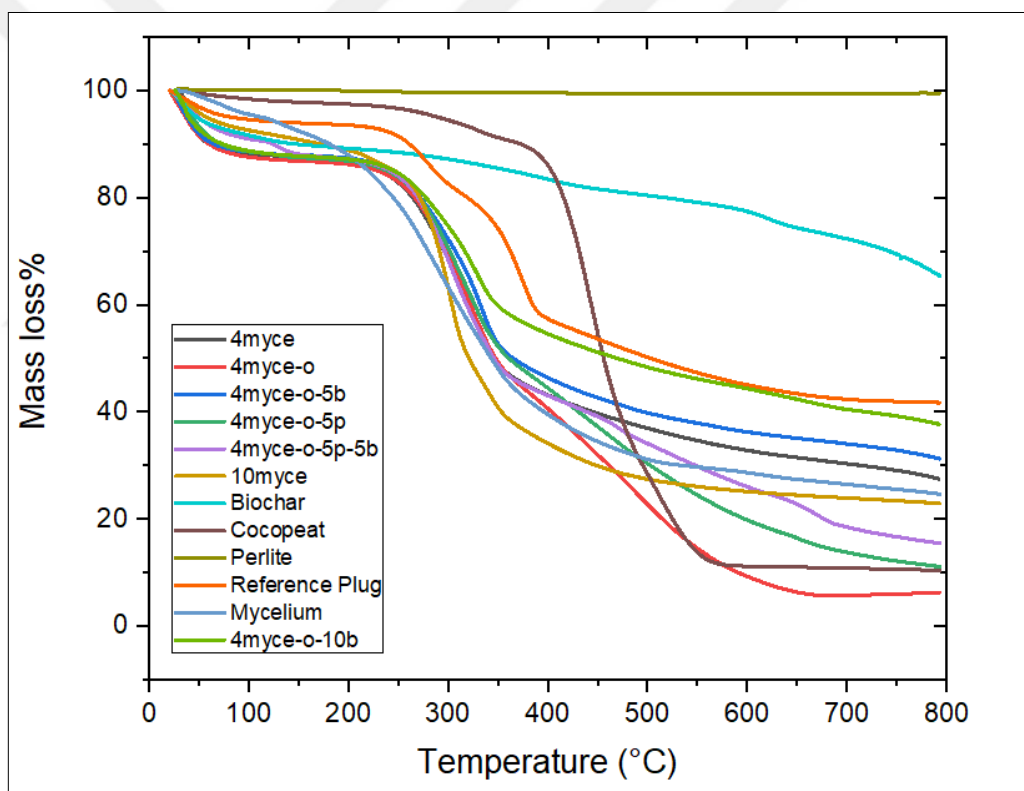


**Figure 3.2:** TGA graph of mycelium-cocopeat biocomposite plugs and raw materials vs reference plug.

**Table 7:** Thermal stability table of mycelium-cocopeat biocomposite plugs and raw materials from **Figure 3.2**.

| Material/Plug Name | T <sub>decomposition</sub> (°C)   | Residual Mass @800°C (%) |
|--------------------|-----------------------------------|--------------------------|
| Perlite            | Very low degradation 100–800      | 99                       |
| Biochar            | Slow, gradual degradation 150–600 | 65                       |
| Reference Plug     | 275 and 350 (binary curve)        | 42                       |
| Cocopeat           | 400                               | 10                       |
| 4myce-o-10b        | 270                               | 37                       |
| 4myce-o-5p-5b      | 255                               | 15                       |
| 4myce-o-5p         | 260                               | 11                       |
| 4myce-o            | 250                               | 8                        |
| 4myce-o-5b         | 252                               | 32                       |
| 4myce              | 250                               | 28                       |
| 10myce             | 260                               | 23                       |
| Mycelium           | 235                               | 24                       |

**Figure 3.2** shows TGA graph of mycelium-biocomposite plugs, perlite, biochar, mycelium and reference plug. Perlite, being an inorganic material, has not shown decomposition in the 100-800 °C degree range [100]. Biochar has shown high stability up to 600 °C thanks to its high carbon content [101]. It was observed that the thermal degradation temperature of mycelium plugs increased (4myce: 250 °C) with the addition of biochar (4myce-o-10b: 270 °C) and perlite (4myce-o-5p: 260 °C). Thanks to the formation of a composite with cocopeat, the thermal degradation temperature of the mycelium has increased by approximately 20-35 °C. The degree of thermal degradation increased as the plug incubation time increased (4myce: 250 °C, 10myce: 260 °C). The highest thermal stability among the mycelium biocomposite plugs was observed with the addition of 10% biochar (4myce-o-10b: 270 °C) which showed a residual mass of 37% at 800°C. (**Table 7** and **Figure 3.2**). When examining materials used in the literature as plant grow plugs (reference plug 42% at 800 °C) or plant grow media, such as perlite (99% at 800 °C) [100] and vermiculite (80% at 800 °C) [102], our mycelium biocomposite plug (max 37 % 800 °C), being composed entirely of organic materials, lags only slightly behind other materials in terms of thermal stability.

For the reference plug, at the beginning of the curve, a slight mass loss is observed up to 200°C, which is generally due to the volatility of relative humidity. Foamy materials can

retain moisture due to their porous structure. A significant and rapid mass loss is observed between 300 °C and 350 °C. The weight loss is approximately 55%. Polyurethanes typically experience significant mass loss between 300-400 °C degrees, and the isocyanates and polyols in their structure evaporate from the structure within this temperature range [103]. This is a clue that the plug may contain polyurethane. After approximately 450 °C degrees, the rate mass loss decreases, indicating the presence of additives within the structure that remain stable at these temperatures. These additives are thought to be glass wool and rock wool (dolomite rock) [104].



### 3.1.3. SEM

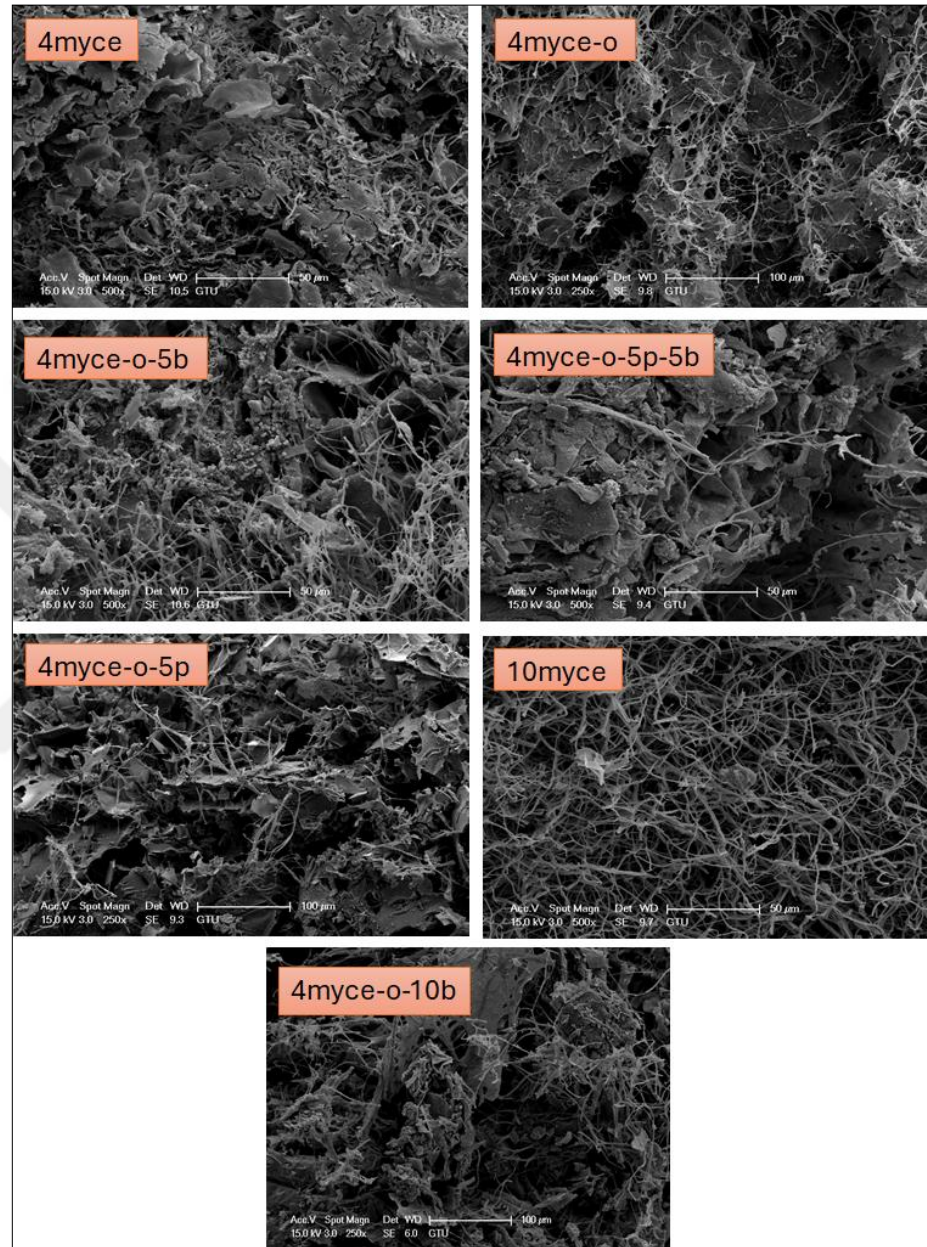


**Figure 3.3:** SEM images of mycelium-cocopeat biocomposite plugs.

**Figure 3.3** shows the SEM images of the mycelium-cocopeat biocomposite plugs that were examined separately. Each plug exhibited a sufficiently porous structure to support root development. As the mycelium incubation period increased, the wrapping density and the hyphae diameter (approximately 2 times) of the mycelium was observed to increase

