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Review

Current State of Greenhouse Waste Biomass Disposal Methods, with a Focus on Essex County Ontario

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Abstract: Managing organic waste produced from agricultural greenhouse production is becoming an increasing concern for growers and communities that contain significant greenhouse production. Currently, in North America, the waste vines, leaves and stems, and fruit grade-outs that are produced during in-season greenhouse production and post-harvest processes are most commonly sent to local landfills. With landfills rapidly filling and increasing pressures to improve the sustainability and circularity of greenhouse production, alternative waste management solutions are needed. This review examines greenhouse organic waste characteristics and composition, focusing on Essex County, Ontario, Canada, which has the highest density of greenhouse production in North America. Current worldwide research on greenhouse waste disposal methods is reviewed, including landfilling, land application, incineration and waste-to-energy, anaerobic digestion, char production, organic fertilizer production and composting, and insect digestion. Seasonal timing, waste composition, cost, space, and the state of research influence the feasibility of implementing these solutions on an industrial scale. This review also contains a case study of greenhouse organic waste characteristics and quantity, and the most suitable management strategies for Essex County (containing the Leamington and Kingsville areas) in southern Ontario, Canada, where this issue is becoming an increasing concern to the local community. Gaps in policy and data are highlighted, including barriers that may limit the adoption of the innovative solutions proposed.

Keywords: organic waste; biowaste; greenhouse; greenhouse agriculture; sustainability; waste management; circular economy; waste treatment innovations

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1. Introduction

Agricultural greenhouses have become essential to food production in today's world. Greenhouses rely on sunlight from the outdoors while using controls to dictate other elements of the growing atmosphere, such as irrigation and temperature. A large greenhouse industry brings many advantages and disadvantages to the local area. For example, increased food security and economic opportunities add value to the local community. On the other hand, labour shortages and environmental challenges, like water pollution and large volumes of waste, have been challenging for the sector [1–3].

The term "greenhouse waste" is a general term that could refer to packaging, wastewater, growing media, plant matter, or discarded fruits. More specifically, biowaste is defined as "waste (such as manure, sawdust, or food scraps) that is composed chiefly of organic matter" [4]. Under this definition, plant matter such as vines, discarded fruits, or organic growing media can be considered "biowaste". This review will focus on this greenhouse biowaste and look to explore potential utilization opportunities for greenhouse waste to reduce its environmental impact.

Cucumbers, tomatoes, and peppers are the most common greenhouse vegetables grown in Canada [5]. These crops are grown exclusively for fresh market sales [6]. Nationally, 94% of the fruit and vegetable greenhouse area was reported by farms with annual revenues of greater than CAD 2 million [7]. This demonstrates the significant size and scale of the Canadian vegetable greenhouse industry, as well as the businesses that support it. Specifically, Essex County, Ontario, Canada is home to the second-largest greenhouse cluster in the world, with over 1400 hectares (3500 acres) of greenhouse operations [8]. Within this county, Kingsville and Leamington are hubs of the growing industry, where the Leamington greenhouse industry has a farm gate value of CAD 1 billion [9]. As of 2022, approximately 65% and 75% of all Canadian tomato and cucumber greenhouse production, respectively, took place in the Leamington area [6].

The importance of quantifying the environmental impacts of greenhouses is well established, but greenhouse biowaste has often been overlooked in the past [3,10]. Researchers and industrial partners are beginning to investigate the issues of greenhouse biowaste management locally and globally [11–13].

2. Literature Review

Research surrounding greenhouse biowaste management is relatively recent, with the majority of work beginning around 2010 and starting even later in a local context. Some initial efforts focused on exploring the issues of greenhouse-related environmental concerns, specifically dealing with greenhouse biowaste [1,11,14] However, much of this research was on a small scale and several gaps have been identified. Overall, there is a lack of understanding of how to deal with biowaste and how the different options would impact the environment. Further, it is unclear how to scale-up or bring these solutions to the greenhouse industry within Essex County.

There is a lack of a comprehensive literature on greenhouse biowaste disposal options, particularly related to their environmental impact. Technical articles focusing on the feasibility of a particular solution often lack a connection to environment impacts [14,15]. Policy reviews typically focus on how existing policies have led to current practices and lack information on technical aspects and environmental data [3]. Articles focused on environmental impacts typically only consider one practice and explore its impacts in-depth, or do not specifically examine greenhouse biowaste, preventing easily comparable results due to unique methodologies [16,17]. Almost all available literature is focused on geographical locations other than Essex County [18,19]. A literature review outlining the potential options for greenhouse biowaste management will make future research easier and provide useful information to growers and policymakers. Connections will specifically be made to Essex County to fill this existing gap.

2.1. Waste

Each crop and growing system use a unique greenhouse configuration and a different growing cycle. For example, in Essex County, one tomato crop is typically grown annually. New vines are started in January, then harvesting begins in late March–early April and ends in November. Alternatively, artificial lighting allows production during winter, with vines started in September and harvesting completed the following July [6].

Throughout the growing season, some crops such as tomatoes require pruning. This is known in the industry as “de-leafing”. Leaves are selectively pruned and dropped to the floor. In some greenhouses, these leaves are collected for on-site waste management. However, due to labour and land limitations, most often leaves are left on the floor until the crop is removed from the greenhouse. At the end of a growing season, the greenhouse is cleaned out and sanitized. This so-called "clean out" waste removed from the greenhouse is a mixture of vines and plant matter, growing media, strings, and plastics [6].

Most Ontario greenhouse vegetable crops are grown hydroponically in soil-less media. Certified organic growers, who are not permitted to use hydroponic methods, use organic growing media made of materials such as coconut fibers, while conventional growers commonly use rockwool [3,6]. Rockwool is a mineral-based product spun into wool that is normally used contained in plastic bags known as grow bags (Figure 1) [20]. Growing media is usually set on raised troughs [6].

