Review

A Conceptual Framework for Incorporation of Composting in Closed-Loop Urban Controlled Environment Agriculture

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Abstract: Controlled environment agriculture (CEA), specifically advanced greenhouses, plant factories, and vertical farms, has a significant role to play in the urban agri-food landscape through provision of fresh and nutritious food for urban populations. With the push towards improving sustainability of these systems, a circular or closed-loop approach for managing resources is desirable. These crop production systems generate biowaste in the form of crop and growing substrate residues, the disposal of which not only impacts the immediate environment, but also represents a loss of valuable resources. Closing the resource loop through composting of crop residues and urban biowaste is presented. Composting allows for the recovery of carbon dioxide and plant nutrients that can be reused as inputs for crop production, while also providing a mechanism for managing and valorizing biowastes. A conceptual framework for integrating carbon dioxide and nutrient recovery through composting in a CEA system is described along with potential environmental benefits over conventional inputs. Challenges involved in the recovery and reuse of each component, as well as possible solutions, are discussed. Supplementary technologies such as biofiltration, bioponics, ozonation, and electrochemical oxidation are presented as means to overcome some operational challenges. Gaps in research are identified and future research directions are proposed.

Keywords: bioponics; carbon dioxide enrichment; circular economy; greenhouse gas; hydroponics; waste management

1. Introduction

The human population is growing at an exponential rate. By 2050, the world population is expected to hit 9.7 billion [1], with 68% of the total population being urban [2]. This surge in global population brings with it a 50% increase in global food demand, most of it disproportionately concentrated in the densely populated urban areas. However, food security is threatened by land degradation, pollution, pests and pathogens, and climate change [3]. Continued advances in high-input conventional agriculture have allowed humanity to keep food production on pace with the growing population but this continued expansion of intensive field production is both threatened by, and contributes to, climate change, land degradation, deforestation, ecological imbalance, crop pests and diseases, and water scarcity [4,5]. These facts challenge our capacity to feed ourselves sustainably moving forward.

The idea of what constitutes agriculture needs to evolve. As the world changes in ways that question the ability of conventional agricultural systems to meet the increasing food demands, we need to hedge our food supply through supplementation of field agriculture with new and innovative food production practices. One such practice to address the concerns surrounding conventional agriculture and the increasing urban food demand is to take full advantage of controlled environment agriculture (CEA) in urban areas. Controlled environment agriculture can take many forms, but perhaps the

model that is best suited to ameliorate the aforementioned issues is high intensity urban (and peri-urban) agriculture. These urban CEA systems include farming techniques such as climate-controlled greenhouses and plant factories with artificial lighting, or more colloquially, vertical farms. Although the exact definition for each of these techniques may vary, the core working principle remains the same—high-intensity and high-density crop production where crops are grown using soil-less methods on multiple levels under artificial lighting in a controlled environment indoor space [6–8]. The term CEA systems will be used throughout this review and collectively refers to all urban CEA systems such as climate-controlled greenhouses, plant factories, or vertical farms.

Controlled environment agriculture's strength lies in the production of crops indoors under optimized and consistent environmental conditions. Controlled environment agriculture is weather and climate independent, generally requires less overall resources, and has higher net productivity compared to field agriculture [9]. Less water consumption, year round production, reduced pesticide/herbicide use, and chemical runoff prevention are some of the key advantages of these systems over land-based farming [10]. These advantages and various other environmental, social, and economic advantages of urban CEA uphold its potential to tackle effects of climate change and urbanization on urban food insecurity.

Food insecurity is on the forefront of critical global issues due to the shift in global trends and unfurling of unprecedented events [11–15]. At its core, food insecurity is a complex multi-dimensional problem hinging on food availability, socio-economic access to food, food quality, and sustained stability of the first three dimensions [15,16]. Sourcing food from distant regions through complex food supply chains compromises the fundamental aspects of food security, making the urban populations vulnerable to food insecure conditions [17]. The current COVID-19 pandemic has shed a light on the fragile state of our globalized food supply chains and highlighted food insecurity concerns worldwide [13]. Restrictions in global food production and logistics have hindered the availability of fresh and finished food products in urban areas, inducing a state of food insecurity in several cities [18]. In addition, access to available food was affected by the socio-economic differences of the urban population [19]. The COVID-19 pandemic is a wake-up call to prioritize the multi-dimensional aspect of food security and to increase resilience of urban food systems. Shortening the food supply chains through local food production is a key strategy to improve resilience and food security [17,20]. Localized production is in fact one of the key strengths of high-intensity urban crop production, especially for perishable fresh produce [21]. Urban CEAs reduce food transportation distances, enable year-round production of nutritious fresh produce, and can help ensure adequate nutrition for vulnerable communities, while improving overall food security in urban populations [6].

Controlled environment agriculture systems are generally considered to be more efficient, productive, and environmentally benign compared with conventional farming practices [7]. Nonetheless, there is still much room for improvement and now is the time to push the boundaries of sustainability and efficiency through technological innovations in this emerging agricultural sector. Controlled environment agriculture systems still follow a linear pattern of resource use (Figure 1a) that ultimately restricts the level of sustainability that can be achieved. Most of the resources used to produce crops (energy, water, nutrients, carbon dioxide) are sourced from elsewhere. After harvest, most of these resources are lost or exported from the system, either as harvested produce, or as inedible crop residue. The inedible crop residue—which can account for up to 50% of the cultivated biomass and represents a substantial portion of the resources invested during production—is often landfilled or otherwise is managed by municipalities and waste management companies. Inputs of water, nutrients, and energy lost in this linear production pattern reduces the resource use efficiency of these systems and lowers profit margins. Crop residue in the landfill degrades anaerobically and produces potent greenhouse gases, such as methane and nitrous oxide, contributing to global climate change. If urban CEA is to reach its full

impact, then, this linear resource use needs to become more circular (Figure 1b); CEA needs to move towards a closed-loop or semi closed-loop farming approach.
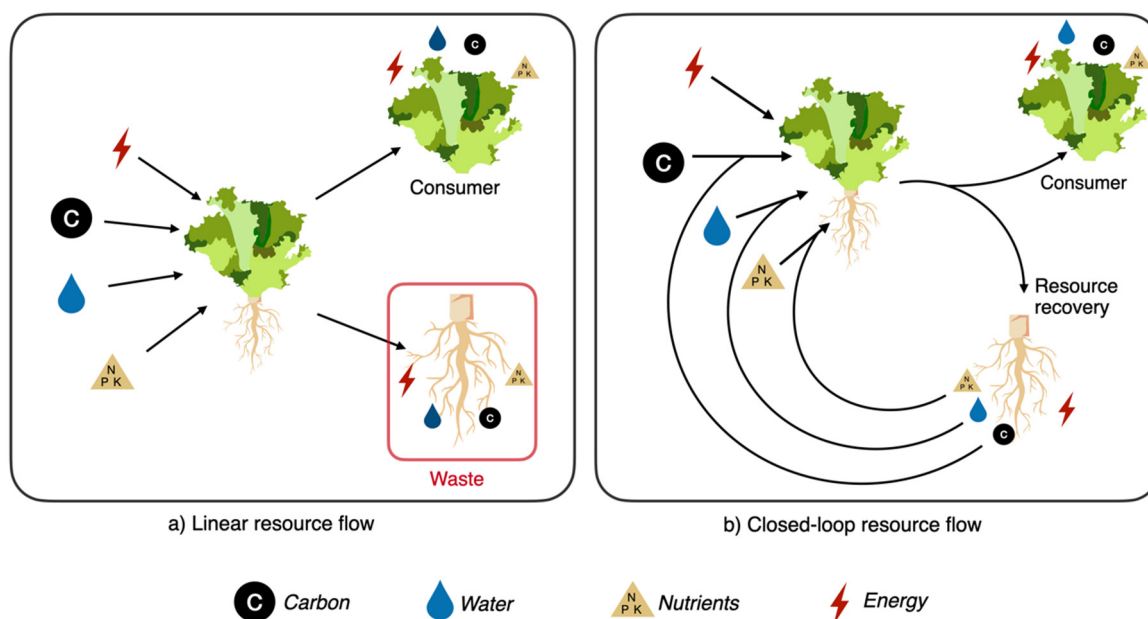
Figure 1. Resource flow pattern in (**a**) linear and (**b**) closed-loop approaches to food production. In a linear resource flow, the inedible crop residues are treated as a waste and disposed of, representing a loss of resources. In contrast, the closed-loop resource flow focuses on recovering resources in the inedible crop residues and reutilizing them in subsequent cropping cycles.