(**Figure 3.3-10myce** vs **4myce**). This morphological evolution is considered the fundamental microstructural indicator of increased mechanical integrity in mycelium-based composites [105]. The successful adhesion between the mycelium hyphae and the cocopeat particles were clearly visible (e.g., **Figure 3.3-4myce-o**). The autoclaving process was found to have no observable effect on the mycelium hyphae, such as changes in density or diameter (**Figure 3.3-4myce** vs. **4myce-o**). It was observed that the additions of biochar and perlite interacted well with the cocopeat matrix and were able to adhere well with the mycelium (e.g., **Figure 3.3-4myce-o-5b** and **4myce-o-5p**).

### 3.1.4. XRD

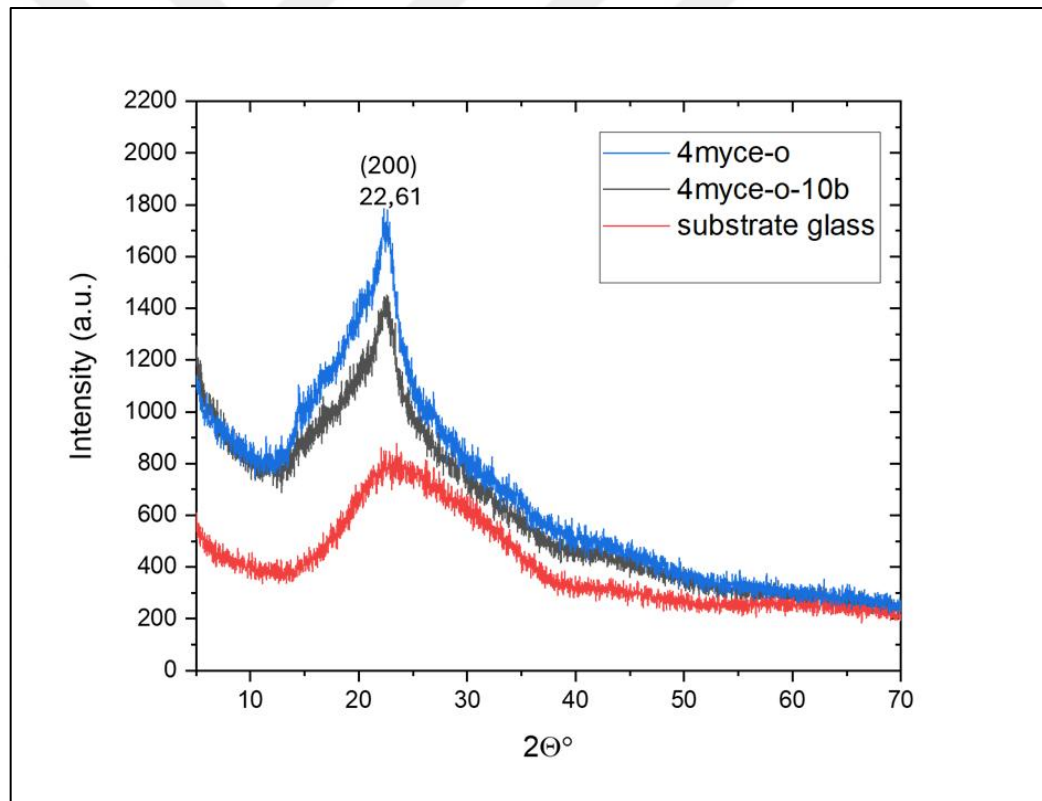


**Figure 3.4:** XRD graph of mycelium-cocopeat biocomposite plugs.

**Figure 3.4** shows the XRD patterns of **4myce-o-10b**, **4myce-o**, which showed the best plant growth performance, and the substrate glass that samples were placed. The reason to include an XRD graph of the glass substrate is to distinguish the possible amorphous

peaks of the glass substrate. The XRD curve of the glass substrate sample, shown by the red line, exhibits a characteristic broad and wavy peak centered between  $15^\circ$  and  $35^\circ$  [106]. This pattern clearly reflects the amorphous, non-crystalline structure of silica-based materials. The 4myce-o plug, represented by the blue line, exhibits a high-intensity, relatively narrow peak at an angle of  $22.61^\circ$ . This peak indicates that the cocopeat substrate is cellulose-derived and highly ordered in the (200) crystal plane (XRD patterns of crystal lattice type 1 of cellulose is given as  $2\Theta = 15.6^\circ$  (110),  $22.7^\circ$  (200), and  $34^\circ$  (004) [107] , [108]). The 4myce-o-10b plug, indicated by the black line, shows that cellulose inside of the plug has not undergone a significant phase change in its crystal structure, maintaining the dominant peak at the same position ( $22.61^\circ$ ) as 4myce-o. This indicates that the addition of biochar does not disrupt the structure of the existing cellulose polymorph.

### 3.1.5. Compression Test

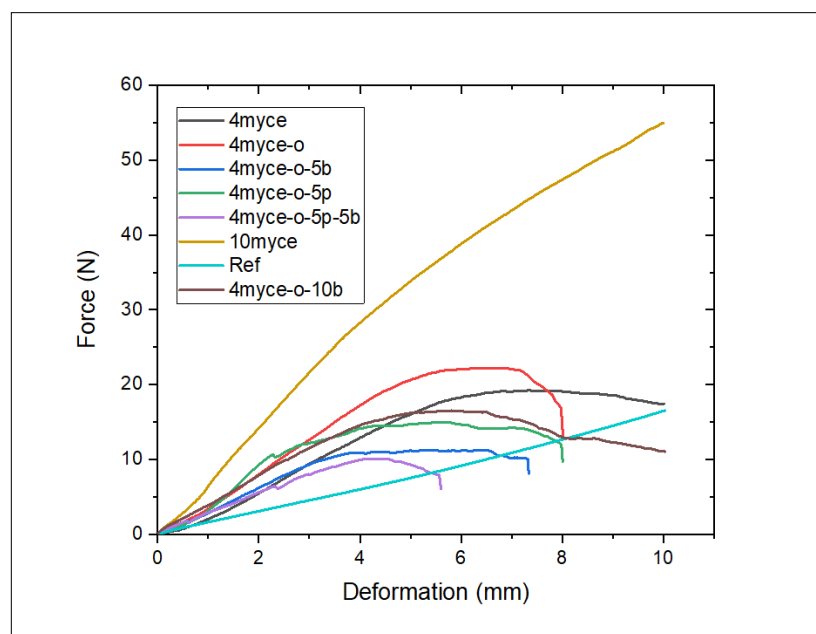


**Figure 3.5:** Force-deformation graph of mycelium-cocopeat biocomposite plugs.

**Table 8:** Force-deformation table from **Figure 3.5**.

| Plug          | F <sub>ultimate</sub> (N) | Deformation@rupture (mm) |
|---------------|---------------------------|--------------------------|
| 4myce         | 18                        | ≥10                      |
| 4myce-o       | 22                        | 8.0                      |
| 4myce-o-5b    | 11                        | 7.3                      |
| 4myce-o-5p    | 15                        | 8.0                      |
| 4myce-o-10b   | 16                        | ≥10                      |
| 4myce-o-5p-5b | 10                        | 5.6                      |
| 10myce        | ≥ 55                      | ≥ 10                     |
| Reference     | ≥ 15                      | ≥ 10                     |

**Figure 3.5** shows the force-deformation curves of the mycelium plugs and the reference plug. Since the mycelium plugs could not be cut in cylindrical form, a standard size, required for the standard compression test, could not be obtained, therefore instead of a stress-strain graph force-deformation relationship was examined. According to these results, the 10myce sample demonstrated the highest performance by far in terms of both maximum deformation and maximum compressive strength capacity. An increase in strength (18 N to 55 N) was observed as the incubation time increased from 4 days to 10 days (10myce vs 4myce – **Table 8**). It has been determined that the autoclave process makes the structure more rigid (18 N to 22 N) but more brittle (10 mm to 8 mm) when comparing to 4myce vs 4myce-o. The biochar additive, especially at the 5% level, resulted in early failure (10 mm to 7.3 mm) and low deformation when comparing to 4myce. The %5 perlite additive provided a more ductile mechanical response (8 mm vs 7.3 mm) by increasing the failure deformation when comparing to %5 biochar added plugs. The combined use of biochar and perlite reduced the mechanical properties when comparing the others. The reference sample did not exhibit fracture probably due to its low stiffness.