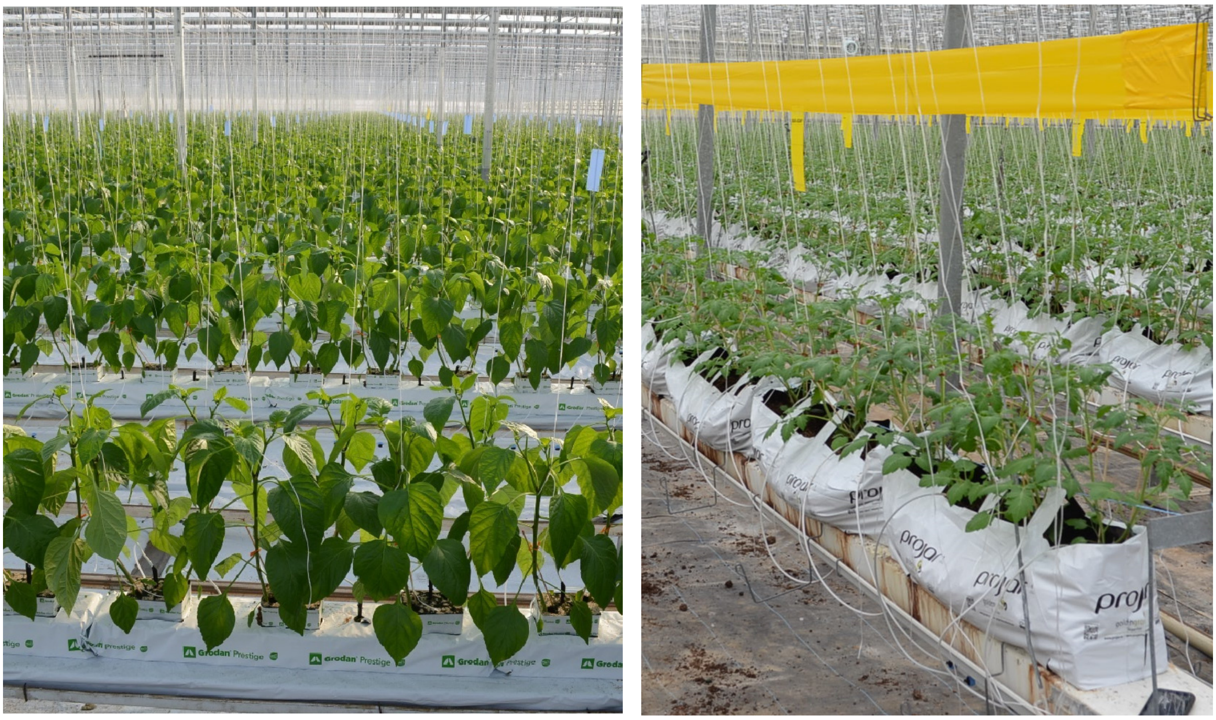
(**a**) (**b**)

Figure 1. (**a**) Young conventional hydroponic pepper plants in rock wool growing media; (**b**) young organic tomato plants in grow bags.

In summary, greenhouse biomass waste consists of several different types of waste that must be considered: fruits, plant vines, plant material such as from de-leafing, and the roots and growing media, if it is organic. In-season biomass waste may consist of non-sellable fruits and cuttings such as stems and leaves. Post-harvest biomass waste may include non-sellable fruits, all types of plant material, and roots [21]. Fruits and plant vines, stems, and leaves will be the focus of this literature review.

2.1.1. Waste Stream Characterization

Understanding the characteristics of waste is essential to determining the most sustainable methods of disposal and associated environmental impacts.

Plastics

A major current concern with the disposal of greenhouse biowaste is that it usually also includes plastic strings and clips used to connect growing plants to the strings (Figure 2) [6,22]. As these components are typically removed from the greenhouse at the same time as the plants, they are often mixed with the biowaste. Because they are typically made from polypropylene-based materials, they do not break down the same way biowaste does, creating challenges in identifying mechanical or biological processes that are suited to deal with this resulting mixed plastic and organic waste [6,23].

Figure 2. Typical polypropylene plastic string and clip system found in greenhouses.

Attempts have been made to use strings made of hemp fibers, recycled cotton yarns, and other natural materials in clips and strings, but these have largely been unsuccessful in practice due to frequent breakage because of heavy loads and early degradation in the greenhouse environment [24,25]. Compostable and biodegradable clips also exist on the market but are not widely used due to their high cost [6]. Significant efforts are being put into testing and demonstrating the efficacy of these products in crops where strings bear heavy loads in both Canada and the Netherlands, with several natural materials reportedly being successful in tomato crops [24,26].

Grow bags are also a source of contamination in post-harvest waste. Reusing bags is practiced in the Mediterranean regions successfully for 3–5-year cycles [27]. However, since this practice may be a source of pathogen spread, Canadian growers generally do not reuse grow bags due to biosecurity concerns. Grow bags may also be made of organic materials like coconut fibre [28].

Growing Media

Significant work is being put into finding and encouraging the adoption of organic growing media. Although conventional growing media is typically a source of contamination for organic waste, options based on coconut coir, wood chips, miscanthus, etc. are now on the market [29]. Growing media is typically landfilled in Canada, along with the rest of greenhouse waste [6].

Efforts are also being put into the reuse or recycling of rockwool through a static aerated composting process. However, plastic contamination and the successful removal of diseases and pathogens remain a challenge with these methods [20].