Hadavi and Ghazijahani [22] define closed agricultural systems as, "any type of environment in which plants are cultured and/or maintained in a restricted space, where free exchange of mass and/or energy between the system's interior and exterior are restricted". Food security, year round market demand, quality planting material production, and the prospects of colonizing extra-terrestrial environments has fuelled the development of closed agricultural systems [22,23]. Dickson Despommier [24], who coined the term and popularized vertical farming, envisioned it as an ecosystem that handles its own waste by recycling and repurposing, just as nature does. Closed agriculture systems reduces fuel consumption, water usage, and waste generation, but there is much room for improvement [22,25]. Implementing a closed-loop approach can increase resource use efficiency and sustainability of urban farming systems [8,26]. Bakalis et al. [17] suggest incorporating waste management and recycling as a means of improving resilience of urban food production systems. Relying on resources recovered from local waste can lower the dependency on long supply chain-based inputs, making urban food production more resilient and self-sustainable.

Modern CEA systems represent a marked improvement over conventional crop production in terms of closing loops, but gains are still available to be made. Achieving completely closed loops is not attainable in terrestrial *local systems*—within the crop production unit—due to the necessity to export resources in the form of food products from the *local system*. The goal, then, is to increase the circularity of resource use within the *local community*—within the urban environment—rather than to achieve complete *local system* closure (Figure 1b). The circularity approach recycles "waste" as a resource and reduces the requirement for virgin materials into the system as resources. Shifting from a linear to a circular approach is necessary to achieve anything resembling true sustainability [27,28].

Composting is an effective and time-tested way to manage waste and to effectively recycle matter within agricultural ecosystems. Although composting is used to manage urban organic waste to some extent, a majority of the urban organic waste in industrialized nations is landfilled [29]. However, with the rapid urbanization and shifting trends, urban

and peri-urban centers are increasingly recognized as centers for localized agriculture, waste management, and resource cycling to achieve resilient and more sustainable urban ecosystems [26]. Based on this premise, integrating composting and urban CEA with the key objectives of waste management and resource recovery is desirable. The process outputs of composting—carbon dioxide and plant nutrients—could be maintained within the CEA system with appropriate engineered systems to achieve a closed-loop resource flow. The goal is to reuse the recovered carbon dioxide (CO_2) for atmospheric enrichment, while returning plant nutrients to the system through hydroponics. The recovered resources can reduce the use of synthetic/fossil fuel-based counterparts (bottled CO_2 and synthetic fertilizers). Composting can also reduce greenhouse gas (GHG) emissions by diverting CEA waste from the landfill and recapturing the carbon in new biomass.

In this review, we present a conceptual framework for a closed-loop urban CEA system using composting to recover and reuse CO_2 and plant nutrients from production biowaste. Certain technical challenges and potential solutions for the successful recovery and reuse of CO_2 for enrichment and plant nutrients for hydroponics are highlighted. The environmental benefits of each component recovered and the system as a whole are also discussed. Based on the discussion, future research directions are identified.

2. Composting

Composting is a process in which microorganisms, in the presence of oxygen, degrade complex organic matter into a simpler and more stable form [30,31]. Microorganisms feed on the organic substrate and produce CO_2, water, and heat as by-products of respiration [32] (Figure 2). This process reduces the volume of the waste material, and forms compost, a highly stable humus-like substance rich in plant nutrients.
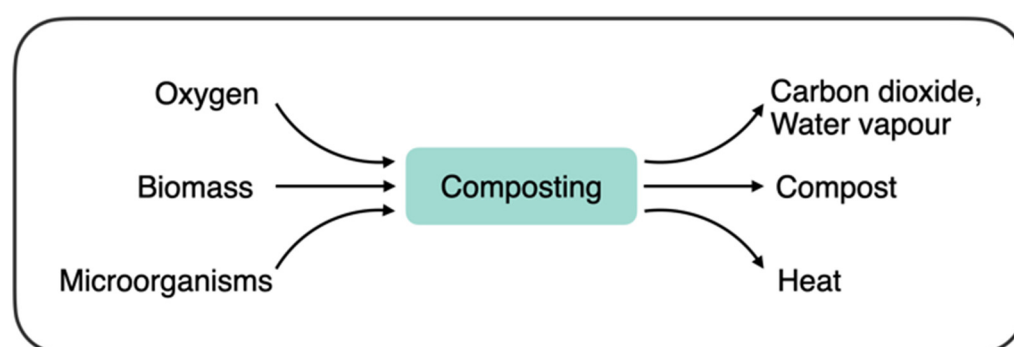

Figure 2. General representation of composting process. Biomass is decomposed by microorganisms in the presence of oxygen. The outputs of composting process include carbon dioxide, water vapour, heat, and compost.

The effectiveness of the composting process depends on the physico-chemical properties (particle size, C/N ratio, pH, moisture) of the substrate and the prevailing environmental conditions (oxygen and temperature). The heat generated by microbial activity initially raises the temperature of the compost, which then gradually declines with the reduction of microbial activity due to depletion of digestible matter in the substrate [31]. The level of microbial activity in the active compost varies, and with it so does temperature. The range can vary considerably but is typically divided into two phases based on the general thermal class of the active microorganisms; mesophilic (<45 °C) and thermophilic (>45 °C) [32,33]. The heat that builds up in the active compost also inactivates certain microbial pathogens in the compost.

Composting for urban CEA systems would need to be carried out through an in-vessel method due to space and odor concerns. In this method, the substrate is retained in a closed container and allowed to decompose under forced aeration. The crop residue generated in CEA systems can be composted on-site along with other feedstocks; the carbon dioxide evolved can be directed back into the growth area for atmosphere CO_2

enrichment. The compost generated can then be used directly as growth medium, organic fertilizer, or indirectly by further processing (extracting nutrients to aqueous medium, also referred to as a compost tea) to be used as a nutrient source for hydroponic crop production. The processed compost can be utilized as a growth substrate, replacing peat. As such, composting can be a key process in closing carbon and nutrient loop in CEA systems. The complete process map of a compost based closed-loop resource flow in a CEA system is illustrated in Figure 3.
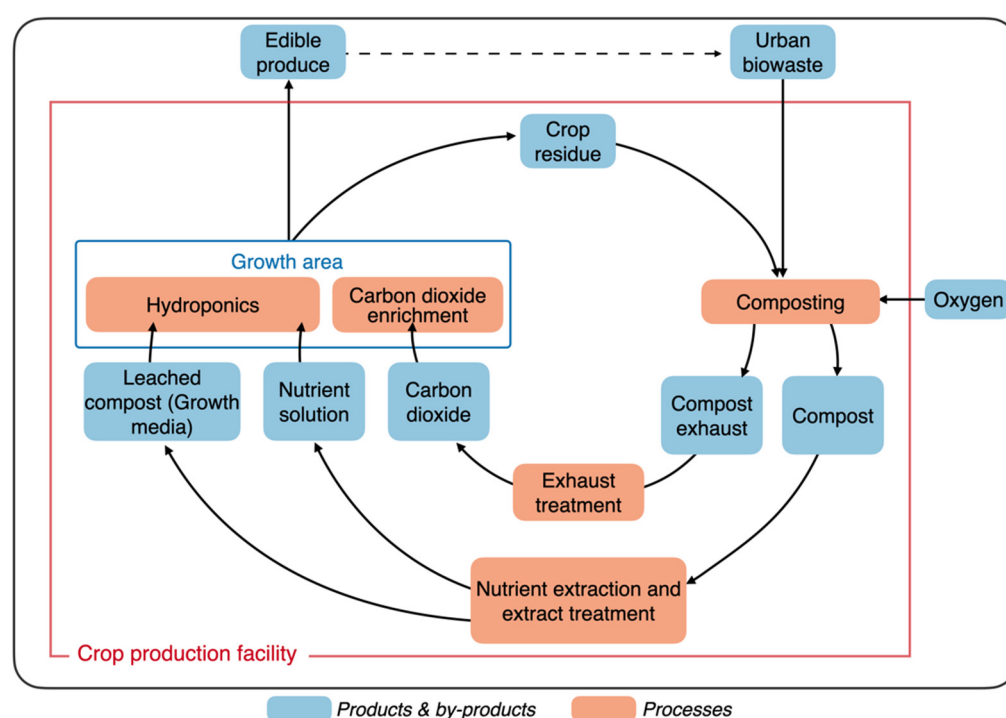
Figure 3. Process map for compost-based closed-loop crop production in an urban controlled environment agriculture system.