## 3.2. PBAT- Cocopeat Biocomposite Plugs

### 3.2.1. FTIR

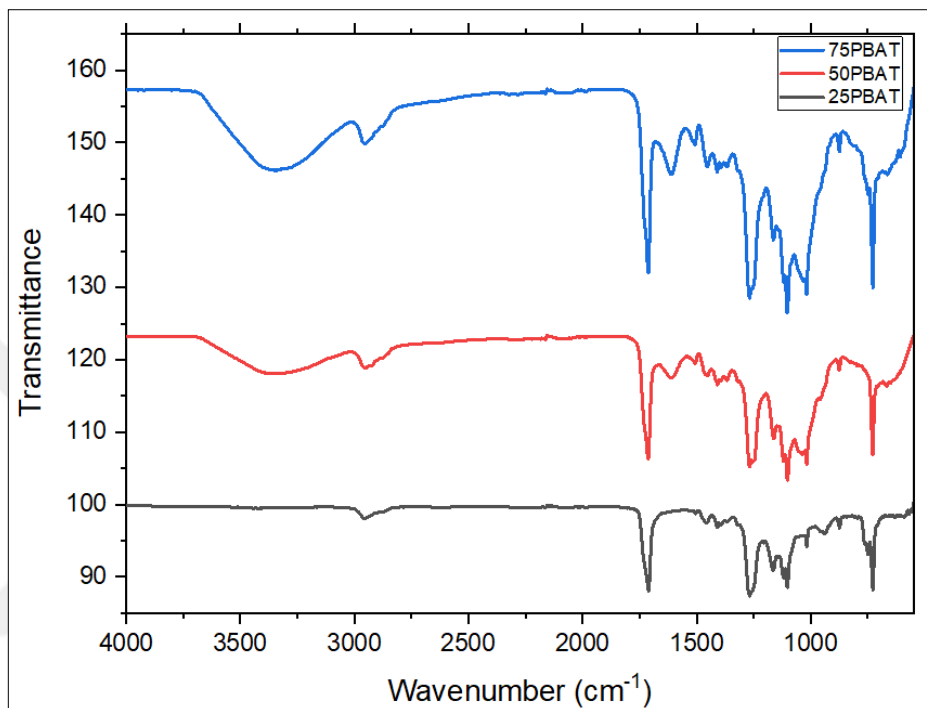


**Figure 3.6:** FTIR graph of PBAT plugs.

**Figure 3.6** shows FTIR spectrum of PBAT-cocopeat biocomposite plugs. In the spectrum, there is O-H stretching band between 3600-3200 cm<sup>-1</sup> [109] which is due to the moisture and/or lignocellulosic content of cocopeat. A C-H stretching band is observed between 2950-2850 cm<sup>-1</sup> [110], which is due to the aliphatic C-H stretching vibrations in the butylene part of PBAT and aliphatic regions of the lignocellulosic content of cocopeat. A C=O stretching band is observed between 1750-1700 cm<sup>-1</sup> [109], which is due to the ester group in the PBAT and cocopeat. As the PBAT density increases, the intensity of C=O peak increases. A C=C stretching band is observed at 1507 cm<sup>-1</sup> corresponds to the benzene ring of PBAT [110]. As the PBAT concentration increases, the intensity of this peak also increases. C-O and C-O-C stretching bands were observed between 1300-1000 cm<sup>-1</sup> [109], due to the vibrations in the ester and ether bonds in the structure of PBAT and

cocopeat. As the cocopeat ratio increases, a decrease in peak intensity is observed [111] [112].

### 3.2.2. TGA

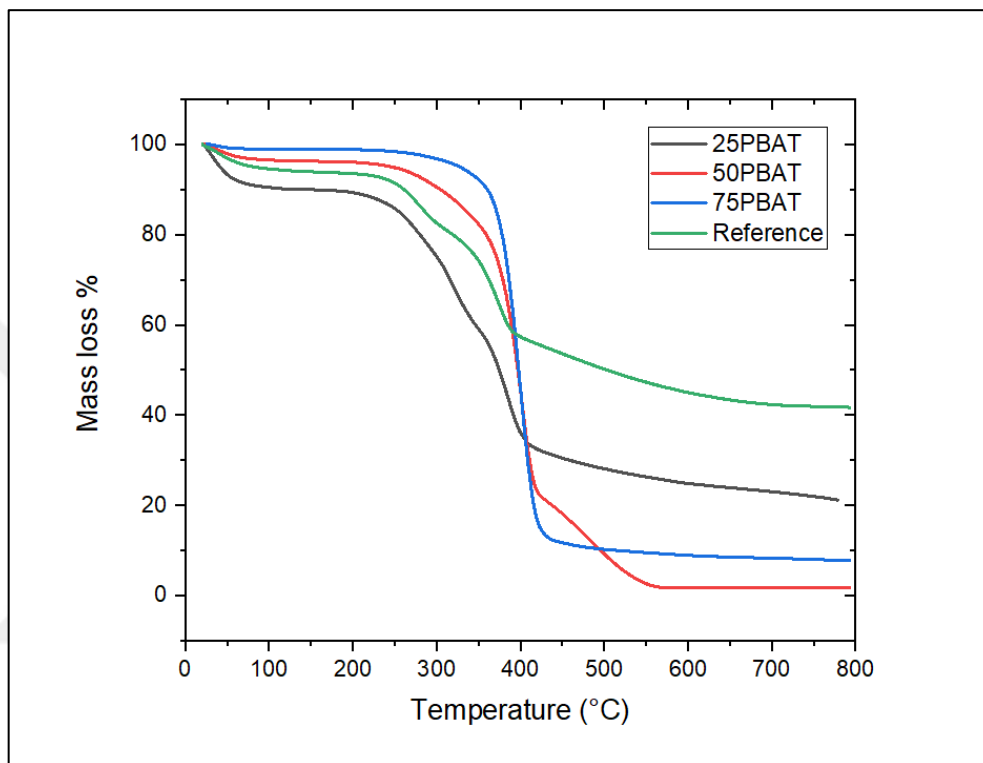


**Figure 3.7:** TGA graph of PBAT plugs vs reference plug.

**Table 9:** Thermal stability table of PBAT-cocopeat biocomposite plugs and reference plug from **Figure 3.7**.

| Material/Plug Name | T <sub>decomposition</sub> (°C) | Residual Mass @800°C (%) |
|--------------------|---------------------------------|--------------------------|
| 25PBAT             | 250                             | 21                       |
| 50PBAT             | 350                             | 2                        |
| 75PBAT             | 375                             | 8                        |
| Reference          | 275 and 350 (binary curve)      | 42                       |

**Figure 3.7** shows the TGA curves for 25PBAT, 50PBAT, 75PBAT, and the reference plug. As the PBAT ratio in the plugs increased, higher thermal stabilization was observed. An increase in thermal degradation temperatures degree is observed as the PBAT ratio increases (250 °C to 375 °C). When we investigate the residual mass amount at 800 °C, the least decrease was observed in the reference capsule, followed by 25PBAT (21%)-75PBAT (8%)-50PBAT (2%) at 800 °C. (**Table 9**). According to the TGA results of PBAT in the literature, the residual mass amount of PBAT at 800°C (10%) can be increased with the addition of 75% cocopeat (e.g., 25PBAT: 21%) [113].

The residual mass of the reference plug at 800 °C was higher than that of the other plugs, because probably the main material is different and the possible presence of the additives such as glass wool and rock wool [114]. The reference plug TGA results have been examined in detail in the mycelium-biocomposite TGA results (p.43).

