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Review Article

Overview and Future Perspectives on the Potential of Post-harvest Cannabis Waste as Agricultural Amendments: Biomass Conversion Processes

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Abstract

Utilizing organic waste to improve soil fertility is a highly ecological strategy for waste management within the framework of a circular economy. This literature review thoroughly examined the potential of post-harvest cannabis waste as an agricultural amendment, emphasizing biomass conversion processes. This biomass can be converted into organic fertilizers using techniques such as composting, microbial digestion, and pyrolysis. The findings indicate that controlled composting, which involves mixing different organic substrates to enhance the carbon/nitrogen ratio, is the most effective process employed. Cannabis biomass decomposes more slowly than other organic materials, such as manure or kitchen waste, due to its elevated lignin and cellulose content. This article delineates significant deficiencies in the literature and proposes avenues for future research to improve the sustainable utilization of cannabis waste in agriculture.

Keywords: Cannabis waste; Biomass decomposition; Bioconversion; Organic fertilizers; Sustainable agriculture

Introduction

Cannabis sativa L., referred to as hemp or cannabis, is one of the oldest cultivated plants in human history and classified within the Cannabaceae family (Liu *et al.* 2017; Zhao *et al.* 2020; Chaowana *et al.* 2024). *Cannabis sativa* is garnering heightened interest due to its extensive array of applications. This crop is applicable in multiple sectors, including industry, medicine, and agriculture. It is conventionally utilized in textile manufacturing and presently harnessed for novel applications, such as the creation of bioplastics, automotive composites and construction materials (Crini *et al.* 2020).

In addition to these industrial applications, *Cannabis sativa* biomass is crucial for multiple environmental aspects. Cannabis significantly contributes to agriculture, as its biomass serves as ground cover or bedding for livestock, aiding in moisture and odor management (Zimniewska 2022; Visković *et al.* 2023). Furthermore, it serves to safeguard the soil owing to its phytoremediation capabilities, facilitating soil decontamination and carbon dioxide sequestration *via* photosynthesis (Linger *et al.* 2002; Adesina *et al.* 2020; Rheay *et al.* 2021; Flajšman *et al.* 2023; Guo *et al.* 2024).

However, the cultivation of *Cannabis sativa* generates significant amounts of agricultural by-products, mainly including stems, leaves and flowers that are not used after harvest. In this context, this waste can be recycled as agricultural amendments to increase soil fertility and encourage responsible farming practices. To this end, previous research has focused on converting cannabis biomass into various forms of bioavailable nutrients, such as digestate, biochar and compost (Stonehouse *et al.* 2020; Tahir *et al.* 2020; Anjum *et al.* 2022; Marrot *et al.* 2022; Malabadi *et al.* 2023; Olson *et al.* 2024).

The valuation of post-harvest cannabis waste as agricultural amendments presents a promising avenue for sustainable agricultural practices. Using various biomass conversion technologies, this tool of management turns nutrient-rich cannabis residues, which are frequently thrown away, into organic fertilizers and other useful products. However, the scientific literature on the valorization of cannabis waste for agricultural purposes is so far limited. In particular, few studies specifically focus on the transformation of post-harvest cannabis waste into organic fertilizers. Existing research has focused on other recovery approaches and legislative management. Although not covered in this literature

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review, the production of cannabis-derived biochar is one of the approaches most often used for waste valorization and employed to improve soil health.

This article aimed to examine literature regarding the potential application of post-harvest cannabis waste as an agricultural amendment, emphasizing technologies for transforming biomass into organic fertilizers. It outlines the biochemical composition of cannabis biomass, explores their decomposition mechanisms, and discusses the forms and effectiveness of resulting organic fertilizers. It also highlights the existing technological advancements for transforming cannabis biomass into organic fertilizers, along with the related challenges.