Apart from composting, several other biomass treatment techniques, such as combustion [34,35], gasification [36], and anaerobic digestion [37], have also been investigated as resource recovery methods from biomass for CEA systems. Some of these techniques (e.g., combustion, gasification) could be used in conjunction with composting where the processed compost after extracting water soluble nutrients can be thermally treated to further recover energy (heat and methane) and carbon.

3. Carbon Dioxide Recovery

Plants require CO_2 to photosynthesize and produce biomass. Normally, plants derive CO_2 from the bulk atmosphere, but, in indoor CEA growth areas, CO_2 is quickly drawn down by photosynthesizing plants and needs to be actively replenished. Carbon dioxide levels in CEA systems are often enriched or elevated (e.g., 800–1200 ppm) beyond ambient (~415 ppm) to increase productivity. Carbon dioxide enrichment of the atmosphere in CEA is known to increase yield [38,39], and improve the nutritional quality of crops [38,40].

The capacity of CEA systems to enrich the growth space with CO_2 is one of the key advantages of this production strategy [8]. Commonly used CO_2 sources are either CO_2 co-generated with energy through fossil fuel combustion or bottled CO_2 produced industrially. Both these methods have their limitations. Direct enrichment through hydrocarbon (fossil fuels) combustion can be detrimental to the crops due to presence of phyto-active and phytotoxic compounds in the exhaust (ethylene, nitrogen oxides-NO_x, sulphur compounds) formed during incomplete combustion of the fuel [41]. This method is also not compatible with the efforts to reduce fossil fuel use and GHG emissions. Furthermore,

with the transition towards alternative energy sources such as solar, wind, geothermal, etc., most of these sources (except biogas and biomass fuels) are unable to co-generate CO_2 for enrichment [42]. Processed bottled CO_2 on the other hand is relatively safe from a contaminant perspective but more expensive than combustion sources [43]. Commercially produced bottled CO_2 is a by-product, recovered from the exhaust streams, of hydrogen or ammonia (NH_3) production [44]. These production plants use natural gas and other fossil fuels as raw materials. As with direct combustion CO_2 enrichment, this method of CO_2 enrichment is far from carbon neutral [45,46]. Carbon dioxide enrichment through bottled CO_2 has the third most significant environmental burden in terms of global warming potential (0.212 kg CO_2 equivalent per kg tomato), after heating and fertilizer in greenhouse tomato cultivation [47]. The CO_2 from fossil fuel based CO_2 enrichment, although initially fixed by the crops as biomass during photosynthesis, eventually reaches the atmosphere resulting in a net addition of CO_2 to the environment [48]. Carbon dioxide produced during the composting of crop residues is considered biogenic—originated from biological processes—and does not result in a net addition of CO_2 to the atmosphere [49]. Hence, CO_2 generated during composting can be used as a sustainable enrichment alternative to fossil fuel-based CO_2. This reduces direct use of fossil fuels for CO_2 enrichment and the carbon emissions associated with production of bottled CO_2.

There is a paucity of literature on the subject of composting as an alternate CO_2 source for enrichment in CEA, with only three studies looking at the process in greenhouse cultivation [38,50,51]. Jin et al. [38] first proposed the technique of enriching CO_2 in greenhouses by directly composting biomass within the growth area. In their study, a mixture of rice straw and pig feces was composted in a composting unit placed within the greenhouse. Carbon dioxide released during the composting process enriched the greenhouse atmosphere resulting in increased yield of celery, leaf lettuce, stem lettuce, oily sowthistle, and Chinese cabbage [38]. The study also showed a reduction in crop nitrate content, increased soluble sugars, and increased ascorbic acid concentrations as a result of CO_2 enrichment. Dilution due to enhanced growth and/or reduction in nitrate reductase activity is speculated to be the reason for reduction of nitrate leaf content. Whereas the increase in sugar and ascorbic acid content is attributed to enhanced photosynthesis and carbon metabolism.
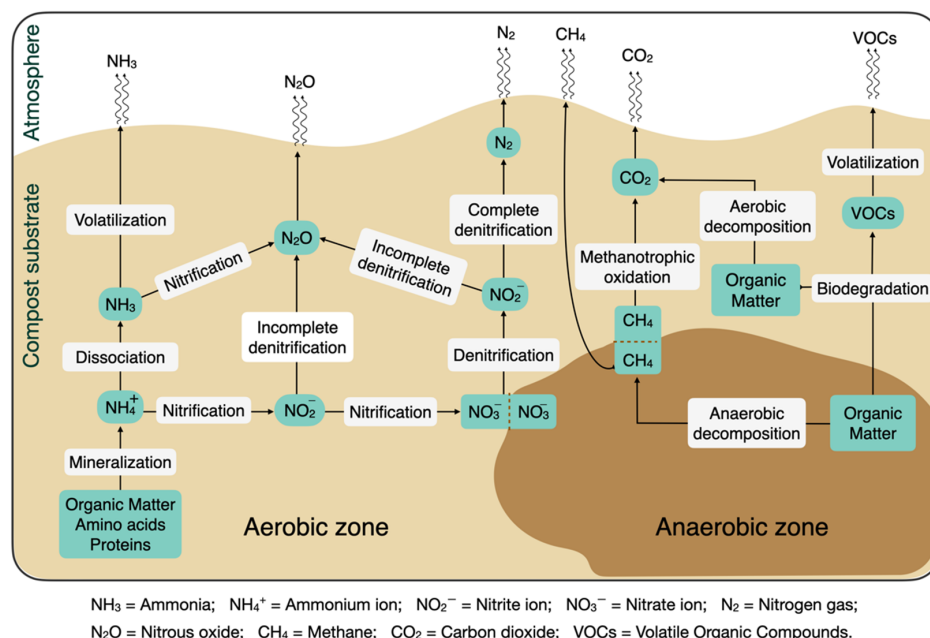
Karim et al. [51] and Hao et al. [50] studied the effect of compost based CO_2 enrichment on growth, yield, and fruit quality of tomato. A composting system similar to Jin et al. [38] was used in both these greenhouse studies. Improvement in overall plant growth (plant height, stem diameter), increased yield (fruit size and fruit weight), and enhanced fruit quality (higher soluble sugar, soluble solids and reduced nitrate content) was observed as an effect of CO_2 enrichment via composting. Hao et al. [50] further reported enhanced amino acid and unsaturated fatty acid metabolism, increased secondary metabolites, and increased levels of stress related proteins under compost based CO_2 enrichment in comparison to tomato grown in a greenhouse under ambient CO_2 levels.

These studies demonstrated the potential of composting for CO_2 enrichment in CEA systems. Carbon dioxide levels of up to 1500 mL L^{-1} was achieved in the studies by Jin et al. [38] and Karim et al. [51]. Although these studies showed positive results, the method of composting was uncontrolled and not suitable for commercial CEA production systems. Furthermore, these studies were conducted exclusively in greenhouses and, to date, there are no studies that the authors could find that examined compost-based CO_2 enrichment in a plant factory or vertical farm scenario.