### 3.2.3. SEM

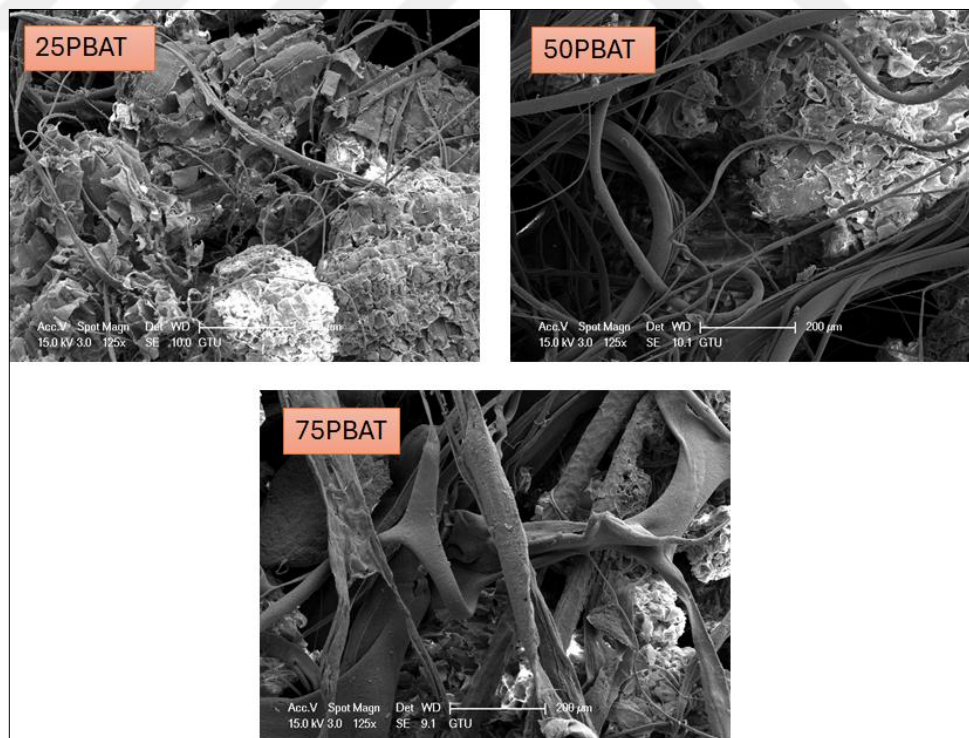


**Figure 3.8:** SEM images of PBAT-cocopeat biocomposite plugs.

**Figure 3.8** shows SEM images of PBAT-cocopeat biocomposite plugs. The interaction between coconut fiber and PBAT fibers was investigated. It has been observed that PBAT fibers adhere to the coconut fiber particles as a result of the precipitation process, thereby ensuring integrity. In fibers produced using phase separation strategies in PBAT, the solvent–non-solvent combination and moisture/evaporation conditions can alter not only the surface porosity but also the average fiber diameter to a size greater than 0.8  $\mu\text{m}$ ; the fundamental reason for this is precipitation/solidification kinetics [115]. An increase in PBAT content (25PBAT to 75PBAT) led to an increase in both the density and diameter of PBAT fibers within the structure. The average diameter was 10  $\mu\text{m}$  in 25PBAT, 20–30  $\mu\text{m}$  in 50PBAT, and approximately 50  $\mu\text{m}$  in 75PBAT. In addition, as the PBAT content increased, the plugs became harder and more rigid, attributed to PBAT’s inherently more rigid structure compared to that of cocopeat.

### 3.2.4. XRD

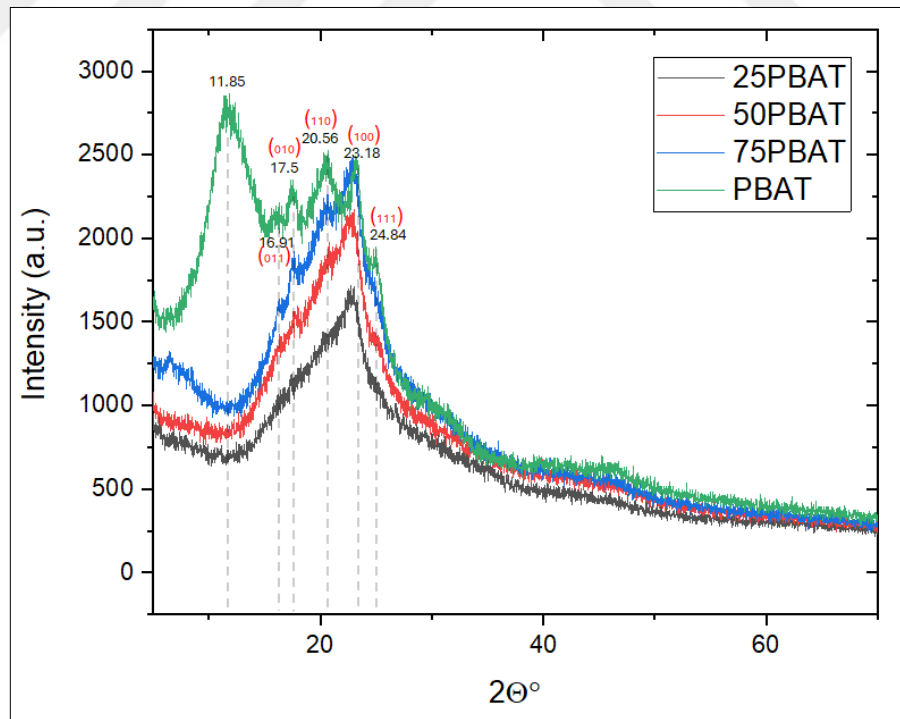


**Figure 3.9:** XRD graph of 25-50-75% PBAT and neat PBAT plugs.

**Figure 3.9** shows the XRD patterns of PBAT-cocopeat biocomposite plugs. Peaks were found at  $11.85^\circ$ ,  $16.91^\circ$ ,  $17.5^\circ$ ,  $20.56^\circ$ ,  $23.18^\circ$ , and  $24.84^\circ$ . The orientation of the peaks is given below by comparison with the literature [116]. The presence and clarity of peaks originating from the PBAT polymer support the ability of PBAT to form a directed crystalline structure with high chain orientation during the fiber formation process (solvent precipitation technique). It has been observed that as the PBAT ratio increases, the number and intensity of peaks in the structure increases (e.g,  $17.5^\circ$ ). The peak at  $11.85^\circ$  could not be found in the literature, but considering the other peaks and the production process, it is estimated to the crystal structure of PBAT belong to the (100) family (001), (010), (100)). This is because the PBAT fibers, which are deposited by winding around a glass rod, are oriented in the (001) direction during production but are placed in the (100) direction on the glass lamella for XRD analysis. Furthermore, since it is the most intense peak, it is thought to belong to the (100) family. The reason why the peak at  $11.85^\circ$  is not found in plug samples is likely due to incomplete orientation of the PBAT fibers in the inner regions, possibly caused by cocopeat fibers disrupting the full alignment of PBAT during precipitation [117].

### 3.2.5. Compression Test

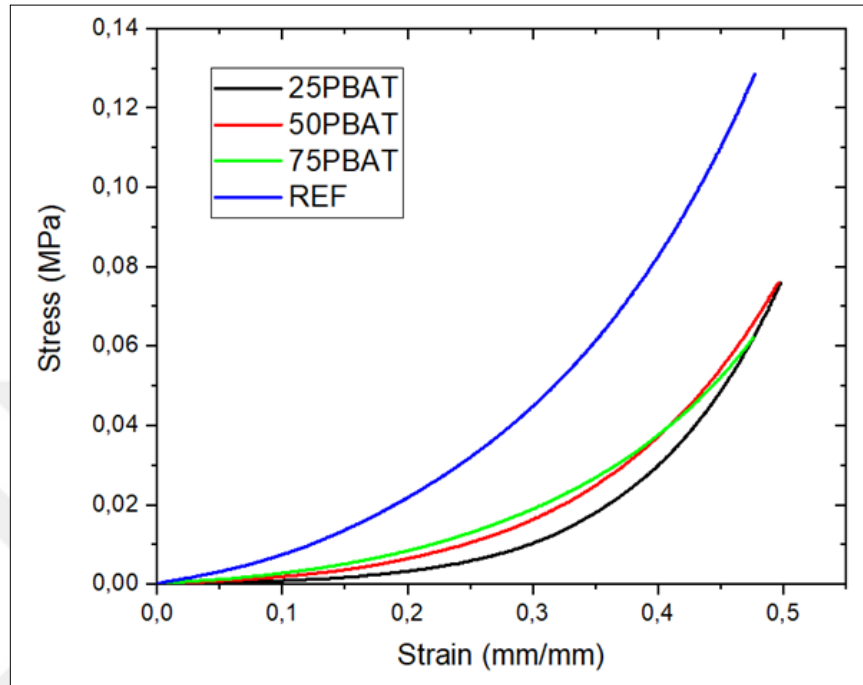


**Figure 3.10:** Stress-strain graph of PBAT-cocopeat biocomposite plugs vs reference plug.

**Figure 3.10** shows the stress-strain graph of PBAT plugs and **Table 10** shows their compression strength at 10% deformation. The reference plug is presumed to be a polyurethane-based plug containing glass wool and rock wool, in the previous characterizations, however, its compression strength value was found to be lower than values reported in the literature (200-800 kPa at 10% strain) [118]. This may indicate that the material is composed of a different material, or that its porosity is higher than that of the samples reported in the literature. In PBAT plugs, it was observed that as the PBAT ratio increased, the compression strength of the plug increased, and the structure became more rigid. The plugs exhibited compression resistance comparable to cocopeat briquettes (3-30 kPa) [119] and lower performance than that of neat PBAT foams (40-50 kPa) [120], [121].

**Table 10:** Compressive strength table of PBAT-cocopeat biocomposite plugs vs reference plug.

| # | Plug      | Compressive stress at 10 % nominal relative deformation (kPa) |
|---|-----------|---------------------------------------------------------------|
| 1 | 25PBAT    | 0.85±0.33                                                     |
| 2 | 50PBAT    | 1.90±1.70                                                     |
| 3 | 75PBAT    | 2.80±1.60                                                     |
| 4 | Reference | 7.50±3.05                                                     |

### 3.3. Reference Plug Examination and Other Characterization Tests



**Figure 3.11:** Reference plug.

One commercial product has been procured as a plant growth plug. It is a plant grow plug called Pafcal (reference) developed by Toyota Suntory Company in Japan (**Figure 3.11**). The plug has a flexible character and a hydrophilic structure that attracts water. Since the plug content was not fully disclosed, some chemical, morphological, and mechanical characterizations were performed to examine the possible content.