Contamination and Separation

Methods to separate organic and non-organic waste do exist and can be found in large industrial composting or recycling plants, but these are typically very costly and limited to city-wide scale applications [3,30]. There is significant potential for mechanical methods specific to the separation of greenhouse waste, but they remain expensive and require further optimization [31]. Self-management of all greenhouse waste streams, including manual labour and on-site solutions, was deemed to be the most cost-effective solution for greenhouses using soil in Spain. It was estimated that farmers would save approximately 615 EUR/ha in the 2017–2018 growing season by self-managing their waste rather than outsourcing this task, reduce fertilization costs by 40% and irrigation costs by 2%, and reduce transportation costs to waste disposal facilities by over 990 EUR/ha [3]. However, these are not common practices in Canada due to high labour costs [1,6]. No economic modelling has been published on the potential for self-management of greenhouse waste in Canada.

In advanced compost production systems, there is some tolerance for plastic contamination, but limitations are put on size and plastic properties to prevent sharp objects from ending up in the resulting compost [31]. As scientific concerns about microplastics increase, public perception is also shifting towards less acceptability of plastic contamination [32]. For example, organisations like the United States Department of Agriculture do not permit the use of biodegradable mulch films in organic farming [33]. In Canada, biodegradable mulches are permitted, but with limitations on the specific processes used and how micronutrients are handled [34]. As such, plastic contamination should be noted as a major issue in greenhouse waste disposal, even with technological advances and new biowaste disposal methods [24].

2.1.2. Waste Chemical Characteristics

The chemical composition of greenhouse waste may vary significantly from crop to crop and impact which disposal methods would be more appropriate. Since vegetable greenhouse waste is the focus of this study, Table 1 summarizes the characteristics of waste from typical greenhouse tomato, pepper, and cucumber crops as found in the literature.

Table 1. Greenhouse Biowaste Chemical Characteristics.

Parameter	**Units (Unless Otherwise Indicated)**	**Tomato**				**Pepper**		**Cucumber**	
		Tomato Leaf Composition	**Tomato Fruit Residue**	**Tomato Plant Residue**		**Pepper Plant Residue**		**Mini Cucumber Leaf Composition**	**Cucumber Plant Residue**
Reference		c	d	e	f	f	g	h	f
Carbon	% [a]	1.2–1.7 g C per tomato leaf	36	38	39.9	42.96	34.02		37.40
Nitrogen	% [a]	2.0–4.9	4.1	2.4–4.2	1.92	2.02	3.15	5.7	3.31
Potassium	g/kg [a]	2.7–5.9%	4.6	4.9–5.0				3.0%	
Phosphorus	g/kg [a]	0.3–0.6%	5.3	5.1–5.7				0.58%	
Calcium	% [a]	2.4–7.3						1.69	
Magnesium	% [a]	0.4–0.8						0.5	
Sulphur	% [a]				1.10	0.31	0.02		0.52
Total Solids	% [b]		12.5	11.9–12.3					
Volatile Solids	% [a]		10.2 [b]	10.9–11.4 [b]	63.21	65.05	56.66		61.70
pH			4.6					5.2	
Cellulose	% [b]		5.1						
Hemicellulose	% [b]		12.2						
Lignin	% [b]		9.7						
Moisture Content	% [b]		87.5		80.77	63.93	7.43 [a]		84.22
Ash content	% [a]				17.47	13.45	23.97 [a]		27.65
Minor Elements	mg/kg [a]	B: 32–97 ppm Cu: 8–16 ppm Fe: 98–391 ppm Mn: 55–220 ppm Mo: 1–10 ppm Zn: 20–85 ppm			Cd: 0.13 Cr: 10.07 Cu: 49.98 Ni: 1.08 Pb: 1.41 Zn: 23.74	Cd: 0.08 Cr: 0.07 Cu: 4.04 Ni: 0.05 Pb: 0.06 Zn: 14.97		B: 43.3 Cu: 14.45 Fe: 177.6 Mn: 73.4 Zn: 52.5	Cd: 0.02 Cr: 0 Cu: 4.48 Ni: 0.22 Pb: 0 Zn: 22.02

[a] On dry weight basis; [b] on wet weight basis; [c] [12]; [d] [35]; [e] [36]; [f] [37]; [g] [38]; [h] [39].

Depending on the ultimate goal of the waste valorization process, it may be desirable to recover minerals from the organic material. Work conducted in the Netherlands suggests that with further research and overcoming barriers related to plastic contamination, there is potential to recover minerals from non-fruit biomass, particularly Mg, Ca, and S [21].

2.1.3. Waste Characteristics in Essex County

Sustainably managing the large and increasing volume of greenhouse biowaste in Essex County is becoming increasingly challenging for the community. Quantifying this biowaste is essential to understanding the magnitude of the issue. The quantity of each type of biomass is heavily dependent on the crop, variety, production methods, and vtop stage. Since this review focuses on the quantification of greenhouse biowaste produced in Essex County, Ontario and the main greenhouse crops produced in this area are tomatoes and cucumbers, these will be the focus of this review. Other notable greenhouse crops that would contribute significantly to waste streams would be peppers, cannabis, and strawberries [6].

Greenhouse tomato and cucumber production in the Leamington area alone produced roughly 60 million pounds (27,215 tonnes) of tomato vines (including plastic contamination and rockwool) and 42 million pounds (19,050 tonnes) of cucumber vines (including plastic contamination, but not rockwool), based on 2022 estimates [6].

Another major source of organic waste is whole-fruit grade-outs. Produce is graded according to defects in visual appearance, ripeness, shape, and cosmetics. Nearly all fruit that is graded as “No. 2” is discarded, although much of this fruit is likely completely edible, as there is little market for it. As a result, 15 million pounds (6800 tonnes) of whole tomato grade-outs and 11 million pounds (4990 tonnes) of whole cucumber grade-outs were estimated in the Leamington area in 2022 [6]. Other experts estimate up to 100,000 tonnes of biowaste is produced annually in this area, with 40,000–50,000 tonnes in-season and 50,000 tonnes at the end-of-season [40]. Recent data suggest that in 2023, 133,796 tonnes were sent to the Essex County landfill, which decreased to 97,312 tonnes in 2024 [41]. As these numbers do not include amounts of waste that were land applied, composted, shipped to other landfills, or disposed through other means, the total amount of organic waste generated from greenhouses in this area still remains highly uncertain.