3.1. Gaseous Contaminants

Composting involves a diverse group of chemical processes resulting in various gaseous end products such as methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), and a host of other volatile organic compounds (VOCs) along with CO_2 (Figure 4). These gaseous by-products are a constraint for using compost as a CO_2 source in CEA. Methane and N_2O are highly potent GHGs, whereas NH_3 and VOCs cause odor problems and

can disrupt normal plant functions [52]. The presence of these contaminant gases raises environmental concerns and concerns regarding compost off-gas as a CO_2 enrichment source. Furthermore, conversion of organic carbon and nitrogen in the substrate into unwanted gases (i.e., N_2O, CH_4, NH_3) represents a loss of resources from the system (CO_2 and nutrient N) thereby reducing recovery efficiency.

NH_3 = Ammonia; NH_4^+ = Ammonium ion; NO_2^- = Nitrite ion; NO_3^- = Nitrate ion; N_2 = Nitrogen gas; N_2O = Nitrous oxide; CH_4 = Methane; CO_2 = Carbon dioxide; VOCs = Volatile Organic Compounds.

Figure 4. Pathways for various gaseous emissions during composting.

3.1.1. Ammonia

Gaseous ammonia is produced during the breakdown of amino-acids and proteins during composting (Figure 4). Ammonia creates odor problems, and has detrimental effects on plants [52]. Ammonia is also a health hazard to humans with permissible exposure limits being <50 ppm [53]. Ammonia emissions also represent a loss of nitrogen from the compost, reducing the fertilization potential of the final product.

Ammonia genesis is greatest during the thermophilic phase (>45 °C) [54,55] and is further enhanced at high aeration rates [55,56]. Increased microbial activity in the thermophilic phase, and the consequent increased degradation of readily available organic N, is presumed to be the reason for increased NH_3 emissions [57]. Alkaline pH of substrate can also increase NH_3 formation due to increased volatilization of NH_4^+ [58]. The emission of NH_3 is also increased when feedstocks with high nitrogen content or low C/N ratios are composted [57].

3.1.2. Methane

Methane generation is an anaerobic process, which means that it takes place in conditions devoid of oxygen. Composting, although aerobic, often has localized anaerobic pockets in the substrate where methanogenic bacteria thrive and drive the evolution of methane from the compost system (Figure 4) [49]. The formation of anaerobic pockets can result via several mechanisms, including inadequate mixing of feedstock, insufficient aeration, and excess water content. Methane generation also is temperature dependent and, like ammonia, is highest at temperatures above 40–50 °C [54] as oxygen solubility decreases with the increasing temperature [49].

3.1.3. Nitrous Oxide

Nitrous oxide (N_2O) is produced as a result of incomplete microbial nitrification of ammonium (NH_4^+) and/or denitrification of nitrate (NO_3^-). Although produced in

negligible amounts, N_2O must be avoided due to its high global warming potential—235 times greater than CO_2 [49]. Unlike CH_4 and NH_3, N_2O has an inverse relation with the temperature; temperatures above 40 °C reduce N_2O emissions, as higher temperatures are unfavorable for nitrifying bacteria [54,59].

3.1.4. Volatile Organic Compounds

Volatile organic compounds (VOCs) are organic compounds with a low boiling point due to their high vapor pressure at room temperature [60]. During the composting process, a variety of VOCs can be produced. The main classes of compounds produced are terpenes and alcohols, along with lesser amounts of carbonyl compounds, esters, sulphur compounds, and ethers [60–64]. These compounds are usually odorous, and some can be potential hazards in terms of human health and safety [65,66]. High rates of VOC emissions coincide with the temperature rise during the initiation of the composting process [60,67].

Composting of municipal biowaste (e.g., yard waste, wood waste, plant prunings, lawn clippings, food waste, kitchen waste) produces considerable amounts of VOCs in the exhaust gases [60,62,63,68–71]. The concern of VOCs from a CO_2 enrichment perspective is odor formation and effect on plant growth. Effect of VOCs on plant growth can vary with the plant species, VOC compounds, duration of exposure, and concentration [72]. Further studies on VOC emissions during crop residue composting and their effects on plant growth in controlled environments are necessary. Scrubbing compost exhaust gas prior to using it for enrichment would be desirable as a precautionary measure for initial adoption until sufficient data are available.

3.1.5. Ethylene

Ethylene is a potent gaseous plant hormone that is bioactive even at extremely low concentrations (<1 ppm) [73]. The presence of ethylene can have inhibitory effects on plant growth and development [74–76]. Concerns with the presence of ethylene is greater in completely/partially sealed environments [77]. Ethylene formation has been observed during the decomposition of immature composts, mostly from animal manure composts [78–81]. Ethylene formation is linked to nitrogenase activity during decomposition. Nitrogenase enzyme is primarily involved in bacterial nitrogen-fixation, where atmospheric nitrogen (N_2) is reduced and converted to NH_3 [82]. In addition to N_2, certain nitrogenases can also reduce CO_2 or carbon monoxide (CO) to form ethylene [83]. As nitrogen fixing bacteria that utilize nitrogenases are typically involved in the composting process [31,84] ethylene production, at some level, is nearly ensured. The possibility of ethylene formation during composting cannot be overlooked in this scenario as ethylene can act as a plant growth inhibitor. There is little information available about ethylene production during the composting process. Given its potential impact under the proposed applications, further investigation is certainly required.

3.2. Greenhouse Gas Emission Balance

The formation of non-CO_2 GHGs (CH_4 and N_2O) during composting is a challenge due to their high global warming potential compared to CO_2 [85]. Agriculture and urban areas are the major contributors of GHGs [86,87] and hence, mitigation of these emissions from composting in urban CEA is crucial. Since CO_2 evolved during composting is biogenic and does not add to the net CO_2 emissions, the most effective GHG savings is observed through avoiding non-CO_2 GHG emissions from composting.

Besides non-CO_2 GHGs, there are also indirect non-biogenic CO_2 emissions associated with electricity and fossil-fuel use for composting process operations. The amount of these CO_2 emissions depends on several factors, such as the source of energy, process management practices (shredding, turning, aeration), and the method of composting [49].

Although the non-biogenic CO_2 adds to the overall carbon footprint of composting, Brown et al. [88] pointed out that the benefits in terms of emission reduction through composting outweighs emissions associated with indirect non-biogenic CO_2. The most

significant savings through composting is achieved by avoiding GHG emissions associated with landfilling these crop residues and urban wastes [88,89]. Additional GHG savings are achieved through using compost as peat or chemical fertilizer alternative, and through carbon sequestration in compost [88–90].

With increased productivity of urban CEAs and prospects of emission reductions through closed-loop approaches, "absolute decoupling"—the simultaneous reduction of GHGs with increasing crop production—can be achieved, [87]. However, estimating the net GHGs reductions and the overall carbon footprint of compost-based closed-loop systems is required to truly understand the carbon savings achieved over conventional systems.

3.3. Enhancing CO_2 Production and Reducing Non-Target Gaseous Emissions

Carbon dioxide production during the composting process is a direct indicator of microbial activity and process efficacy [91,92]. Evolution of CO_2 and other gaseous compounds are dependent on feedstock characteristics including C/N, pH, initial moisture and particle size, as well as environmental and process control conditions (e.g., temperature, moisture, and aeration) during composting. Implementing good process control measures and optimizing the feedstock properties are necessary to minimize the formation of gaseous contaminants while improving CO_2 production and overall process quality. Table 1 summarizes the target ranges of process parameters and feedstock characteristics for optimum composting.

Table 1. Desirable ranges of critical factors that affect composting.

Factor	Desirable Range
C/N	25:1–30:1
Moisture	50–60% wet basis
Particle size	0.5–5 cm
pH	5.5–8.0
O_2	>15%
Temperature	45–55 °C

3.3.1. Feedstock Optimization

The physical and chemical characteristics of the feedstock have a large influence on the composting process [93]. The inherent physico-chemical properties of crop residues may not fall within the optimum range for composting as shown with C/N ratios of crop residues in Table 2. It is desirable to adjust the feedstock properties for effective composting. This adjustment process is called feed conditioning and often targets key factors such as C/N, particle size, moisture, and free airspace of the feedstock [33].

Table 2. C/N ratios of residues from crops commonly grown in controlled environment agriculture systems.