### 3.3.1. FTIR

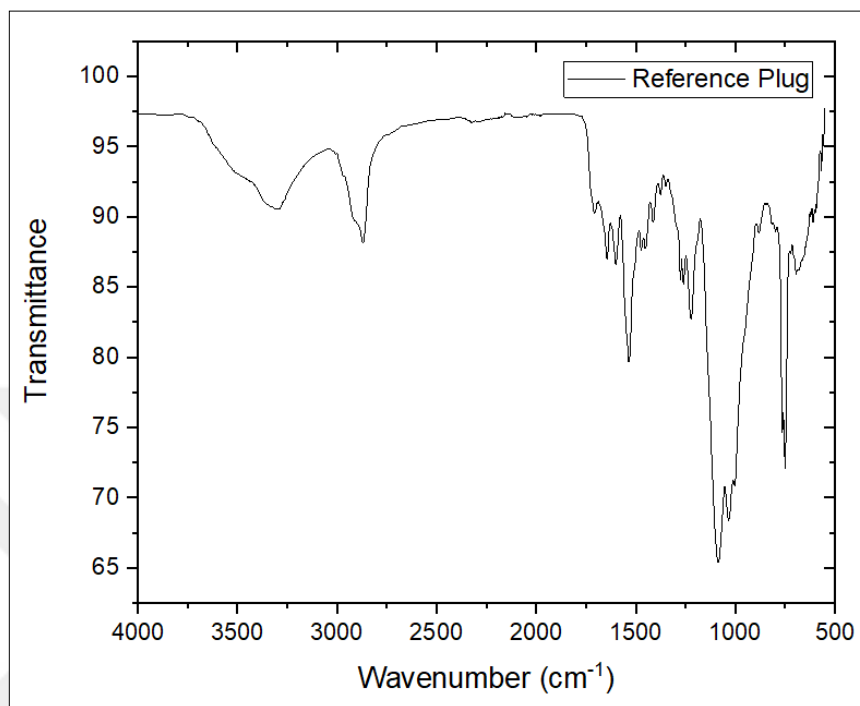


**Figure 3.12:** FTIR graph of reference plug.

**Figure 3.12** shows the FTIR spectrum of the reference plug. In the graph: 3299.4 cm<sup>-1</sup>: may correspond to O-H or N-H stretching [122], 2869 cm<sup>-1</sup>: [124]. C-H stretching [123], 1699 cm<sup>-1</sup>: carbonyl (C=O) group vibrations [123], 1641.6 cm<sup>-1</sup> [123]: C=C or N-H stretching, 1599.3 cm<sup>-1</sup>: C=C stretching, 1532 cm<sup>-1</sup>: C-N or N-H bending, 1220 cm<sup>-1</sup>: C-O stretching, 1085.9 cm<sup>-1</sup> [124]: peaks associated with C-O-C bonds have been detected [125]. All of these peaks are likely associated with the characteristic structure of polyurethane. The other peaks may indicate the possible presence of amorphous or semi-crystalline silicate (quartz-glass wool) with a dominant and broad Si-O and Si-O-Si bond in the 1200-950 cm<sup>-1</sup> region [126]; In addition, O-H contribution in the 3500-3200 cm<sup>-1</sup> region, may also indicate the possible presence of lignocellulosic material (e.g., rattan [123], rice husk [128] and etc.).

### 3.3.2. SEM

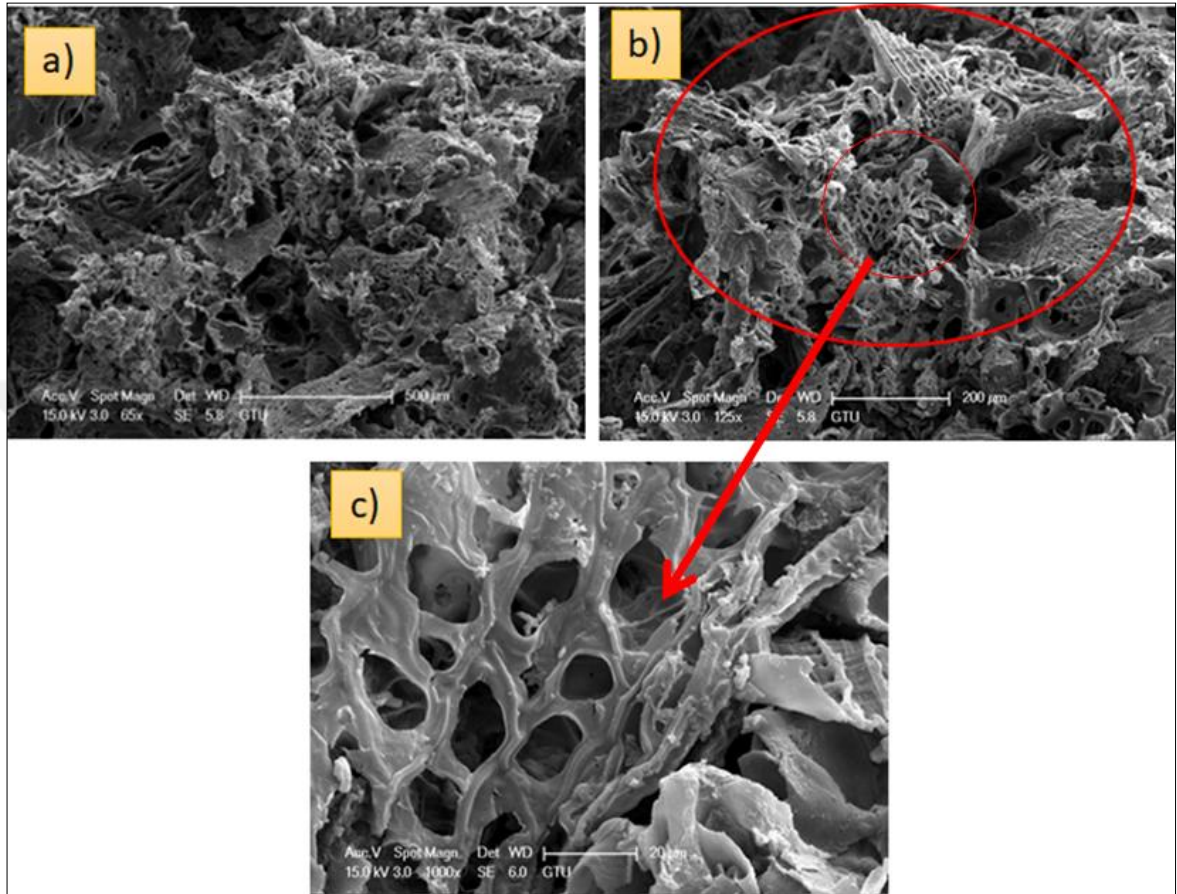


**Figure 3.13:** SEM images of reference plug.

**Figure 3.13** shows SEM images of the reference plug at different magnifications. In image A, we see the structure from a wider angle. Here, the background appears porous and foam-like. In the foreground, we see various reinforcements. At image B and C, which are closer angles of A, we see that these reinforcements have a hollow structure. It is thought that these hollow structures (red circle at image b and c) may be inorganic materials such as glass wool and stone wool [127] or organic materials such as acrylic acid treated rattan and rice husks [128] which can interact well with the foam matrix.