A study completed by van Tuyll et al. in the Netherlands aimed to quantify material flows in a high-tech hydroponic greenhouse producing tomatoes using calculations and data from the literature [21]. Data from this study may be used as another way to estimate total biowaste volumes from the Essex County area. It was concluded that between 140 g and 170 g of plant waste would be produced per kg of fresh product yield during the in-season period. The average waste production from four studies was 160 g of plant waste per every kg of fresh yield [21]. Using this waste generation rate, combined with Ontario production values and the fact that Essex County produces 80% of Ontario greenhouse yields, it can be estimated that 83,360 tonnes of waste would be produced annually in Essex County [8,42]. Estimates of biowaste quantification can be found in Tables 2 and 3.

Table 2. Literature and stakeholder review of local greenhouse biowaste quantification.

Estimation	Year	Quantity (Tonnes)	Reference
Tomato vines (including plastic contamination and rockwool)	2022	27,215	[6]
Cucumber vines (including plastic contamination)	2022	19,050	[6]
Whole tomato grade-outs	2022	6800	[6]
Whole cucumber grade-outs	2022	4900	[6]
In-season waste	2024	40,000	[40]
In-season waste sent to Essex County landfill	2023	23,823	[41]
In-season waste sent to Essex County landfill	2024	23,175	[41]
End-of-season waste	2024	50,000	[40]
End-of-season waste sent to Essex County landfill	2023	110,973	[41]
End-of-season waste sent to Essex County landfill	2024	74,136	[41]
Calculation of in-season waste based on waste per yield	2022–2024	83,300	[8,21,42]

Table 3. Annual Waste Quantification calculated based on van Tuyll et al., 2022 [21].

Output	Quantity
Fruit biomass	73.4 kg/m^2
Stem and leaf production (after being removed from the greenhouses, post-harvest)	4.5 kg/m^2
Stem and leaf production (before being removed from the greenhouses, post-harvest)	11.3 kg/m^2

2.2. Disposal Methods

There are a variety of possible waste disposal methods ranging from new methods that are the subject of research to established industry practices. Several factors determine the most suitable solution for disposal, including quantity and characterization of the waste. Potential disposal methods are reviewed in the following sections.

2.2.1. Pretreatments

Depending on the disposal method, plant material may be treated before disposal to produce more ideal conditions for the disposal process. Pretreatment processes can be biological, physical, and/or chemical in nature. They are ultimately designed and used to improve the product quality or production efficiency of a process [43]. Pretreatments may be useful or necessary for anaerobic digestion (AD), char production, composting and organic fertilizer production, or other unique biomass transformation processes [14,19,44]. By combining various feedstocks and/or implementing additional pretreatment, improved carbon-to-nitrogen ratios, increased hydrolysis rates, or supplements of limiting essential nutrients can be achieved. This will ultimately allow improved performance in processes such as AD or hydrothermal carbonization [12,44].

Biological, physical, and chemical pretreatment methods have been tested to optimize biogas production from other lignocellulosic materials similar to greenhouse waste. Researchers concluded that pretreatment methods using irradiation, chemical oxidants, and electric means were not ready for use at an industrial scale due to high energy requirements, equipment impracticality, and cost in 2012 [43]. This was still the case in 2024 when pretreatment remained one of the most expensive steps in ethanol production from biomass [45]. Other physio-chemical pretreatment methods using ammonia, hot water, and steam explosion were reported to be successful in the literature but also required high energy consumption. Ultrasonic and microwave pretreatment were also reported to be unsuccessful [46]. Further work has shown promise in methods such as irradiation, but no known research has focused on greenhouse plant waste using these treatments [47]. The use of the chemical oxidant alkaline hydrogen peroxide (H_2O_2) has also shown promise for increasing biodegradability and methane generation potential. Experimental results showed pretreatments increasing methane generation potential from 174 mLCH_4/g of volatile solid (VS) to 250–350 mLCH_4/gVS [46].

Torrefaction is another highly promising treatment that has been specifically tested using greenhouse waste. One benefit of this method is that there is potential that the plastic and organic waste streams may not require separation. Optimal conditions were determined depending on the fraction of plastic in the waste [48].

2.2.2. Landfilling

Landfilling of greenhouse biowaste is a common practice in many areas around the world. This practice can occur for in-season or end-of-season waste and can include roots, vines, cuttings, and fruit. However, this practice strains local landfills particularly because seasonal greenhouse waste disposal can produce large volume influxes during short time periods [22,49]. Based on a bulk density of pepper waste of 0.3015 g/cm^3, every 1000 tonnes of greenhouse waste results in approximately 3320 m^3 of waste volume sent to the landfill before compaction [48].

Although organics can potentially readily degrade in landfills, they release significant amounts of methane under the anaerobic conditions of the landfill. Methane is a harmful greenhouse gas that significantly contributes to global warming, having 28 times greater global warming potential than carbon dioxide [50]. Organics also contribute significant waste volumes being sent to landfills, filling landfills at an undesirable rate. Decreasing the amount of waste sent to landfills extends the lifetime of landfills, prolonging the creation of new landfills [19]. Landfilling is also associated with additional concerns including undesirable odours and impacts on surrounding ecosystems including leaching. The overall current environmental impact of landfilling is significant, totalling nearly 400 kg CO_2 per tonne of organic waste [13,22,50].