Crop	C% (Dry Weight)	N% (Dry Weight)	C/N	Reference
Tomato residue	38.17	2.30	16.59	[94]
	30.00	3.40	8.82	[95]
	-	-	9.34	[96]
	-	-	15.27	[97]
Soybean residue	42.30	2.47	17.12	[98]
	38.6	4.4	8.7	[99]
Lettuce roots	38.55	5.41	7.12	[98]
Lettuce residue	39.9	5.1	7.8	[100]
Cucumber residue	-	-	12.01	[97]
	33.81	3.00	11.27	[94]
Basil residue	36	4.6	7.7	[99]
Aubergine residue	42.09	2.18	19.3	
Bean residue	42.86	3.62	11.83	[94]
Pepper residue	39.27	3.28	11.97	

Particle size and moisture status affect the free air space and O_2 availability in the feedstock matrix. A balance has to be struck between these two factors during the composting process to attain optimum physical conditions. Particle size determines the effective surface area available for microbial interaction with the substrate. A particle size between 0.5–5 cm is considered acceptable [101]. The crop residues have to be reduced in size by grinding/shredding. Particle sizes that are too small can reduce the free air spaces creating localized anaerobic zones leading to CH_4 emissions (Figure 4).

Moisture is necessary to sustain an active microbial community within the feedstock material [93]. The moisture content of the crop residue varies with the crop type and the parts of the plant that are inedible or waste biomass. Currently, commonly grown CEA crops are leafy green herbs such as spinach, lettuce, and kale, with soft tissues and high water content. Other crops like tomato, bell pepper, and beans, have comparatively less water content in their inedible biomass. Although the optimum initial moisture percentage for composting is around 60%, it varies with the feedstock materials and their water holding capacity [93]. Too little water content (below 35%) will reduce microbial activity, whereas excessive moisture clogs up the pores in the matrix leading to the formation of anaerobic zones (Figure 4). These zones result in the generation of gaseous contaminants described earlier.

The C/N ratio is a critical parameter that affects microbial activity and chemical dynamics of the process. An initial C/N ratio of 25–40 is a suggested optimum for composting, but the exact figure is dependent on the feedstock itself [93,102]. Crop residues commonly generated in CEA systems are usually nitrogen rich, having lower than optimum C/N ratios (Table 2). Feed conditioning can be achieved through addition of amendments (bulking agents, biochar, minerals), or by composting a mixture of two or more distinct feedstocks together.

3.3.2. Amendments

Bulking Agents

Amendments are materials added to the feedstock to manipulate its physical and/or chemical properties with the goal of improving the overall composting process. Bulking agents are the materials that improve the physical structure of the compost matrix by increasing free airspace, leading to better aeration. Most of the commonly used bulking agents are carbon rich (woodchips, straw, wood shavings, sawdust) and so can also be used to modify the overall C/N of the feedstock. Bulking agents improve the aeration, C/N ratio, microbial activity, and CO_2 production and as a result, reduce the formation of gaseous contaminants [103,104]. Bulking agents also improve the final compost quality and accelerate the overall process [105]. Although bulking agents can reduce VOC emissions, some commonly utilized materials, such as wood chips and saw dust, increase certain types of VOCs (i.e., terpenes) as these compounds are naturally present in these bulking agents [62,106]. Some easily available materials in urban areas that can be used as bulking agents are shredded cardboard, pruning/gardening wastes, and fallen leaves, although the latter two are only seasonally available.

Many other materials such as woodchips, crop residues (wheat, barley straw), bentonite, ash, sawdust etc., have been investigated as amendments, but most studies focus on manure and municipal solid waste composting and there is less focus on their effect on CO_2 emissions [107]. Research specific to amendments and their effect on green waste/lignocellulosic residue composting should be encouraged to find the optimum amendments for enhancing CO_2 production and other process parameters to serve the needs of the CEA sector.

Biochar

Biochar has garnered a lot of attention as an effective compost amendment in recent years [108,109]. Biochar raises the pH and lowers moisture content, which in turn reduces the activity of denitrifying bacteria responsible for N_2O production [109]. Am-

monium ions (NH_4^+) in the compost is one of the precursors for NH_3 formation. The NH_4^+ adsorption capacity of biochar results in a reduction of NH_3 emissions during composting [110,111]. The porous nature of biochar improves compost matrix structure, leading to improved aeration, enhanced mineralization and as a consequence, increased CO_2 production [107,112,113]. With the growing interest for pyrolysis for urban biowaste recycling and biochar production [114], biochar generated from such plants could be used as a sustainable compost amendment.

Mineral Additives

Mineral additives such as zeolite, phosphogypsum, and lime are effective compost amendments to reduce GHG emissions and improve the composting process [115–120]. Addition of zeolite reduced non-CO_2 GHG emissions and increased CO_2 production during dewatered sewage sludge composting by acting as a bulking agent and enhancing microbial activity [115,118]. Rock phosphate and phosphogypsum reduced GHGs in green waste, animal manure and food wastes composts [116,117,119,120]; however, phosphogypsum also resulted in increased N_2O emissions through a lowering of feedstock pH favoring N_2O formation [119,121]. Zhang and Sun [122] showed that adding bentonite (2.5%–4.5% dry weight) to green waste compost increased the nutrient content and improved the porosity of the matrix, increased CO_2 emission, improved the nutrient content, C/N ratio, and reduced phytotoxicity of final compost. The porous nature of bentonite helped adsorb and assimilate NH_3 thereby reducing total NH_3 emissions [122].

An evaluation of various mitigation strategies to reduce NH_3, N_2O, and CH_4 emissions during composting showed that bulking agents are more effective than other amendments (chemical and mature compost) and aeration control [123]. It is proposed here that a combination of bulking agents, chemical additives, and effective aeration will enhance CO_2 production and reduce evolution of non-target gases, a key operational consideration in CEA composting concepts.

3.3.3. Co-Composting

Co-composting refers to composting a mixture of two or more distinct yet complementary feedstocks with the aim of improving the final product and effectively managing diverse waste streams [124–126]. Co-composting can be used to alter the C/N ratio of the overall feedstock mixture such that desired ratios are achieved [127]. There are many biowastes generated in the urban environment that can be collected and incorporated into the crop residue feedstock to optimize the composition of the overall mixture for CO_2 and nutrient recovery. Organic wastes from restaurants, cafés, and grocery stores, to name a few, are all viable sources of feedstock for co-composting.

Food waste is one of the major organic wastes in urban areas, rich in organic matter and plant nutrients. The main challenge with incorporating food waste into a CEA resource recovery system is its highly heterogeneous nature. The physico-chemical characteristics of food waste varies geographically (city, region, country) and temporally (seasonal) [128], making standardization and prediction of composting process outcome more challenging. Food wastes also have a higher tendency for odor production as they are rich in protein and lipid content, leading to NH_3 and sulphur compound formation [30]. In contrast, more homogenous waste streams such as source separated spent coffee grounds collected from local cafés are more amenable to the standardization of composting processes. Spent coffee grounds improved physical and process parameters when co-composted with green waste [129] making them attractive from a CEA resource recovery perspective. Addition of such externally sourced biowaste allows for the manipulation of the feedstock characteristics to optimize the performance of the CEA compost-based resource recovery system. Table 3 shows the C/N ratios and pH of common urban biowastes that can be co-composted with crop residues.

Table 3. C/N ratios and pH of common urban biowaste.

Waste	C/N	pH	Reference
	21.3	7.64	[130]
	22	-	[131]
Spent coffee grounds	20.2 ± 0.09	-	[132]
	21.5	6.0	[133]
	23.11	5.48	[134]
Food waste	18.5	5.1	[135]
Lettuce waste (from grocery store)	10.3	-	[136]
Sawdust	211	5.55	[137]
	792	-	[136]
Food waste: restaurant	4.3–9.2	3.8–5.2	[138]
Food waste: Grocery	2.8–20.5	4–5	[138]
Food waste: University Residence	22.8	4.6	[138]
Yard wastes (dried fall leaves: grass clippings: wooden debris, 1:1:1)	10.8 ± 0.1	4.8±0.1	[139]
Pruning waste	46.8	6.9	[140]
Woodchips	98.2, 107.5	4.8, 4.9	[62]

While co-composting allows for the manipulation of the physico-chemical properties of the feedstock, it also provides an opportunity to divert urban biowastes from landfill and reduce the associated GHG emissions. Realization of effective urban biowaste diversion and co-composting needs setting up a functional, source separated, waste collection system specific to the needs of the CEA sector. Given the use of these waste sources as inputs for food production, systems to check levels of critical contaminants (e.g., toxic metals or other non-compostable chemical contaminants) must be put in place. Furthermore, optimization studies should be conducted to develop co-composting protocols for different CEA crop residues and urban biowaste.