### 3.3.3. XRD

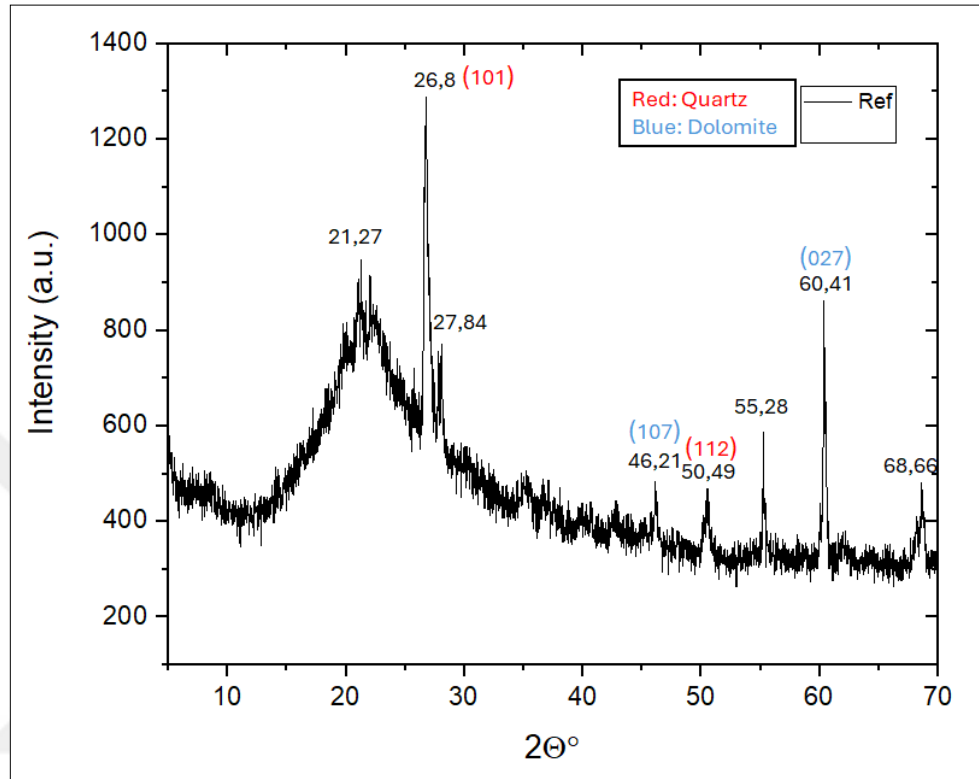


**Figure 3.14:** XRD graph of reference plug.

**Figure 3.14** shows the XRD graph of the reference plug. At 21.27°, the amorphous peak of the glass lamella substrate is observed [106]. The most characteristic and intense peak of  $\alpha$ -quartz is observed at 26.8° (JCP2.2CA: Pattern: 00-046-1045). The peak at 27.84° is thought to be a peak from minerals such as feldspar used in glass production or a satellite peak of  $\alpha$ -quartz. Dolomite phases were detected at 46.21° and 60.41° (JCP2.2CA: Pattern: 00-036-0426), [127]). The other peaks are thought to be secondary peaks of quartz.

### 3.4. Water Absorption

**Table 11:** Water absorption data of plugs.

| #                                                              | Plug Name         | AVG<br>m <sub>0</sub> | S.D<br>(m <sub>0</sub> ) | AVGg<br>2h | S.D<br>(m <sub>2h</sub> ) | AVG-<br>R <sub>2h</sub> (%) | S.D<br>(R <sub>2h</sub> ) | AVGg <sub>2</sub><br>4h | S.D<br>(m <sub>24h</sub> ) | AVG-<br>R <sub>24h</sub> (%) | S.D<br>(R <sub>24h</sub> ) |
|----------------------------------------------------------------|-------------------|-----------------------|--------------------------|------------|---------------------------|-----------------------------|---------------------------|-------------------------|----------------------------|------------------------------|----------------------------|
| 1                                                              | 4myce             | 2.13                  | 0.05                     | 7.71       | 0.30                      | 262.32                      | 8.96                      | 11.82                   | 0.48                       | 455.70                       | 15.37                      |
| 2                                                              | 4myce-o           | 2.13                  | 0.05                     | 13.77      | 0.60                      | 518.74                      | 32.75                     | 14.17                   | 0.66                       | 565.88                       | 22.78                      |
| 3                                                              | 4myce-o-<br>5p    | 2.31                  | 0.09                     | 13.05      | 0.60                      | 464.87                      | 9.35                      | 15.23                   | 0.55                       | 559.90                       | 20.76                      |
| 4                                                              | 4myce-o-<br>5b    | 2.82                  | 0.14                     | 14.99      | 0.82                      | 430.84                      | 3.95                      | 16.08                   | 0.47                       | 470.10                       | 13.77                      |
| 5                                                              | 4myce-o-<br>5p-5b | 2.77                  | 0.15                     | 13.45      | 0.65                      | 373.37                      | 9.73                      | 15.15                   | 0.76                       | 434.30                       | 36.59                      |
| 6                                                              | 4myce-o-<br>10b   | 2.51                  | 0.07                     | 12.91      | 0.56                      | 413.45                      | 7.62                      | 15.02                   | 0.20                       | 497.77                       | 10.36                      |
| 7                                                              | 10myce            | 2.51                  | 0.04                     | 9.22       | 0.75                      | 267.11                      | 24.61                     | 14.61                   | 1.01                       | 481.61                       | 31.84                      |
| 8                                                              | 25PBAT            | 1.83                  | 0.15                     | 13.37      | 0.44                      | 646.65                      | 40.87                     | 13.86                   | 0.03                       | 683.72                       | 56.49                      |
| 9                                                              | 50PBAT            | 1.74                  | 0.02                     | 10.72      | 0.47                      | 500.78                      | 24.42                     | 10.93                   | 0.19                       | 527.11                       | 4.67                       |
| 10                                                             | 75PBAT            | 2.07                  | 0.09                     | 6.99       | 0.12                      | 238.13                      | 19.36                     | 7.42                    | 0.24                       | 259.14                       | 25.81                      |
| 11                                                             | 100PBAT           | 1.64                  | 0.06                     | 3.29       | 0.43                      | 100.43                      | 22.19                     | 3.47                    | 0.43                       | 111.24                       | 22.31                      |
| 12                                                             | Reference         | 3.31                  | 0.19                     | 10.99      | 0.48                      | 232.83                      | 26.08                     | 13.04                   | 0.59                       | 294.08                       | 11.19                      |
| Note: m: mass, h: hour, AVG: averaged, S.D: standard deviation |                   |                       |                          |            |                           |                             |                           |                         |                            |                              |                            |

**Table 11** presents the water absorption test results for all mycelium biocomposite plugs, PBAT biocomposite plugs, and the reference plug. Equation (3.4) was used for the weight gain ratio:

$$\text{Increase in weight, \%} = \frac{\text{wet weight} - \text{conditioned weight}}{\text{conditioned weight}} \times 100 \quad (3.4)$$

Compared to the reference plug (294% water uptake after 24 hours), both the mycelium biocomposite plugs (565% water uptake after 24 hours) and the PBAT biocomposite plugs

(683% water uptake after 24 hours) demonstrated superior performance. For mycelium biocomposite plugs, the following ranking from highest to lowest was obtained after 24 hours: 4myce-o (566%) > 4myce-o-5p (560%) > 4myce-o-10b (498%) > 10myce (482%) > 4myce-o-5b (470%) > 4myce (456%) > 4myce-o-5p-5b (434%). For PBAT plugs, the following ranking from highest to lowest was obtained after 24 hours: 25PBAT (684%) > 50PBAT (527%) > 75PBAT (259%). The results showed that each plug demonstrated good water absorption performance and has the potential to be used as a plant growth plug when comparing to reference plug.

Water absorption saturation occurred earlier in autoclaved samples compared to non-autoclaved samples (e.g., 4myce vs. 4myce-o). The plugs added with 5% biochar and perlite by weight showed the weakest water absorption performance. This was attributed to an increase in density and a decrease in porosity in the structure. Among the mycelium biocomposite plugs, the best water absorption performance was shown by the plug incubated for 4 days and autoclaved (4myce-o). Mycelium, which are normally hydrophobic [95] (<4% water uptake [43]) were found to absorb water over time as a result of proper interaction with cocopeat (eg., 10myce). In PBAT biocomposite plugs, a decrease in weight gain was observed as the PBAT ratio increased. The PBAT polymer, which is normally hydrophobic, has been given a physical hydrophilic property by being converted into a highly porous fiber form by precipitation that can act as a hydrophilic material. (0.81% water absorption in 24h in neat form [129]). Among all plugs, the 25PBAT plug demonstrated the best water absorption performance (as weight increase). A significant difference was observed compared to PBAT water absorption rates in the literature (0.81% to 111% water absorption) [129], [130].

Considering that the reference plug is polyurethane-based and reinforced with glass wool, it can be stated that a plug with better water absorption performance than the data in the literature was obtained. It has been determined that polyurethane foam, which can normally absorb water at levels of 20% [131], and glass wool reinforcements, which can absorb water between 4-8% [132], can achieve good matrix-reinforcement bonding with alkaline treatments to improve their performance. However, in our case, no chemical or physical modification is required for high water absorbance properties.

### 3.5. Energy Dispersive Spectroscopy (EDS)

**Table 12.** Energy dispersive spectroscopy datas of all plugs (% in weight).

| #  | Plug Name   | C     | O     | Na   | Mg   | Fe   | K    | Ca   | Cl   | P    | Si    | S   | Al   | Hg | Pb |
|----|-------------|-------|-------|------|------|------|------|------|------|------|-------|-----|------|----|----|
| 1  | 4myce       | 50.35 | 42.87 | 0.16 | 0.22 | -    | 2.5  | 0.67 | 0.38 | 2.29 | 0.53  | -   | 0.02 | -  | -  |
| 2  | 4myce-o     | 45.1  | 44.24 | 0.66 | 0.37 | -    | 1.29 | 2.13 | -    | 5.16 | 0.87  | -   | 0.17 | -  | -  |
| 3  | 4myce-o-5p  | 14.22 | 43.46 | 2.05 | -    | -    | 4.33 | 0.69 | -    | -    | 29.05 | -   | 6.2  | -  | -  |
| 4  | 4myce-o-5b  | 54.47 | 37.5  | -    | 0.41 | -    | 3.09 | 3.72 | -    | -    | 0.66  | -   | 0.14 | -  | -  |
| 5  | 4myce-o-5p- | 51.62 | 35.64 | -    | 0.25 | -    | 1.91 | 2.51 | 0.26 | 3.44 | 1.79  | 2.3 | 0.29 | -  | -  |
| 6  | 4myce-o-10b | 44.13 | 27.15 | -    | 0.89 | -    | 6.44 | 4.7  | -    | 16.7 | -     | -   | -    | -  | -  |
| 7  | 10myce      | 49.83 | 42.55 | 0.58 | -    | -    | 0.85 | -    | 0.29 | 3.51 | -     | 2.2 | 0.18 | -  | -  |
| 8  | 25PBAT      | 51.14 | 42.65 | 0.88 | 0.38 | -    | 1.7  | 0.36 | -    | -    | 2.27  | -   | 0.62 | -  | -  |
| 9  | 50PBAT      | 50.1  | 45.12 | -    | 0.65 | -    | 2.81 | 0.88 | -    | -    | -     | -   | 0.44 | -  | -  |
| 10 | 75PBAT      | 58.41 | 39.89 | -    | -    | -    | 0.98 | 0.35 | -    | -    | -     | -   | 0.37 | -  | -  |
| 11 | Reference   | 47.89 | 32.54 | 0.86 | 0.29 | 4.44 | 1.01 | 1.28 | -    | -    | 8.09  | -   | 3.58 | -  | -  |