A life cycle assessment of Mediterranean-region greenhouses found that when the landfilling of all waste was considered, 90% of the overall impact on climate change, 50% of the overall impact of eutrophication, and 40% of the impacts on the category of photochemical oxidant formation were associated with waste management. Although these numbers demonstrate the significance of waste management choices on environmental impacts, assumptions in these calculations included using soil-based growing and assumed the landfilling of plastics and metals, which are typically at least partially reused or recycled [51].

2.2.3. Land Application

The direct spread of biowaste on fields, also known as land application, is a practice where whole-fruit grade-outs or plant wastes are mulched, spread, and incorporated into the surrounding agricultural land. The practicality of this practice is heavily dependent on the geographical location, crop types, and pest and disease issues associated with the greenhouse industry in that location. In high-density greenhouse locations, diseases may spread more rapidly, or neighbours may be in close proximity and it would be more important to avoid putting biowaste on outdoor agricultural fields [49,52]. Although the greenhouse sector is currently far more impacted by diseases such as the tomato brown rugose fruit virus than the field crop sector, it is suspected this is from reduced human handling in field growing, rather than resistance to the virus as it is highly transmittable and impacts a broad range of varieties [53]. Currently, mulched cucumbers are one of the few greenhouse wastes that are commonly land-applied in North America due to a lower risk of disease spread than the land application of other greenhouse crop materials [13]. In other field-based horticultural systems, plant residues are typically left in situ and a combination of discing, plowing, and/or tilling practices may be used to bury crop residue, allowing it to decay [54].

However, there may be environmental benefits that should be researched further for a complete understanding of the impacts of land application. Scientifically, it is understood that the exact emissions resulting from land application will vary based on several factors. Specifically, for N_2O emissions, these factors include N mineralized from mineral and organic fertilizer N inputs, N in plant residues, and the fraction of N inputs leached as nitrates or volatilized as ammonia [55].

2.2.4. Incineration and Waste-to-Energy

Another disposal method for greenhouse waste is incineration, essentially burning the waste and collecting the usable thermal energy. Usable energy can also be in the form of biogas and the most common outputs are fuel, heat, or electricity. Gasification, pyrolysis, and other thermochemical processes that produce biogas are currently better suited to other biomass feedstocks, such as woody biomass, due to the high moisture content in greenhouse waste.

High moisture is the largest barrier to the waste-to-energy use of greenhouse biowaste. High moisture content reduces the waste caloric value, further reducing the efficiency of the biofuel production and gasification processes. To combat this, pretreatments such as torrefaction may be used. The ash and nitrogen content of waste material are additional barriers to energy production [37]. Pretreating the waste by washing it may decrease ash content and improve its characteristics for use as a fuel [39]. Chlorine may also be an issue depending on the irrigation system and methods used. The carbon content of greenhouse waste is within the typical range of feedstock known to be usable for biofuel production [37].

Greenhouse waste can be used as an alternative fuel for other industries. For example, researchers in Spain proposed greenhouse waste as an alternate power source to supply a cement plant. This study used washing and drying pretreatments and estimated that replacement of 51% of the thermal energy from pet coke in the kiln would produce reductions of up to 0.16 tons of CO_2 per ton of clinker produced [56].

Some greenhouses are heated with biomass boilers. However, the chemical properties of greenhouse biowaste typically result in a low heating efficiency. The most economical biomass options include willow wood chips, miscanthus grass, and waste wood. However, the economics of using greenhouse biowaste have not proven favourable [57].

Some researchers have also considered processing greenhouse tomato, pepper, and eggplant biowaste into briquettes. These briquettes could then be burned to produce energy for the greenhouse. A prototype of a mobile briquette-producing machine successfully produced high-quality bio-briquettes, demonstrating that greenhouse waste was an ideal feedstock for this purpose. These bio-briquettes may be used for heating, including greenhouse heating, and in combination with other energy sources such as coal. Little to no research has been put into determining the potential environmental benefits of the bio-briquettes. Although significant reduction in environmental impacts may be achieved in Canada, the potential is even greater in Turkey, where the research was conducted, because of the common practice of burning greenhouse biowaste [19].

Gasification and pyrolysis are also associated with various emission-producing processes and would contribute to the ultimate environmental impact of biowaste disposal methods [3,12]. The net benefits of this process would be case-specific but should continue to be explored.

In 2016, a Korean study modelled several scenarios using thermal effluent from a power plant and waste incineration heat and concluded that for a 10 ha greenhouse, the payback period would be between 0.3 and 46 years depending on the distance between the facilities and the heating requirements of the greenhouse. Using waste heat from an incineration plant was found to be economically feasible for greenhouse heating [58].

The value of using waste-to-energy approaches may differ significantly depending on the method and location. For example, on European markets, research on hydrothermal upgrading has proven to be a potential end use worth approximately EUR 0.5–10/kg. Comparatively, biomass in this area can be used in incinerators to produce heat where there is a much lower market value of EUR 0.01–1/kg [59].

2.2.5. Anaerobic Digestion

Anaerobic digestion (AD) is the process by which microbial communities break down organic matter in an environment without oxygen using a series of four processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This results in biogas, containing mainly methane and carbon dioxide, and digestate, in liquid and/or solid forms [60]. A sealed environment prevents the methane and other gases from entering the atmosphere. The resulting products can then be used as a renewable energy source, renewable gas, or biofuel and organic fertilizer that can be applied to agricultural fields. This technology is being increasingly implemented worldwide to treat manure, farm waste, sludges, agricultural residues, wastewater, and industrial and municipal organic and solid wastes in a way that generates less emissions than would otherwise result from the decomposition of the materials [61].