Overview of cannabis culture and waste management

Cannabis production has grown rapidly in many countries, mainly in China and Europe, due to its sustainable cultivation that requires few agricultural inputs (Amaducci *et al.* 2015). It is currently widespread in various regions of the world, particularly for cultivars rich in tetrahydrocannabinol and cannabidiol, which are used in pharmacology. Its essential oils and inflorescence extracts have shown cytotoxic effects against certain cancer cell lines and antimycotic activity, suggesting potential for pharmaceutical and nutraceutical applications (Fiorini *et al.* 2019; Sotto *et al.* 2022). Moreover, cannabis is also produced for human and animal sustenance, primarily for its edible oil from the seeds and fibers (Fig. 1).

However, optimal cannabis cultivation requires well-drained soil, adequate light, and controlled humidity. Currently, growing cannabis depends on lab techniques and genetic changes to boost production and enhance cannabinoid quality (Shukla 2023). Furthermore, local conditions closely influence both the quality and quantity of yields (Toth *et al.* 2020). In particular, the production of cannabis for CBD requires best practices, including careful selection of cultivars and optimization of growth conditions (Chandra *et al.* 2017; Backer *et al.* 2019; Burgel *et al.* 2020). Medicinal cannabis, on the other hand, involves very strict post-harvest practices to better maintain the quality and efficacy of the resulting products (Birenboim *et al.* 2024). This involves post-harvest cultivation techniques such as advanced drying, efficient pruning, and proper drying and storage conditions (Jin *et al.* 2019; Ubeed *et al.* 2022). These practices help preserve the therapeutic potential of cannabis through maintaining safety and compliance with industrial requirements.

For several years now, cannabis cultivation has been linked to the production of large quantities of waste. Consequently, waste production represents a major challenge for waste management. Therefore, it is vital to understand cultivation techniques to minimize the environmental impact and maximize the benefits. Thus, the valorization of its by-products must consider the amount of organic waste produced and the strategies to be used. This waste consists of leaves, stems, and roots left behind after harvesting (Yakti *et al.* 2023). Many hemp plants grown for cannabidiol (CBD) either leave their total biomass in piles for decomposition, incinerate it, or landfill it after harvest. Unfortunately, poor management of such waste can lead to pollution and environmental degradation.

However, cannabis contains aromatic compounds, notably terpenes, which contribute to its aroma and the taste of the products derived from it. These compounds are important to its development and cultivation because they can affect its medicinal benefits (Booth *et al.* 2017). In this context, managing terpene-based waste is crucial, as it allows for its recovery and subsequent transformation into high-value products. Therefore, managing this waste should include recovering these substances in a way that supports a circular economy, especially since they are commonly used in the pharmaceutical and cosmetics industries (Hazekamp *et al.* 2016).

In addition, cannabis cultivation and waste management systems vary considerably from country to country. Whatever the scale, cultivation depends on some factors, including cultivation techniques, management infrastructures, and regulations. In some countries, for example, cannabis cultivation is under control, while in others it is highly desirable, thanks to its contribution to the country's economy and its medical benefits. The latter scenario creates significant challenges in the management of cannabis waste, as practices must comply with local and international regulations while meeting environmental standards (Aristiani and Bagiastra 2024). Indeed, in regions with strict controls, waste handling must comply with security and disposal regulations, while in other ones, cannabis regulations often overlook significant waste streams, including hazardous waste from electronic cannabis delivery systems (Colbert *et al.* 2024). This lack of regulatory clarity complicates waste management strategies, necessitating changes to allow better disposal options and reduce environmental contamination. In this way, the legalization of medical and recreational cannabis laws is associated with increased releases of toxic chemicals from production facilities (Dhanorkar *et al.* 2023).