**Table 12** presents the elemental analysis values applied to all plugs. In general, in the mycelium biocomposite plugs, the elements C and O were observed due to the organic material mycelium and cocopeat contains, along with Na, Mg, K, and Ca from the cocopeat and biochar (p.62) and similar minerals such as Na, Mg, Ca, K and P from the mycelium [133], [134]. In PBAT biocomposite plugs, similarly, the dominant C and O elements originating from the polymer and other minerals originating from cocopeat were observed. The absence of heavy metals such as Pb, Hg, and As in all plugs is encouraging as it indicates that they are unlikely to leave toxic residues on the plants during use as plant growth plugs. In the reference plug, consistent with the assumption that it is organic-based and reinforced with glass wool and rock wool, C and O were dominant, and the presence of the dominant Si element supporting the glass wool (based on SiO<sub>2</sub>) and Ca and Mg elements supporting the dolomite phase (CaMg(CO<sub>3</sub>)<sub>2</sub>) was detected.

### 3.6. Plant Growth Tests

**Table 13.** First plant growth test part 1

| Plug Types    | Total Harvested Plant Weight<br>(Fresh weight) (g) | Plant weight by plug<br>(Fresh weight) (g/plug) | AVG  | S. D |
|---------------|----------------------------------------------------|-------------------------------------------------|------|------|
| 4myce-o       | 13.7                                               | 3.4                                             | 13.6 | 10.6 |
|               | 27.6                                               | 9.2                                             |      |      |
|               | 84.6                                               | 28.2                                            |      |      |
| 4myce-o-5b    | 63.4                                               | 15.8                                            | 16.5 | 1.0  |
|               | 53.6                                               | 17.9                                            |      |      |
|               | 47.0                                               | 15.7                                            |      |      |
| 4myce-o-10b   | 78.0                                               | 19.5                                            | 24.1 | 3.3  |
|               | 77.8                                               | 25.9                                            |      |      |
|               | 80.6                                               | 26.9                                            |      |      |
| 4myce-o-5p    | 33.0                                               | 8.2                                             | 11.4 | 6.2  |
|               | 17.5                                               | 5.8                                             |      |      |
|               | 60.1                                               | 20.0                                            |      |      |
| 4myce-o-5p-5b | 23.0                                               | 5.8                                             | 11.0 | 4.6  |
|               | 30.9                                               | 10.3                                            |      |      |
|               | 51.0                                               | 17.0                                            |      |      |

**Table 14.** First plant growth test part 2

| Plug Types | Total Harvested Plant Weight (Fresh weight) (g) | Plant weight by plug (Fresh weight) (g/plug) | AVG         | S. D |
|------------|-------------------------------------------------|----------------------------------------------|-------------|------|
| 25PBAT     | 78.8                                            | 15.8                                         | <b>18.6</b> | 2.8  |
|            | 94.6                                            | 18.9                                         |             |      |
|            | 83.8                                            | 16.8                                         |             |      |
|            | 114.8                                           | 23.0                                         |             |      |
| 50PBAT     | 88.1                                            | 17.6                                         | <b>17.3</b> | 1.7  |
|            | 88.9                                            | 17.8                                         |             |      |
|            | 72.8                                            | 14.6                                         |             |      |
|            | 96.6                                            | 19.3                                         |             |      |
| 75PBAT     | 73.0                                            | 14.6                                         | <b>15.7</b> | 1.9  |
|            | 67.1                                            | 13.4                                         |             |      |
|            | 83.6                                            | 16.7                                         |             |      |
|            | 90.9                                            | 18.2                                         |             |      |

The plant growth tests were conducted in greenhouses affiliated with the KutmanLAB at the Biotechnology Institute of Gebze Technical University. **Table 13 and 14** show the results of the initial plant growth tests. Here, the mycelium and PBAT plugs were compared to each other to assess their potential and determine which would deliver the best performance. According to the data in **Table 13**, first pot has 4 plugs, and the other pots have 3 plugs each. **Table 14** shows that each pot has 5 plugs.

As a result of the plant growth test, each plug was found to be suitable for use as a potential plant growth plug (**Table 13-14** and **Figure 3.15-3.16**). The best average green basil leaf weight per plug was obtained from the 4myce-o-10b mycelium biocomposite plugs, while the best average green basil leaf weight per plug from the PBAT biocomposite plugs was obtained from the 25PBAT plugs. In water absorption tests (**Table 11**), these plugs also showed better water absorption performance than others, and it was observed that water absorption performance was directly proportional to plant growth performance. Plant growth tests were not conducted on 4myce and 10myce plugs because they did not demonstrate sufficient wetting performance after immersion in hydroponic pots and showed signs of mold growth.

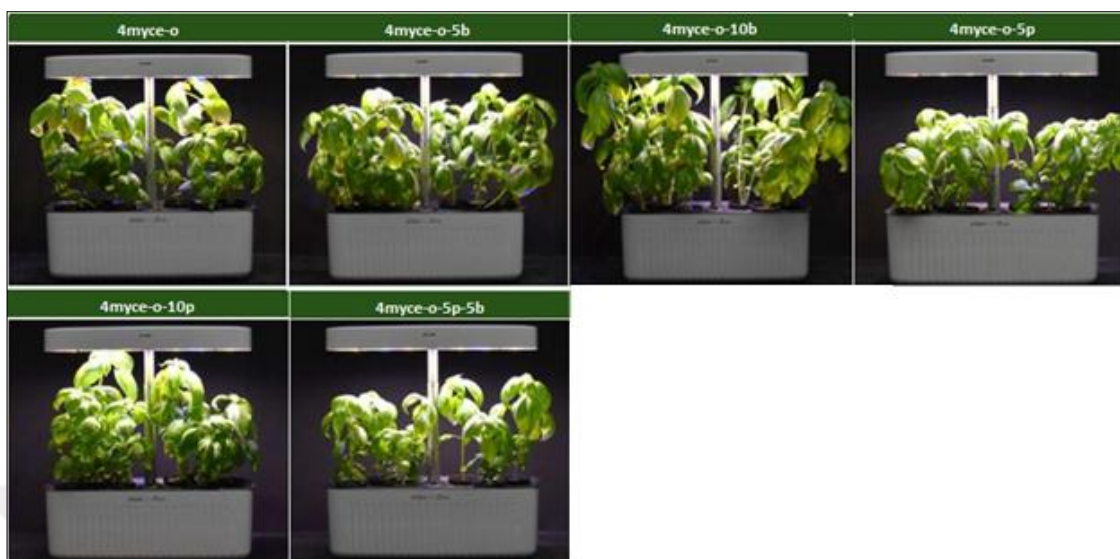


**Figure 3.15:** Plant growth results images of mycelium-cocopeat biocomposite plugs after 4 weeks.



**Figure 3.16:** Plant growth results images of PBAT-cocopeat biocomposite plugs after 4 weeks.

**Table 15.** Final plant growth test.

| Plug Types  | Total Basil Plant Weight (g) | AVG  | S.D  | Total Red Leaf Lettuce Plant Weight (g) | AVG   | S.D  | Total Dill Plant Weight (g) | AVG   | S.D  | Total Purple Basil Plant Weight (g) | AVG  | S.D  | Total Lettuce Plant Weight (g) | AVG   | S.D   | Total Red Chard Plant Weight (g) | AVG   | S.D   | Total Harvested Plants Weight (g) | Plant weight by plug (Fresh weight) (g/plug) |
|-------------|------------------------------|------|------|-----------------------------------------|-------|------|-----------------------------|-------|------|-------------------------------------|------|------|--------------------------------|-------|-------|----------------------------------|-------|-------|-----------------------------------|----------------------------------------------|
| Reference   | 11,37                        | 3,79 | 1,55 | 90,26                                   | 30,09 | 2,09 | 37,71                       | 12,57 | 7,82 | 5,04                                | 1,68 | 0,36 | 148,17                         | 49,39 | 7,77  | 113,28                           | 37,76 | 9,77  | 405,83                            | 22.55                                        |
| 25PBAT      | 12,72                        | 4,24 | 0,2  | 102,07                                  | 34,02 | 3,61 | 57,63                       | 19,21 | 2,6  | 5,05                                | 1,68 | 0,54 | 145,88                         | 48,63 | 6,36  | 103,44                           | 34,48 | 11,36 | 426,79                            | 23.71                                        |
| 4myce-o-10b | 9,26                         | 3,09 | 0,14 | 29,26                                   | 9,75  | 5,2  | 47,03                       | 15,68 | 1,44 | 5,24                                | 1,75 | 0,38 | 97,93                          | 32,64 | 11,1  | 75,02                            | 25,01 | 11,72 | 263,74                            | 14.65                                        |
| 4myce-o     | 5,24                         | 1,75 | 1,28 | 41,99                                   | 14    | 4,12 | 9,36                        | 3,12  | 2,32 | 2,74                                | 0,91 | 0,34 | 42,13                          | 14,04 | 11,79 | 75,64                            | 25,21 | 12,37 | 177,1                             | 9.84                                         |