Implementing AD can divert waste from landfills or other harmful disposal methods to reduce greenhouse gas emissions and potentially produce carbon neutral or negative outputs [62]. Other potential environmental benefits of AD include reduced odour, reduced water pollution from nutrients, and the potential to remove or reduce pathogens [44].

Biogas production from AD also adds an increased potential for sustainable energy production. This biogas may be used with gasification or power-to-gas processes to produce heat, electricity, renewable natural gas to supply the gas grid, or biofuel for vehicles. Replacing carbon-intensive fossil-based products with sustainably produced AD ones is an added environmental benefit of using AD to process waste. Typically, a major barrier preventing even lower carbon intensities associated with AD for food waste treatment is the need to transport food waste from each waste producer to the AD site. This may require more transportation overall (with associated environmental impacts) than the large volumes of manure that are collected on farms [62]. As Essex County greenhouses are densely located and individually produce large volumes of waste, it is expected that an AD in this community could have significant potential to reduce greenhouse gas emissions [63].

AD may be designed to operate as wet or dry digesters. Wet AD can accept feedstocks with up to 16% dry matter and dry AD can handle wet wastes of between 22% and 40% dry matter. With moisture contents typically above 80% in greenhouse biowaste, wet AD may be a suitable option for waste disposal, or greenhouse waste may be mixed with other feedstocks to reach an optimal moisture content. Optimization of the reactor can be performed to account for the expected moisture content of feedstock materials. Wet AD require that the feedstock has gone through a slurrying or pulping process before it enters the digester [44].

AD for greenhouse biowaste could include whole fruit grade-outs or leafy biomass. Both of these components have the potential to generate methane. This ability ranges depending on the exact characterization [12]. This is a viable option for sustainable greenhouse biowaste management at an industry scale.

Currently, one anaerobic digester processing greenhouse waste operates in Leamington, Ontario. At this plant, portions of greenhouse organic waste are combined with other commercial, municipal, and agricultural feedstocks [64]. This facility has capacity and an environmental permit to take up to 110,000 metric tonnes of organic waste [65]. However, additional research is needed to explore the opportunity of AD to solely process greenhouse biowaste and the associated environmental impacts [13,40]. Difficulty obtaining a consistent supply of greenhouse waste from the industry has prevented further research at the University of Windsor [40]. Another noted research gap was in the availability of reliable sensors and control equipment to monitor digestors in situ [44].

Optimization of the digester to accommodate greenhouse biowaste depends heavily on the anticipated inputs and conditions and will determine the overall environmental impact. This can relate to the feedstock used, temperature, pressure, pH, buffering capacity, and/or fatty acid concentrations. The impact of variation in feedstock properties has been a main focus of AD research [12,44]. In a review of methane yields from different feedstocks, it was found that food waste was able to generate comparable or higher amounts of methane than manure [44]. However, in research when only food waste was digested, significant amounts of dry matter and organic carbon were found within the digestate. This suggested that the performance could be further optimized [12]. Dr. Seth has conducted preliminary unpublished work on the biomethane potential from various greenhouse feedstocks [40], although there has been little AD research focused on greenhouse waste.

The chemical composition of greenhouse waste impacts the composition of the biogas. For example, a sulfur content between 1.0% and 3.2% in tomato leaves resulted in biogas with H_2S present at 0.08–2.2%. This is a corrosive contaminant and microbial inhibitor that may be mitigated with the use of a multi-stage digester to separate the differing ideal conditions of hydrolysis/acidification and acetogenesis/methanogenesis processes [44].

Separating the acidification process from methanogenesis has been shown to increase stability and biogas production and improve the effluent quality [44]. For example, the potential for cucumbers to be used in AD has been explored by Lowe et al. (2019), where ground cucumber waste was added to sewage sludge at 8% of the volume. Using a two-stage continuously stirred tank reactor (CSTR) for cucumber digestion resulted in increased specific gas production (64%) compared to one-stage co-digestion of cucumber waste and digestion in CSTRs without cucumbers [13].

An additional economic and environmental advantage of AD is that the digestate by-product can replace synthetic fertilizers on agricultural lands [6]. When compared to scenarios utilizing digestate as an additional fertilizer or using no digestate or synthetic fertilizer, the results showed higher yields when the digestate was used as a base fertilizer on agricultural land. This also has the potential to provide economic advantages to growers if they can sell or reuse digestate from an AD. Replacing synthetic fertilizers would give the potential to significantly reduce the environmental impact associated with producing the current commonly applied synthetic fertilizers [66].

Zhang, Bi, and Clift conducted an experiment on the environmental impacts of AD of dairy manure and using the AD outputs to heat a greenhouse [17]. The results from this system showed that overall, AD has significant potential to reduce eutrophication, respiratory effects caused by inorganic emissions, non-renewable energy consumption, climate change, and acidification by 65–90% [17]. Although only dairy manure was used in the study, the results suggested that the use of greenhouse waste in the AD would have improved these results further by supplementing additional limiting nutrients and improving the efficiency of biogas production in the digester [12,17]. It was shown that anaerobic digestion of organic waste resulted in -36 to -2 kg CO_2e per tonne of organic waste [50] although this would be highly dependent on the specific system inputs and outputs.

Using AD of greenhouse biowaste to entirely heat an average hectare of Canadian greenhouse would require an average of 77 to 193 tons of fresh biomass per week. Using greenhouse tomato leaf waste from one greenhouse alone would not meet this energy demand. Pretreatment of greenhouse waste biomass or mixed feedstocks are proposed to improve the bioreactor outputs [12]. Overall, more research is required to understand the implications of using AD for processing greenhouse biowaste and the environmental impacts that would be associated with this process.

2.2.6. Char Production

Greenhouse biowaste can be processed into biochar or hydrochar. Biochar is typically produced through the process of pyrolysis and hydrochar is produced through hydrothermal carbonization (HTC). In these processes, the biomass undergoes the relevant treatment, and a char is produced [67]. This product could then be used as a source of energy, soil amendment, or wastewater treatment medium [14].