Biochemical composition of cannabis parts and their potential as agricultural amendments

Cannabis waste, including leaves, stems, and residual biomass, can be converted into nutrient-rich fertilizers. It contains macro- and micronutrients that can be used to improve the nutritional quality of the soil. Their concentration varies depending on the variety and the part of the plant considered. Hemp seeds are a beneficial source of total minerals compared to some oilseeds such as flax and chia (Farinon *et al.* 2020). As indicated by Angelini *et al.* (2014), cannabis leaves have the highest concentrations of macronutrients, followed by the bark, while the lowest

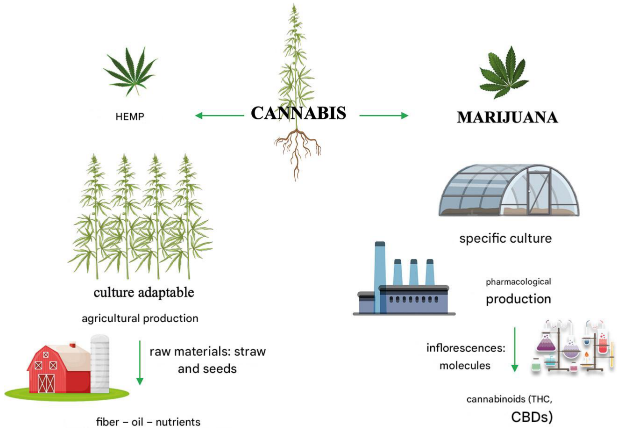

Fig. 1: Agricultural and pharmacological production of hemp and cannabis plants (Source: Mongiovi and Crini 2024)

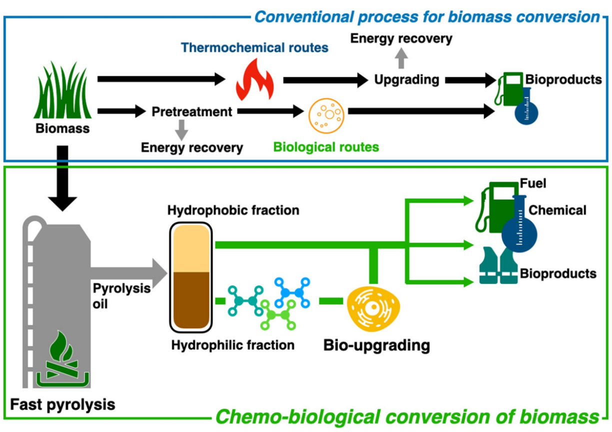

Fig. 2: Process scheme for transforming lignocellulosic biomass into valuable products based on fast pyrolysis combined with biological upgrading (Source: Ashoor *et al*. 2023)

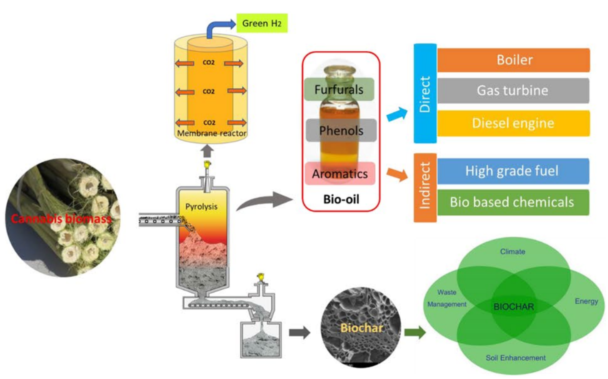

Fig. 3: Thermochemical processing of biomass for the biosynthesis of advanced biofuels and oleochemicals (Brar *et al.* 2024)

concentrations are recorded for the heart of the plant. Similar results have been reported by Ghani (2012), Kleinhenz *et al.* (2020) and Kpai *et al.* (2024). They highlight that nitrogen is the most dominant nutrient, followed by potassium and calcium, respectively. Other nutrients, such as phosphorus, magnesium, and sulfur, are present in lower proportions. On the other hand, the macronutrient analysis conducted by Corrado *et al.* (2022) on different *Cannabis sativa* varieties highlighted notable variations between hemp microgreens cultivars. Among the varieties studied, Finola had different concentrations of potassium and calcium than those observed for Antal, Kompolti, Silvana and Tisza.