**Table 15** shows the results of the final plant growth tests. The averages (AVG) and standard deviations (S.D) obtained from the 3-replicate plant growth tests are provided for each plant. Subsequently, all plants were harvested by weight, and the averages per 6 plugs are provided. Here, in the first plant growth tests, the two best-performing mycelium plugs (4myce-o- and 4myce-o-10b) and one PBAT plug (25PBAT) were selected and a comparative plant growth test was conducted against the reference plug.

When looking at the total harvested plant fresh weights (**Table 15**), the following ranking from highest to lowest was obtained: 25PBAT (427g) > Reference plug (406g) > 4myce-o-10b (264g) > 4myce-o (177g).

These results demonstrate that a plug can be produced using a biodegradable polymer (25PBAT) that yields better results than the reference plugs, and that plugs produced entirely from organic materials can also compete with the reference product (e.g, 4myce-o-10b).

As a result of the final plant growth test, each plug was found to be suitable for use as a potential plant growth plug (**Table 15** and **Figure 3.17**).



**Figure 3.17:** Final Plant Growth Test image (After 4 weeks).

## 4. CONCLUSIONS

This study aims to develop two prototypes of plant growth plugs made from dimensionally stable, non-toxic, environmentally friendly, and fully biodegradable materials for the soilless agriculture and seedling production sector. This transforms cocopeat, an agricultural waste material, into a valuable product component, thereby promoting effective waste management and increasing sustainable agricultural production.

In the SEM analysis of our first plant growth plug, which consists of cocopeat and fungal mycelium, the diameter of the mycelium hyphae, its bond and structure with cocopeat, biochar and perlite, and its porous structure were examined, and its suitability as a plant growth plug was observed. EDS analysis roughly confirmed the absence of heavy metals in the content. FTIR analysis examined the chemical bond structure and confirmed the presence of hydrophilic properties due to the -OH groups in its structure. The thermal degradation temperatures of mycelium biocomposite plugs were examined (TGA), and the decomposition temperature of 250 °C was increased to 270 °C with perlite and biochar additives. The crystal structure and orientation of the mycelium composites were examined by XRD analysis, and a highly oriented cellulose peak (at 22.61°) was detected. A compression test was performed, and the effects of incubation time, biochar, and perlite addition were examined. An increase in strength (18 N to 55 N) was observed as the incubation time increased from 4 days to 10 days (10myce vs 4myce). The biochar additive, especially at the 5% level, resulted in early failure (10 mm to 7.3 mm) and low deformation when comparing to 4myce. The %5 perlite additive provided a more ductile mechanical response (8 mm vs 7.3 mm) by increasing the failure deformation when comparing to %5 biochar added plugs. Water absorption tests have proven their hydrophilic properties, capillary action, and the presence of physical porous areas in their structure. For mycelium biocomposite plugs, the following ranking from highest to lowest was obtained after 24 hours: 4myce-o (566%) > 4myce-o-5p (560%) > 4myce-o-10b (498%) > 10myce (482%) > 4myce-o-5b (470%) > 4myce (456%) > 4myce-o-5p-5b (434%). Plant growth tests proved that the mycelium biocomposite plug can be successfully used as a plug. An increase in plant growth performance was observed with

the addition of biochar. Among these plugs, the mycelium-cocopeat biocomposite plug with 10% biochar addition provided the best plant growth performance (4myce-o-10b).

The second plant growth plug contains poly(butylene adipate-co-terephthalate) (PBAT), a biodegradable polymer, and cocopeat. SEM analysis of PBAT-cocopeat biocomposite plugs examined the diameter of the precipitated polymer fibers, their relationship with cocopeat, and their porous structure, observing their suitability as plant growth plugs. EDS analysis confirmed the absence of heavy metals in the content. FTIR analysis examined the chemical bond structure and confirmed the presence of hydrophilic properties due to the -OH groups in its structure. The thermal degradation temperatures of PBAT biocomposite plugs were examined (TGA), and the decomposition temperature of 250°C was increased to 375°C with PBAT ratio. The crystal structure and orientation of the PBAT composites were examined by XRD analysis, and peaks were found at 11.85°, 16.91°, 17.5°, 20.56°, 23.18°, and 24.84°. A compression test was performed and the effect of PBAT-cocopeat ratios was examined. With the increase in the PBAT ratio, the compression resistance has been increased from 0.85 kPa to 2.80 kPa. Water absorption tests have proven their hydrophilic properties, capillary action, and the presence of physical porous areas in their structure. For PBAT plugs, the following ranking from highest to lowest was obtained after 24 hours: 25PBAT (683%) > 50PBAT (527%) > 75PBAT (259%). Finally, plant growth tests proved that the biodegradable polymer plug can be successfully used as a plant grow plug. Among these plugs, the 25PBAT plug, containing 25% PBAT and 75% cocopeat by weight, provided the best plant growth performance.

In the SEM analysis of the reference plug, various possible inorganic and organic additives were observed within the foam matrix, and its porous structure was examined. Its elemental composition was analyzed using EDS, and attempts were made to verify its content by combining it with other analyses. The test results were compared with locally produced mycelium and PBAT biocomposite plugs. In the comparative characterization and tests performed with the reference plug, our plugs were only weak in terms of mechanical strength (compression strength), but in all other tests and in terms of content, they yielded better and more efficient results than the reference plug. Finally, a plant growth test was performed on the reference plug, and our plugs achieved comparable

results providing the final proof of their potential use. The 25PBAT plug has yielded even better results than the commercially available reference capsule.

As a result, these locally produced biocomposite plugs show high potential for use as non-toxic and sustainable plant growth plugs.



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## **BIOGRAPHY**

Abdullah Hilmi COŞAR graduated from the Materials Science and Engineering undergraduate program at Gebze Technical University in 2021. Since 2024, he has been working as a research assistant in the same department at the same university.



## **PUBLICATIONS AND PRESENTATIONS FROM THESIS**

[1] A.H. Cosar, M. Mocan, B.Y Kutman, U.B Kutman, H. Mutlu “Production and Characterization of Fully Biodegradable Biocomposite Plant Grow Plug Alternatives for Soilless Agriculture” 6th International Polymeric Composites Symposium and Workshops, Izmir, Turkiye, Oct 02-04, 2025 (Poster Presentation).

[2] A.H. Cosar, M. Mocan, B.Y Kutman, U.B Kutman, H. Mutlu “Fabrication and Characterization of Sustainable Biocomposite Plant Grow Plugs for Soilless Agriculture” 2nd International Congress on Biotech Solutions for Sustainability, Gebze Technical University, Oct 22, 2025 (Oral Presentation - English).

[3] A.H. Cosar, M. Mocan, B.Y Kutman, U.B Kutman, H. Mutlu, E.D Arisan “Sustainable Plant Growth Plugs for Use in Soilless Agriculture” 2nd International Congress on Biotech Solutions for Sustainability, Biotech4Sus Bioentrepreneurship Competition, Gebze Technical University, 3rd Best Entrepreneurship Award, October 24, 2025.

[4] A.H. Cosar, M. Mocan, B.Y Kutman, U.B Kutman, H. Mutlu, E.D. Arisan “MYCELIUM PLANT GROW PLUG AND PRODUCTION METHOD”, PCT Patent Reference Number: 1332PCT58TR, Apply date: 24.09.2025 (Pending).

[5] A.H. Cosar, M. Mocan, B.Y Kutman, U.B Kutman, H. Mutlu, E.D. Arisan “BIODEGRADABLE POLYMER PLANT GROW PLUG AND PRODUCTION METHOD”, PCT Patent Reference Number: 1332PCT59TR, Apply date: 24.09.2025 (Pending).

[6] A.H. Cosar, H. Mutlu, M. Mocan, B.Y Kutman, U.B Kutman, “Mycelium biocomposites as a soilless plant growth plug: novel and sustainable approach” under preparation.

[7] A.H. Cosar, H. Mutlu, M. Mocan, B.Y Kutman, U.B Kutman, “Biodegradable polymer biocomposite plant growth plugs; a novel production method and sustainable approach” under preparation.