3.3.4. Process Control

Composting is microorganism driven and the CO_2 evolution depends on the microbial activity during the composting process [91,92]. The environmental conditions such as temperature, moisture, and oxygen level affect the microbial population and activity [93,141]. Hence, maintaining favorable environmental conditions through process control measures can improve the composting process, enhance CO_2 production, while reducing the evolution of unwanted gases [49,55,142,143]. The CEA composting process itself needs to be a controlled environment system.

Temperature

Composting is an exothermic process where microbial metabolism generates heat. This heat accumulates in the substrate and raises the substrate temperature during the process, which can reach internal temperatures of 70 °C [93]. The temperature of the substrate affects the microbial population and diversity. In the mesophilic (30–45 °C) phase of composting, microbial diversity and biodegradation rates are high [93]. Temperatures above 60 °C reduce the microbial population and diversity especially of fungi responsible for the degradation of complex structural compounds like lignin and cellulose [31]. Some studies report temperatures around 55 °C to have the highest biodegradation rate and CO_2 production [142,144,145], but this may vary with the compost substrate itself. Thus, maintaining temperature around 55 °C is desirable for maximum degradation and CO_2 production.

Oxygen

Microorganisms responsible for biodegradation during composting require O_2 for respiration. Maintaining O_2 levels above 15% in the compost matrix is necessary to sustain microbial activity throughout the process [93]. Inadequate O_2 supply can result in anaerobic conditions leading to proliferation of anaerobic microorganisms and formation of undesired CH_4 [49]. The oxygen demand of microorganisms is met through aeration methods such as forced aeration or mixing [146]. Ample aeration should be ensured to keep the compost oxygenated and prevent formation of anaerobic zones in the compost. As the O_2 consumption rate is high during the early rapid decomposition phases of composting, aeration with O_2 concentrations higher than the ambient levels can be desirable. In tightly sealed CEA systems this additional oxygen could be sourced from the crops themselves.

Moisture

Maintaining adequate water content in the compost substrate is necessary to support microbial growth and metabolism [93]. An initial moisture content of 60% of total weight is considered acceptable for composting [93]. Moisture content in excess of 60% can saturate the free airspaces, restrict air movement, form anaerobic conditions, and lead to methane formation. Too little moisture (i.e., below 35%) is undesirable and inhibits microbial activity [147]. Excess moisture is normally controlled through heat or air drying, but this is energy consumptive. Mixing substrate with dry biomass or bulking agents can also lower the overall moisture levels. Conversely, water is added externally if the moisture percent during composting drops too low [147]. Moisture content should be monitored and adjusted throughout the process to optimize composting and prevent CH_4 formation.

3.4. Treatment of Exhaust Gases

Process and feedstock optimization can reduce, but may not eliminate non-target gases altogether. Therefore, filtering or scrubbing methods may be required to remove gaseous contaminants from the exhaust stream that would be fed into the CEA production areas. Although physico-chemical treatment methods like acid scrubbing are available for treating the exhaust gas, they are relatively expensive for long-term operations, as well as creating a secondary waste stream and safety concerns [148,149]. Furthermore, in an optimized composting process, the amount of impurities generated are relatively low and under these conditions, biologically-based systems may be more appropriate and effective than physico-chemical treatment options [49].

Biofilters

Biofilters comprise a matrix of biologically active components through which the gases to be treated are passed [150]. The undesirable compounds in these gases are broken down by the microorganisms in the matrix, reducing their concentration in the air. Microbial degradation of these compounds primarily produce CO_2 and water as by-products [151,152]. The commonly used materials for biofilters are mature compost by itself or mixed with other materials like woodchips, perlite, peat, zeolite, bark, mulch, and oyster shells [150].

Ammonia has been successfully treated with biofilters using materials like finished compost, rockwool, peat, woodchips, and perlite [153–157]. Perlite used for in-house plant propagation can be re-used as a biofilter medium. Although NH_3 can be treated effectively, the efficiency of the biofilters is limited by the concentration/ammonia load. Liang et al. [158] suggest using biofiltration for NH_3 removal under low concentrations of <200 ppm. Excess ammonia increases pH of the biofilter media due to increased NH_4^+ content. This reduces the efficiency of the biofilters by inhibiting nitrification process in the biofilter matrix [149,153]. To improve the efficiency of the biofilters, Amlinger et al. [54] suggests stripping excess NH_3 before the exhaust gases are introduced into the biofilters. Diluted sulphuric acid is a prevalent and an effective technique for scrubbing ammonia, where gaseous ammonia dissolves with sulphuric acid to form ammonium sulphate [159].

Use of acid scrubbers is justified only when the composting unit produces high NH_3 levels and overloads the biofilters. A simpler alternative to chemical scrubbers would be cooling of compost exhaust. Considerable amount of ammonia was recovered from compost exhaust, dissolved in the condensed water as ammonium [142,144,160,161], suggesting the use of upstream condensers to trap moisture and reduce the ammonia load on the biofilter. Both, the condensate containing dissolved ammonia and acid scrubber output containing ammonium sulphate could be used as nitrogen fertilizers [159,162]. Moreover, if moisture in the airstream is not reduced it can create problems commonly associated with excess humidity, including fungal proliferation when the exhaust is used for CO_2 enrichment. Hence, the moisture in the compost exhaust gases should be stripped/recovered regardless of the potential contaminants present.

Mature compost is suggested as the most effective biofilter material for CH_4 removal due to the typical presence of methanotrophs which metabolize methane [151]. Up to 85% of methane was removed in a compost and perlite based biofilter [163]. Biofiltration has also been found effective for VOC removal [152]. Ergas et al. [164] demonstrated greater than 90% VOC removal in a compost, perlite, and crushed oyster shell biofilter. Despite high VOC removal efficiency, the biofilter itself produced small amounts of VOCs that could be a concern in a CEA system [71,165]. Biofiltration of N_2O and CH_4 has proven more challenging than ammonia due to their low solubility in water [166]. The degradation process happens in a gas-liquid interphase around a layer of biofilm in the biofilter matrix [167]. The low solubility of these gases in water reduces their removal efficiency via biofiltration. Hence these gases would be better dealt with by reducing the likelihood of their formation through ensuring proper process conditions during composting.

Reducing the formation of non-target gases during the composting process, as suggested above, helps reduce the load on biofilters and increases their efficiency. Reducing off-target emissions through the maintenance of optimum composting conditions throughout the process should be the highest priority with exhaust gas treatment measures taking more of a supporting role. A balanced combination of process management practices and exhaust gas treatment could result in a substantial decrease of the non-target gaseous effluents in the exhaust streams. Implementing this technology still requires more investigation to evaluate the effectiveness of these various components in an overall system. Due to the multitude of factors involved, individual component testing to determine the optimum working conditions is necessary.