However, cannabis contains essential micronutrients such as iron (F), manganese (Mn), zinc (Zn), and copper (Cu), which are essential and needed in small amounts but also play a crucial role in its growth and improving its health. Various studies have revealed that most of these micronutrients are concentrated in the roots compared to other parts of the plant (Saloner and Bernstein 2022; Morad and Bernstein 2023). Ultimately, different parts of cannabis are rich in bioactive compounds that can be harnessed for agricultural purposes (Table 1).

The analysis of the biochemical composition of the various cannabis parts given in the table above shows that this plant is a valuable resource for agricultural soil amendments. Therefore, cannabis can be a sustainable alternative to synthetic fertilizers thanks to its various characteristics, including its richness in nutrients, its anti-disease properties, and its ability to improve soil health.

Decomposition of cannabis biomass

Degradation of cannabis biomass can be accomplished through several methods, including microbial digestion, composting, and chemical treatments. Some methods aim to turn cannabis waste into organic fertilizers by using special microbes that break down lignin. Others investigate thermochemical pretreatment and enzymatic hydrolysis to extract valuable compounds from various parts of cannabis.

A variety of thermochemical processes can be used to convert biomass into useful products such as heat and energy, charcoal, gasses, liquid fuels, and chemicals. One important method is pyrolysis, which breaks down biomass at temperatures over 400°C without oxygen (Branca *et al.* 2017; Shahzad *et al.* 2024). The latter comprises three main types, namely slow, intermediate, rapid, and flash pyrolysis, each characterized by distinct heating rates and operational conditions (Jerzak *et al.* 2024). Additionally, Fig. 2 shows a combined method of thermochemical conversion that merges pyrolysis with biological recovery processes, improving the change of lignocellulosic biomass into valuable products.

The predominant chemical degradation method for cannabis biomass is pyrolysis, which efficiently decomposes plant fibers at elevated temperatures. Specifically, when cannabis biomass is treated with pyrolysis, it mainly produces bio-oil, which constitutes about 75% of the biomass, along with some gases and solid biochar (Fig. 3). One can further refine biochar for use as a bio-adsorbent, biofertilizer, or catalyst. Additionally, Marrot *et al.* (2022) found that slowly heating

Table 1: Biochemical composition and agricultural potential of cannabis parts

Plant part	Main biochemical components	Agricultural potential	References
Leaves	Cannabinoids, terpenes, flavonoids, amino acids	Soil health improvement, nutrient supply, pathogen suppression	Audu *et al.* (2014) Pellati *et al.* (2018)
Stems	Lignin, cellulose, phenolic compounds	Microbial breakdown of bioactive nutrients	Olson *et al.* (2024) Frazzini *et al.* (2024)
Seeds	Proteins, lipids, essential fatty acids, polyphenols	Nutrient-rich organic fertilizers, antimicrobial properties	Frazzini *et al.* (2024) Arango *et al.* (2024)
Inflorescences	Cannabinoids, terpenes, flavonoids	Disease suppression, nutrient cycling, promotion of soil biota	Tzimas *et al.* (2022) Mazzara *et al.* (2022)

Table 2: Main biomass conversion processes

Process type	Key features and outputs	Benefits	References
Thermochemical (Pyrolysis, HTC)	Produces biochar or hydrochar; high C content; nutrient retention varies by feedstock	Enhances soil structure and water retention; can concentrate nutrients	Marchelli *et al.* (2021); Li and Cai (2022); Okolie *et al.* (2022)
Biochemical (Composting, Anaerobic Digestion)	Produces compost or digestate; nutrient-rich; solid and liquid fractions possible	Improves soil fertility, promotes microbial activity and reduces the need for chemical fertilizers.	Kataki *et al.* (2017); Chew *et al.* (2019); Chojnacka *et al.* (2024)
Chemical	Uses acids/alkalis to process biosolids	Modulation of nutrient content and rapid release of nutrients	Izydorczyk *et al.* (2022); Chojnacka *et al.* (2024)
Integrated/Hybrid	Combines thermochemical and biochemical methods	Balances C/N ratio, flexible nutrient profiles, and can reduce environmental impact	Marchelli *et al.* (2021) Okolie *et al.* (2022) Huzir *et al.* (2023)

hemp produces not just biochar but also useful chemical compounds like phenols and furans, which can be used in various ways, possibly improving how we use hemp biomass sustainably.