The optimal conditions for pyrolysis and HTC are different. Pyrolysis uses anaerobic conditions and heat. HTC, also known as wet torrefaction, pretreats the biomass to increase its energy density [14]. As HTC is more ideal for feedstocks with a higher moisture content, it is likely that this method is better suited to char production from greenhouse biowaste [68,69]. In cases of wet feedstock being used in pyrolysis, additional pre-drying is required, increasing the cost requirements of the process. Additionally, the anaerobic conditions in the pyrolysis kiln may produce heat at such a high rate that self-ignition could occur, potentially causing safety concerns and decreasing the reliability of the process [69].

Tomato greenhouse waste from Essex County was used in a study determining the potential impacts of hydrochar in various applications. Hydrochar processing was found to be able to remove 6–30% of nutrients from wastewater. In this study, the wastewater used was greenhouse nutrient feedwater. If this process was implemented in the industry, it could significantly increase the environmental circularity of greenhouse production [14]. This solution may also be able to reduce eutrophication, but it is unknown to what extent this would have an impact on parameters within a life cycle assessment.

Additional benefits of both hydrochar and biochar continue to be uncovered. Hydrochar has been associated with resistance against disease and immobilization of heavy metals in contaminated sites [14]. Biochar has been known to be algae-suppressing, to deter pests which may also reduce disease spread, and to reduce the toxic effects of herbicides [70].

The environmental impact of char will depend heavily on the production methods and use of the char. HTC is an environmentally sustainable technique [71]. Although both methods are known to be relatively efficient at producing char, less energy is needed to produce char through HTC than through pyrolysis. Pyrolysis is known to release harmful oils and gases such as CO, CH_4, and PAHs into the atmosphere. These can be controlled through complex mechanical processes, but this significantly increases the cost of the method. HTC has been successful at producing processing water and hydrochar as products, without requiring any pre-drying processes. The harmful gas production associated with pyrolysis does not exist in the HTC process [69]. The environmental impact of chars produced from greenhouse wastes has not been assessed using life cycle assessment methods.

Hydrochar from greenhouse waste may also be well suited as a source of energy due to its high heating value of 25.9 MJ/kg, which is relatively high compared to char produced from other wastes. This ranks hydrochar from greenhouse tomato plant waste comparably to hay, and above poplar, for energy and heating uses [14].

Although there are many benefits of HTC, this technology remains challenging to scale. Cost is a main prohibitive factor [72]. There are several avenues that have the potential to result in profit opportunities, but further research is needed to scale and implement these solutions in cost-effective ways [14,72].

Studies have shown that when using chars as a soil amendment, there may be significant variation in the carbon sequestration potential and effect on greenhouse gas emissions from the soil. A hydrochar addition (1% w/w) increased the CO_2 and CH_4 emissions from all types of soil that it was tested in. It was also able to reduce N_2O emissions in some cases. The biochar addition (1% w/w) had no impact on the CO_2 and CH_4 emissions, except for one scenario where CO_2 emissions from the soil decreased. The biochar was able to contribute to intermediate N_2O emission reductions [71]. Similar results have come from related research. The rapid decomposition and inconsistency of hydrochar in soil prevents the long-lasting benefits that can be obtained from biochar [14,69].

More research is needed to optimize hydrochar for soil amendments before this is implemented at a larger scale. Currently, the benefits of pyrolysis and biochar may exceed those of HTC and hydrochar, but the promising outcomes of hydrochar should continue to be explored, especially in the context of agricultural use and for the use of carbon sequestration or nutrient addition to the soil [69].

2.2.7. Organic Fertilizer Production and Composting

Spurred by policy changes, practices of composting and turning greenhouse plant waste into organic fertilizer are also slowly increasing in popularity around the world, particularly for organic greenhouse farming. Composting allows organic matter to decompose in a moderately controlled environment. It may be aerated or left to passively decompose. The result is a compost that could be used as a growing media or spread on other agricultural land [73]. Green or organic fertilizer is understood to be land applied to other agricultural areas. Both composting and fertilizer production may be economically advantageous to a greenhouse grower [22].

Composted material can be considered an organic fertilizer. It has been suggested that composted plant material may be able to be fully substituted for organic fertilizer [22]. Traditionally, compost is used to improve soil health, whereas fertilizers typically aim to directly impact plant health [73]. Both have proven benefits to crops [3,73].

Composting can be feasibly implemented over a range of scales and would have been possible in 85% of commercial greenhouses studied within soil greenhouses in Spain [3]. This study concluded that in two regions of organic production in greenhouses, self-management of waste was practiced by 15–22% of the studied farms. In Campo de Dalias, composting was overwhelmingly popular in greenhouses that practiced self-management of waste; 98% of these greenhouses composted. Alternately, in Campo de Nijar and Bajo Andarax, composting was used by 6% of farms, vermicomposting was used by 5% of farms, and green fertilizer was produced by 1% of the farms practicing self-management of waste [3].

Vermicomposting biowaste from tomato crops has also been studied. Difficulties were found due to the existence of undesirable salinity values [74]. However, these challenges can be overcome by mixing plant residues with other feedstocks such as paper-mill sludge [75]. With the incorporation of other feedstocks, this practice has been successfully used in the European greenhouse industry, particularly in Spain [3].

Plastic contamination remains an issue in composting, where mechanical or biological issues may occur when non-biodegradable strings and clips are included in the composted material. Advanced industrial composters capable of removing plastic strings and clips do exist, but are not located in Essex County [76].