3.5. CO₂ Enrichment Control

Carbon dioxide enrichment is normally a discontinuous process, carried out only during the daytime when the plants are photosynthesizing and actively drawing down CO_2 [43], whereas CO_2 production during composting is continuous, happening day and night. The CO_2 injection rate into the growth area to maintain a specific concentration is usually controlled based on several factors such as overall photosynthesis rate, crop growth stage, ventilation, size of growth area, internal CO_2 levels, and CO_2 leak rates [36,168]. In contrast, the CO_2 evolution from a composting process can be either roughly steady or more dynamic depending on the feedstock input profile, i.e., batch-fed or continuous fed (Figure 5). Additional systems could be used to store CO_2 produced by composting at night and to release it in a controlled manner for enrichment during the day. Sánchez-Molina et al. [34] developed an activated carbon-based CO_2 capture, storage, and controlled release system for CO_2 enrichment by biomass combustion. Similar systems can be used for CO_2 enrichment via composting. It should be noted that CO_2 capture, storage, and release systems are vital to achieve controlled CO_2 enrichment with biomass-based CO_2 generation methods (i.e., combustion, gasification, anaerobic digestion).
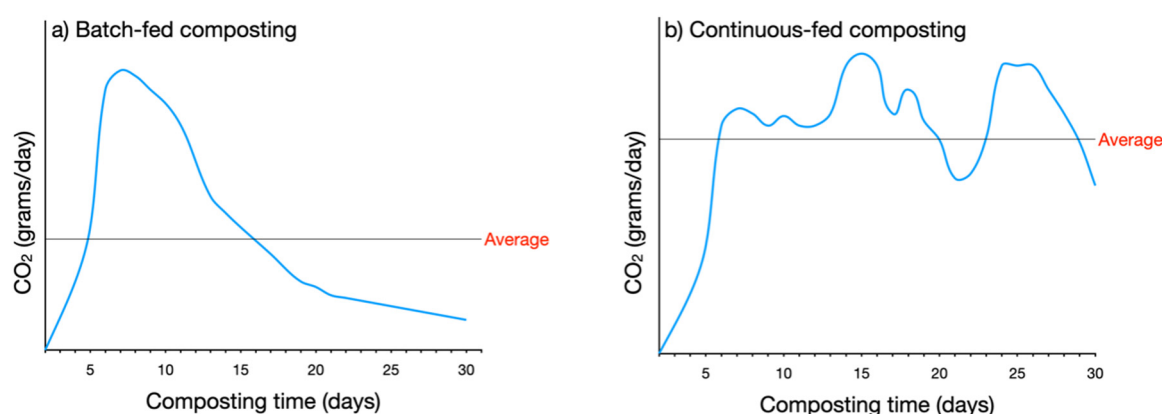
Figure 5. Typical carbon dioxide (CO_2) evolution pattern in (**a**) batch-fed vs. (**b**) continuous-fed composting systems. In batch-fed composting, CO_2 evolution is more variable as feedstock is composted in batches without adding new feedstock to the composter. In contrast, the CO_2 evolution from continuous-fed composting is more stable as fresh feedstock is added regularly to the composter.

Estimating the quantity of CO_2 produced from the composted biomass is desirable for effective enrichment control. Based on the elemental carbon, hydrogen, nitrogen, and oxygen composition of the substrate, the amount of CO_2 produced when the substrate is composted can be theoretically estimated through an empirical formula [33,169]. Furthermore, the pattern of CO_2 evolution under pre-defined conditions can be both measured and predicted using mathematical modelling of composting process [170,171]. With composting, there is a chance of generating less CO_2 than required. In this situation, the deficit of CO_2 to achieve desired enrichment levels must be supplemented through other means. Bottled CO_2 may be required only for supplementation, since a majority of the CO_2 will be derived from compost, provided external feedstocks supplement the crop residue biomass from the facility. In the long run, this will reduce the use of bottled CO_2 in comparison to conventional enrichment means and can still provide environmental benefits. Alternative chemical CO_2 traps, e.g., Na_2CO_3, can also be exploited for storage and release as needed, but this is an area requiring more research [172]. In case of excess CO_2 production, the surplus can be either stored, as described above, or vented out to avoid toxicity effects on plants. Furthermore, employing monitoring systems and automated control strategies can lead to effective and efficient CO_2 enrichment control [43].

4. Plant Nutrient Recovery

Finished compost is a rich and dense source of plant nutrients. The nutrients in the compost generated from crop residues, or food waste are in fact the nutrients that were initially invested in the production of the crop. Mismanagement of these organic wastes (e.g., landfilling) results in loss of these nutrients from the system and can have negative environmental impacts at the site of disposal. In CEA systems, crops are generally grown using soil-less hydroponic techniques, where the nutrients are provided through an aqueous nutrient solution. Typically, these nutrients are sourced from fossil fuel-based synthetic fertilizers [173]. Recirculating hydroponics in CEA systems has reduced the environmental impact of crop production in comparison with field production through improved fertilizer use efficiency and reduced nutrient runoff [174]. Despite that, production and transport of chemical fertilizers still cause significant environmental deterioration and have substantial global warming potential [175–178]. Replacing chemical fertilizers with biomass-based nutrient sources (organic fertilizers, treated biowaste, compost), can reduce the environmental burden associated with supplying plants with the nutrients they require for optimal production [177]. Hence, recovering and reusing nutrients from crop residues and urban biowaste can be beneficial from an ecological standpoint and can also improve the nutrient use efficiency in these systems.

Early studies on recirculating nutrients from crop residues were conducted by NASA in the 1990s, as part of the R&D activities surrounding the development of closed-loop bioregenerative life support systems [179–181]. These studies showed that nutrients from crop residues can be returned to the production system but only after treatment; in this case processed through bioreactors [181]. The researchers found that applying untreated biomass leachate as nutrient solution to the crops impaired crop growth due to the presence of dissolved organics [180,181]. Recently, the prospect of utilizing organic nutrient sources for hydroponic cultivation has gained more interest owing to the increased consumer demand for organic produce [182]. There is an ongoing debate over considering hydroponic cultivation using organic nutrient sources as "certified organic" or not [183]. There are several arguments for and against this proposition [182,183]. Despite these unsettled arguments, using organic nutrient sources such as compost offers positive benefits for sustainable crop production.

Compost as a plant nutrient source reduces use of synthetic fertilizers and the environmental impact associated with fertilizer production, transport, and use [90]. Using compost also reduces harmful ecological implications of phosphate and peat mining, which are also non-renewable resources [184–187]. In addition to acting as a nutrient source, compost extracts have shown phyto-stimulatory properties by promoting germination, growth and nutrient absorption/metabolism [188,189]. Bioactive aromatics and humic substances in the compost shows hormone-like properties resulting in increased plant growth and yield [188,189]. Adding compost extracts to nutrient solution also resulted in reduction of nitrate content in baby leaf lettuce along with improving the yield [188]. Hence, nutrient recovery from compost along with reducing chemical fertilizer use, can also improve crop yield and quality.

4.1. Nutrient Mineralization

Effective utilization of nutrients from compost requires proper nutrient extraction and mineralization, as plants take up nutrients primarily in their mineralized form. Nutrients can still be taken up some nutrients are taken up as organic compounds (e.g., amino acids, urea), but to a lower degree [190]. Compost usually contains plant nutrients already mineralized during the composting process. However, the compost still contains bound nutrients in organic form and not mineralized during the main phases of the composting process. These nutrients can be made available through secondary processing, further improving the nutrient cycling in CEA systems.

The process of promoting microbial activity to release nutrients into the hydroponic media—termed bioponics—relies on microbial mineralization [173]. Nutrients are normally extracted by placing the organic material in an aerated water tank to enhance the microbial activity [188,191]. This technique when used for compost is equivalent to brewing a compost tea [192,193]. The nutrients are released into the aqueous medium through microbial mineralization and solubilization.

A technique based on microbial mineralization called "multiple parallel mineralization" was developed by Kawamura-Aoyama et al. [191]. In this process, microbial inoculums are utilized to mineralize organic nitrogen through sequential processes of ammonification and nitrification. Although plants can take up nitrogen both as nitrate and ammonium, the former is the more preferred form [194]. Furthermore, NH_4^+ as the predominant nitrogen source can have inhibitory effects on plants [195,196]. Nitrifying microorganisms added to the nutrient solution derived from organic source can convert NH_4^+ into NO_3^- and eliminate the phytotoxicity associated with high ammonium levels and improve plant growth overall [194].

Bioponics also facilitates the development of microbial biofilm on the root surface of plants [194]. Biofilms, teeming with microbial activity, mineralize organic matter and increase the bio-availability of mineral ions (NH_4^+ and NO_3^-) to the plant roots [194]. These root biofilms have also been speculated to impart pathogen resistance to the plants [197].