In contrast, microbial decomposition is a biological process that transforms organic waste into soil amendments. The latter depends on inoculants specifically designed to decompose lignin, increasing biomass bioavailability. Indeed, the breakdown and mineralization of cannabis fibers entail complex interactions between microbial communities and plant components. However, microbial retting is a key process that separates cannabis fibers from the rest of the biomass (Fig. 4). During retting, the quality of the stalks as well as the progression of microbial colonization depends on the harvest time, which significantly affects the retting process. In this regard, stalks harvested at the flowering stage have a higher soluble content and lower lignin content compared to stalks harvested at maturity (Bleuze *et al.* 2020). This process is strongly influenced by several factors, including microbial activity, environmental conditions, and the chemical composition of the hemp. In fact, microbial colonization increases over time and can even cover the epidermis. Key microorganisms used in this process include fungi, Proteobacteria and Bacteroidetes. These microorganisms facilitate the degradation of plant tissues, with their abundance being particularly sensitive to humidity levels during the retting process (Bleuze *et al.* 2018; Fernando *et al.* 2019; Law *et al.* 2020).

However, the mineralization of carbon and nitrogen from different parts of the plant, such as roots, stems and leaves, is largely dependent on their biochemical composition. More specifically, this degradation is influenced by polyphenol and lignin content. Cannabis leaves generally have higher polyphenol content, while roots are richer in lignin-type compounds, which directly affects their mineralization rate (Abbasi *et al.* 2015). According to Gregg and Saddler (2005), the degradation of lignocellulose in agricultural waste is particularly hampered by the presence of hemicellulose and lignin. Therefore, these components strongly limit the accessibility of cellulose to hydrolytic enzymes, thus making the enzymatic degradation process more complex and less efficient.

Transformation of post-harvest cannabis waste into organic fertilizers

Several processes, each with distinct advantages, limitations, and impacts on nutrient content and soil health, can convert biomass into organic fertilizers. The main processes include thermochemical (*e.g.*, pyrolysis, hydrothermal carbonization), biochemical (*e.g.*, composting, anaerobic digestion), chemical, and integrated approaches (Table 2).

Typically, like other organic materials, cannabis biomass can be converted into organic fertilizers or bio-fertilizers using various methods that offer a sustainable solution for waste management and soil fertility improvement. Each method has its advantages and challenges, and the choice depends on factors such as cost, time, and environmental impact. Previous studies indicate that biological processes primarily convert cannabis by-products into organic fertilizers, including:

- Controlled composting and NADEP composting

Controlled composting involves maintaining specific conditions such as temperature, humidity and aeration to optimize the decomposition process. Compared to natural composting, this method significantly improves the

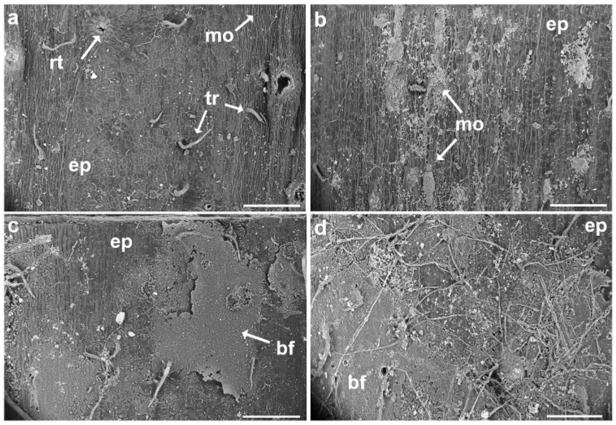

Fig. 4: SEM micrographs of the hemp stem surface before and during the retting period; (**a**) before retting, after (**b**) 14, (**c**) 28, and (**d**) 42 days of retting; (bf) biofilm, (ep) epidermis, (mo) microorganism, (rt) remnant of trichome and (tr) trichome. Scale bar = 200 μm (Bleuze *et al.* 2018)

transformation of organic matter into mature compost (Vargas and Cortés 2022).

Using controlled composting, Dresboll and Thorup-Kristensen (2005) transformed hemp residues (straw) into fertilizer by combining them with clover hay and wheat straw. The hemp, harvested fresh, was mixed with these materials at an initial C/N ratio of 16, favorable to rapid mineralization. As a result, the hemp broke down into soft particles with high nitrogen content. These particles showed properties such as excellent water retention and improved compost structure. This process resulted in stable, nutritious compost, especially suitable for horticultural crops. In complementary research, Dresboll and Magid (2006) composted air-dried hemp stalks after harvest, which had previously undergone a retting process. These residues of *Cannabis sativa* were combined with wheat straw and clover hay to adjust the C/N ratio to 35. As a result, the hemp fibers degraded slowly compared to those of the wheat straw. Subsequently, they attributed flexible structures to the compost, likely to improve water retention and substrate stability. However, a minimal mass loss of only 17% after eight weeks was noted, indicating a certain resistance of hemp fibers to decomposition.

Furthermore, Ngo *et al.* (2013) have adopted a rigorous method to assess the compostability of hemp residues. Hemp fibers, along with other natural fibers such as bamboo and cotton, were integrated into polyester or epoxy polymer matrices reinforced with tertiary oils (linseed or pine oil). These composites underwent controlled composting for 49 days in glass reactors maintained at 58°C. The study revealed that hemp fibers exhibited a slower decomposition rate than other natural fibers, suggesting that their degradation requires specific environmental conditions.

However, NADEP composting involves layering organic materials, such as agricultural residues, kitchen waste, and harmful weeds, in a pit or heap. The materials are then allowed to decompose over time, aided by microbial activity. This process typically takes about 45 to 60 days, resulting in high-quality compost. Indeed, the study conducted by Kumar *et al.* (2012) involved two specific treatments for cannabis biomass: dry cutting and green cutting. In the dry cutting method, the cannabis plants were cut and allowed to dry before being added to the compost heap. In contrast, the green cutting method involved using fresh, unprocessed cannabis plants directly in the composting process. The results indicated that the compost produced from cannabis biomass, particularly through the green cutting method, contributed positively to its nutritional profile.

- Microbial digestion

The decomposition of cannabis can be achieved by microbial inoculation to convert its lignin-rich biomass into a bioavailable form. Specific microbial inoculants have transformed hemp biomass, loaded with residual lignin, into organic fertilizers (Olson *et al.* 2024). Specifically, hemp fibers underwent semi-aerobic microbial decomposition using lactic acid bacteria, yeasts of the genus *Saccharomyces* spp., and ligninolytic fungi such as *Irpex lacteus* and *Phanerochaete chrysosporium*. These microbes, applied in liquid or solid form to shredded hemp stalks, produced oxidative enzymes and organic acids capable of degrading lignin and releasing nutrients. After incubation under semi-aerobic conditions for 21 days, followed by maturation in a mixture with soil or coconut fiber for two weeks, this conversion resulted in a fertilizer with a balanced nutritional profile. To assess the agronomic quality of the fertilizer obtained, germination and growth tests were carried out with species such as CDB hemp, watercress, and red clover. As a result, the fertilizer helped these plants grow well and increased the ratio of roots to pods; it also effectively reduced harmful soil pathogens like *Rhizoctonia solani.*

-Direct incorporation into the soil with nitrogen additive

Very recently, Stulpinaite *et al.* (2024) examined the impact of different nitrogen sources on the mineralization rate of hemp-based residues. The technique employed consisted of introducing these chopped residues into bags of bedding before mixing them with soil or leaving them on the surface. To stimulate decomposition, several nitrogen additives were tested: nitrogen fertilizer granules, liquid nitrogen, an organic fertilizer (pig digestate) and a commercial microbial mixture called "Bioversio." Results indicated that degradation was significantly accelerated when residues were incorporated into the soil, with mass loss exceeding 54%, particularly in the presence of organic and microbial additives.