Although bioponics provides plant growth benefits due to rootzone microbial activity, microbial nutrient mineralization is slow and has low mineralization efficiency [191].

Oxidative processes such as ozonation, have shown potential for mineralizing organic matter to release plant nutrients for hydroponic crop production [198]. Furthermore, advanced oxidative and electrochemical oxidative techniques have also shown to mineralize organic matter in water [199–204]. The suitability of these techniques for hydroponic nutrient solution treatments is still questionable, but on-going research should address currently unresolved questions. These techniques are very attractive due to their potential to address pathogen and phytotoxicity concerns, while also mineralizing organic matter (discussed in Section 4.3.1).

4.2. Nutrient Solution Challenges

Other challenges associated with using compost extracts as nutrient solutions include drastic variations in pH, nutrient level management, electrical conductivity (EC) regulation, and associated yield reductions [205,206]. The compost extracts cannot be used directly due to the possible imbalances in the nutrient profile and chemical characteristics of the untreated extracts. The imbalanced nutrient profile of the compost leachate affects the growth and nutrient composition of the plants [205,207]. Thus, using compost extract as nutrient solution requires regular monitoring and fortification of deficient nutrients to ensure proper nutrient availability and plant growth. Compost extract used as hydroponic nutrient solution also shows significant fluctuation in pH due to nutrient uptake, variation of NO_3^-/NH_4^+ balance and low buffering capacity [205]. Hence, achieving proper plant nutrition with compost-based nutrient recovery will continue to require some level of mineral fertilizer input.

4.3. Phytotoxicity and Pathogenicity

Phytotoxicity of compost can happen due to various factors: organic compounds, salinity, heavy metals, trace elements, and ammonia [32]. The content of heavy metals depends on the feedstock material and its source. Anaerobic conditions during composting caused by insufficient aeration and excess moisture can lead to the formation of phytotoxic organic compounds like acetic, propionic, and butyric acids [32]. Some organic wastes like coffee grounds, inherently contain phytotoxic compounds (phenolics), but composting is capable of reducing phytotoxicity of these compounds [208]. The presence of dissolved organic compounds could also increase microbial activity and oxygen demand in the nutrient solution leading to hypoxic phytotoxic effects.

Compost may also contain pathogenic microorganisms that enter through externally sourced waste when co-composted with crop residues. Usually, regulations require compost to be free from human and plant pathogens to be used as a plant nutrient source. Composting, being a self-heating process, is capable of inactivating pathogens during the thermophilic phase. Based on legal standards for compost sanitization set by various authorities, the eradication of plant pathogens requires a minimum temperature of 55 °C for 3–14 days depending on the composting method [209,210]. Although this can reduce the pathogen levels in the compost, it is not guaranteed and the extract may still have some pathogens. This risk may not be tenable with many producers and a sterilization step may be required. However, it should be noted that several of the mineralization processes (e.g., ozonation, electrochemical oxidation) can achieve this goal [211–213].

4.3.1. Treatment of Nutrient Extracts

Nutrient extracts should be treated to reduce pathogen levels, organic compounds, and its phytotoxicity. Several techniques such as activated carbon adsorption, electrodegradation, advanced oxidation processes, ion exchange and ozonation have been investigated to effectively remove organic materials in hydroponic nutrient solutions [214]. Such systems can be used to treat compost leachate and reduce the phytotoxicity caused, due to organic compounds.

Ozonation is a potential method for compost extract treatment. Ozone treatment has been successfully used for irrigation water treatment [215], nutrient solution treatment [216,217], and sludge treatment for hydroponics [198] without detrimental effects on the crops. Ozone is capable of destroying pathogens [211], while degrading and often mineralizing organic materials [218].

Recent studies on electrochemical oxidation techniques have also been shown to inactivate pathogens while mineralizing organic matter in the hydroponic nutrient solution [212,213]. Although a wide variety of pathogen control techniques are available [219], the prospect of simultaneously managing pathogens and mineralizing organic matter makes ozonation and electrochemical oxidation technologies very appealing in the context of the current discussion. Further testing of these treatment methods, specifically for compost extracts treatment, should be carried out in order to successfully utilize compost as a nutrient source in hydroponic systems.

4.4. Alternate Use of Compost

Apart from using compost as a source for hydroponic nutrients, compost can also be used as a growth medium in soilless cultivation [220]. Compost can be used either entirely or as a partial substitute for peat as a growth medium [221–223]. The proportion of peat replacement will depend on the chemical properties and available nutrient levels of the compost. The effect of compost substitution varies with compost quantity, crop species, and compost feedstock material [186]. Using compost as growth medium can reduce the use of peat, a non-renewable resource, and the GHG emissions associated with peat mining and supply [224,225]. Compost can also be sold as a finished product to other urban community farms, garden centers, etc., thereby providing an extra source of income to the producers. Compost can be used within the urban or peri-urban areas as a soil amendment, substituting synthetic fertilizers. Even leached compost (compost with nutrients extracted) can be further used as a biofilter medium, germination substrate or soil amendment. The post-leached compost still contains substantial carbon in the form of highly stable humic substances [102]. Application of leached compost to soil will act as a carbon pool, contributing towards carbon sequestration.

5. Future Research

Recovering resources from crop residue and urban biowaste through composting has immense potential as a means of generating input for crop production and managing waste. Successful implementation of this technique has many challenges that need to be overcome. This requires further research and the major research areas are given below.

- Composting is a dynamic process and the optimum composting parameters are dependent on multiple factors (feedstock properties, composting methods, process control methods). Characterizing physical, chemical, and biodegradation properties of different crop residues from CEA systems is critical in determining degradation rates, optimum environmental parameters for composting, and maximizing CO_2 recovery. This also includes evaluating different urban biowastes as amendments for effective composting of crop residue.
- Despite process control measures, composting can still produce small amounts of not-target gases that should be stripped off in order to use the compost exhaust for CO_2 enrichment. Developing environmentally friendly treatment methods including biofiltration must be a priority.
- Developing effective and automatic enrichment control strategies in conjugation with capture, storage, and controlled release of CO_2. Making these technologies low cost, low energy demand, and low environmental impact are also equally important priorities.
- Evaluating the effects of compost-based CO_2 enrichment on crop growth in a completely controlled environment setup and comparing with conventional means of CO_2 enrichment in terms of the crop yields and nutritional quality. This extends to

detecting the presence of non-target gases (NH_3, CH_4, N_2O, VOCs and ethylene) in compost exhaust and evaluating their effect on crop growth.

- Investigating ozonation, electrochemical oxidation, and other oxidative techniques to achieve pathogen control in conjunction with organic matter mineralization in hydroponic systems. These techniques should be tested specifically on compost extracts to be used as hydroponic nutrient solution for their effectiveness to manage pathogens and organic matter without disrupting plant functions.
- The environmental impact of these techniques must be evaluated by carrying out life cycle analysis (LCA) studies. Comparing compost based closed-loop operation to existing conventional (fossil fuel-based) technologies and also alternate technologies (anaerobic digestion, combustion and gasification) can provide insights to make economically and environmentally sound choices.

6. Conclusions

Closing the resource loop by recovering and reusing CO_2 for enrichment and plant nutrients for hydroponics from crop residue and urban waste can help in reducing the overall carbon footprint and improving sustainability of urban CEA systems. Employing this technique also provides opportunities for diverting urban biowaste from landfill. Implementing optimal composting process control and management practices can maximize the resource recovery and efficiency of the process. Carbon dioxide from the compost as a source for CEA atmospheric enrichment can improve yield and efficiently cycle carbon within the system. It also reduces the fossil fuel usage and the associated net carbon addition to the environment by acting as an alternate source for CO_2 and nutrients. Further research is necessary to overcome technical, economical, and operational challenges. Other methods of recovering resources from waste biomass such as combustion, gasification, and anaerobic digestion should also be explored in isolation or as part of an integrated system to achieve similar goals. Achieving closed-loop farming systems is necessary in order to enhance sustainability and intensify food production amidst resource scarcity and other environmental challenges.

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