Comparison of the nutrient profile and decomposition dynamics of cannabis biomass with other organic waste

Comparing the nutritional profiles and decomposition rates

Table 3: Comparison of nutrient profiles and decomposition rates of cannabis, wheat straw, cow dung and kitchen waste

Material	Nutrient profile	Decomposition rate	References
Cannabis biomass	High in crude protein, NDF, and ash; lower ether extract; contains cannabinoids.	Relatively slow due to high C/N ratio and lignin content.	Kleinhenz *et al.* (2020); Altman *et al.* (2022); Stevens *et al.* (2022)
Wheat straw	High C/N ratio (80:1–100:1); primarily cellulose, hemicellulose and lignin.	Progresses slowly in the absence of nitrogen additives; accelerates with nitrogen fertilization.	Ameta *et al.* (2016); Bonanomi *et al.* (2017); Liu *et al.* (2021); Mmonwuba *et al.* (2024)
Cow dung	Rich in nitrogen, phosphorus, and potassium; lower C/N ratio (20:1–30:1).	Faster due to lower C/N ratio and microbial activity.	Liu *et al.* (2021); Stulpinaite *et al.* (2024)
Kitchen waste	Low C/N ratio (fruit and vegetable: 18.56); high in soluble carbohydrates, proteins, and fats.	Accelerated by elevated nitrogen levels and microbial decomposition.	Hadas *et al.* (2004); Slopiecka *et al*. (2022); Azis *et al*. (2023)

of cannabis biomass with other commonly composted organic biomass, such as wheat straw, cow dung, and kitchen waste, is essential for understanding its potential as organic amendments or bioresources. Each material has unique characteristics that influence its decomposition dynamics and nutrient release.

For instance, wheat straw is a common agricultural byproduct, primarily composed of cellulose, hemicellulose, and lignin, with a high carbon-to-nitrogen (C/N) ratio, typically ranging between 80:1 and 100:1 (Ameta *et al.* 2016; Bonanomi *et al.* 2017; Mmonwuba *et al.* 2024). However, this high C/N ratio slows down its decomposition, as microorganisms require additional nitrogen to break down the carbon-rich material. Furthermore, its nutritional profile may be influenced by the addition of nitrogen additives, which can improve its decomposition rate while promoting microbial activity (Liu *et al.* 2021).

In contrast, cow dung is a rich source of nutrients, including nitrogen, phosphorus, and potassium, making it a valuable organic amendment. It has a lower C/N ratio compared to wheat straw, typically around 20:1 to 30:1, which facilitates faster decomposition (Stulpinaite *et al.* 2024). Additionally, the presence of microorganisms in cow dung also accelerates the breakdown of organic matter, releasing nutrients into the soil (Sathiyapriya *et al.* 2024).

However, kitchen waste has a highly variable composition and generally consists of a mixture of organic materials, including food scraps, vegetable peelings, and fruit residues. It typically has a low C/N ratio (often less than 20:1), which is explained by their high nitrogen content, favoring rapid decomposition (Hadas *et al.* 2004; Azis *et al.* 2023). Indeed, composted kitchen waste can vary widely in nitrogen content, typically ranging from 1% to 3% (Pareek *et al.* 2021). Consequently, the nutritional composition of fruit and vegetable waste is more conducive to rapid microbial activity and decomposition (Wang *et al.* 2024).

As previously discussed in the sections above, researchers have studied the potential of cannabis biomass, particularly industrial hemp, as a bioresource due to its diverse nutrient composition. It contains significant amounts of crude protein, neutral detergent fiber (NDF), and ash, with lower levels of ether extract compared to other materials like kitchen waste (Altman *et al*. 2022; Wang *et al.* 2022). The nutrient composition varies depending on the part of the plant and processing methods, such as CBD extraction (Araiza-Rosales *et al.* 2023). For instance, hemp leaves have higher *in vitro* true digestibility (IVTD) compared to stalks, making them more suitable for certain applications (Lopez *et al.* 2025). In addition, cannabis biomass also contains cannabinoids, such as CBD and THC, which are not present in wheat straw, cow dung, or kitchen waste (Parker *et al.* 2022; Stevens *et al.* 2022). In fact, the comparative nutrient contents of cannabis biomass, wheat straw, cow dung, and kitchen waste reveal significant differences that influence their decomposition rate (Table 3).

As shown in the table above, decomposition rates vary considerably from one material to another, depending on factors such as lignin content, microbial activity, and environmental conditions. Specifically, cannabis biomass, with its high C/N ratio and lignin content, decomposes relatively slowly compared with kitchen waste and cow dung. Wheat straw, which also has a high C/N ratio, decomposes at a similar rate to cannabis biomass but can be accelerated with nitrogen additives. In contrast, cow dung and kitchen waste, due to their lower C/N ratios and higher nitrogen content, decompose more rapidly, releasing nutrients quickly into the environment.

Constraints and limitations of cannabis biomass mineralization

Converting cannabis biomass into organic fertilizer has many benefits, but certain constraints and limitations remain. Although current technologies have great potential, their effectiveness depends largely on biomass composition, operating conditions, and the local socio-economic context. Biological processes, such as composting and microbial digestion, are promising for their low cost and sustainability; however, they also have limitations. The main constraints and limitations include:

High lignin content: Cannabis stems and lignified parts have a high lignin and cellulose content, slowing down their biodegradation, even under controlled composting. In addition, lignin's resistance to microbial degradation necessitates specialized microbial inoculants to enhance mineralization and nutrient release (Bleuze *et al.* 2020).

Processing challenges: The logistics of composting, including material, labor costs, and space requirements, pose significant barriers for smallholder farmers. Alternative methods, such as thermochemical processes, while promising, can result in incomplete combustion and lower energy recovery efficiency (Souza et *al.* 2024).

High energy costs: Thermochemical processes such as pyrolysis require significant infrastructure investments and high energy consumption, limiting their large-scale application, especially in small-scale farms.

Future research directions

As described in this review, cannabis biomass can be successfully converted into sources of valuable materials such as organic fertilizers through various conversion processes. Unfortunately, the scientific literature on this subject is still limited by a lack of empirical data, which hinders the implementation of the most suitable solutions. To better resolve the challenges mentioned above, future research should focus on addressing the slow decomposition rates of lignin-rich cannabis biomass by developing specialized microbial inoculants or pretreatment methods to improve biodegradability. Moreover, further exploration of hybrid conversion processes that combine thermochemical and biochemical approaches could enhance nutrient recovery efficiency. Furthermore, long-term field trials are needed to evaluate how the cannabinoids and terpenes present in cannabis biomass impact soil health, crop productivity, and soil microbial communities when using cannabis-derived amendments.

Conclusion

This review emphasizes the prospects for utilizing post-harvest cannabis biomass for agricultural purposes, particularly through its conversion into organic fertilizers. Although this area of research remains largely unexplored, current research shows that hemp waste can be managed for agricultural purposes, like other organic materials. However, there are still big technical problems to solve, like the slow breakdown of lignocellulosic fibers and the high energy needed for thermochemical treatments. Addressing these challenges will require targeted research efforts and the development of innovative conversion technologies. These innovative technologies will help increase the potential of cannabis post-harvest waste as agricultural amendments, thereby promoting more sustainable agricultural practices.

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Authors Contributions

All authors have made significant contributions to the conceptualization and development of the content presented in this paper.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

The data will be supplied by the respective author upon request.

Ethics Approval

Not applicable to this paper.

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