There is a significant difference in emissions between landfilling and composting. This has been demonstrated in studies of municipal solid waste practices. Although composting is known to release emissions, it may produce as little as 5% of the emissions produced by landfilling the same waste [77]. Additionally, life cycle assessments have been performed on the composting and land application of garden waste to compare the associated environmental impacts [78]. Garden waste, particularly in scenarios where woody waste was excluded, may have many similar properties to greenhouse waste. The impacts of composting this waste were mainly associated with the depletion of abiotic resources, marine and terrestrial eutrophication, and acidification. The results indicated that although greenhouse gas emissions would be produced by the composting process, particularly from the energy required to complete it, scenarios implementing the land application of composted material were able to reduce the environmental impacts of the overall process even further [78]. When compared to landfilling and AD, composting had the lowest GHG emissions at -41 kg CO_2e per tonne of organic waste [50]. Additionally, composting resulted in reduced water quality impacts, such as eutrophication and acidification, by approximately 50% relative to AD [79].

Although there are few studies focused on composting biowaste from greenhouses, one life cycle assessment of greenhouse biowaste compared landfilling and composting practices in a hydroponic greenhouse where the compost was reused as an organic amendment. The results found that the environmental burden associated with composting the biowaste was less than the burden of landfilling biowaste [51].

2.2.8. Insect Digestion

The use of insects, such as soldier flies, crickets, or mealworms, to process greenhouse waste into usable co-products, is also being increasingly explored in research and as private business cases [80,81]. Research has specifically been conducted with mealworms consuming mashed and whole leafy waste from a high-wire cucumber crop and tomato fruit waste. This was tested both in the greenhouse in chambers located under the growing troughs and in a controlled environment, as is currently the standard for insect production. The results showed that all feedstocks tested were suitable for mealworm consumption. Tomatoes outperformed standard feedstocks and leaf mashes were comparable to harvest using agar. Mealworm harvest in the controlled environment was less variable than in a greenhouse, but did not significantly impact mealworm yields overall [80].

Insect digestion of waste as an alternative biowaste processing method shows significant potential, but it is challenging to determine how this technique could be used at an increased scale and how to optimize industry-scale farming of these insects. Due to the limited flexibility of insect feed intake and typical variability in available biowaste feedstock, more research is needed to optimize this method. Temperature, moisture, housing, and timing are variables that will require significantly more research [81]. With approximately 70–80 days required for mealworm growth, timing of insect life cycles must be coordinated with the crop to optimize processing efficiency and outputs [80].

An additional benefit of using insect digestion to process greenhouse waste is that as the insects consume the plant waste, the resulting frass can be utilized as a fertilizer. There is potential to harvest and utilize this fertilizer for indoor or outdoor vegetable production, creating additional value [82].

The insects themselves may be able to be used as an alternate protein source and value add, as is already the case with insect use in pet foods [81]. It is unknown whether a local third-party insect farm would be best suited to meet greenhouse waste processing demands or if individual farms would be able to deploy this technology on their own [31].

2.2.9. Other Relevant Valorization Processes

Growing Media

Research into reusable or biodegradable growing media is also becoming increasingly popular. In some cases, organic waste from greenhouses can be collected and upcycled into growing media for continued use [11]. Research has shown that this alternative growing media can even closely resemble the properties of traditional growing mediums [15]. Producing more organic media will also reduce the separation required to dispose of biowaste and inorganic waste separately. Research on rockwool, which is typically landfilled due to its inorganic nature, suggests it may be possible to clean and reuse this material. However, there are disease contamination concerns with this process [20].

Bio-Polyurethane (BPU) Foams

Researchers in London, Canada were able to demonstrate that greenhouse biowastes were able to be turned into bio-polyurethane (BPU) foams using specialized catalysis, after the use of hydrothermal pretreatment and blending with corn stalk residues. These foams are used as biodegradable material for packing, insulation, cushion, and bedding. At this pilot scale, the greenhouse waste produced a more biodegradable BPU foam than typical organic materials used in the process [15].

Furniture and Building Materials

ECOR BV, a global company that produces building materials from agricultural waste, is using pepper leaves in panel production. These panels can then be used for building furniture such as tables [83].

Protein Extraction and Nutrition

Extraction of proteins, sugars, and other minerals from greenhouse waste may be used to produce a variety of products including animal feed, cardboard, and protein or juice mixes. Depending on the quality and output, profits from this type of disposal can range from EUR 0.5–10/kg of biowaste [59].

Whole Fruit

Entrepreneurs are also finding ways to utilize discarded whole fruits that are still edible that may avoid landfilling and be profitable. One small company freeze-dries produce to increase its shelf life [11]. Another Essex County organization dehydrates whole vegetables to create dehydrated vegetable mixes that are sold or donated [84].

2.3. Industry Practices

Around the world, landfilling, incineration, and spreading waste are common ways currently used to dispose of greenhouse biowaste. Proposed solutions that could reduce emissions associated with this disposal process include AD and biogas production, char, and composting [6]. The value-added products from these processes present both economic and environmental advantages to growers and the extended community [11].

2.3.1. Essex County and North American Practices

Historically, in Essex County, the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA), now known as Ontario Ministry of Agriculture, Food, and Agri-Business (OMAFA), has recommended spreading chopped biowaste on agricultural fields to provide nutrients. This led to contamination and pest- and disease-control issues. Currently, after a greenhouse crop is taken out, most greenhouse biowaste is shredded and then trucked to the local landfill, Essex-Windsor Regional Landfill (EWRL) [2]. However, this landfill is rapidly filling as the greenhouse industry is growing and producing more and more waste in Essex County. Recently, OMAFA has expressed new concerns about the amount of biowaste entering the landfill.

Greenhouses are responsible for arranging transportation to the landfill and paying the tipping fees to dispose of biowaste in the EWRL. The waste is inspected to see if it meets the local criteria of being a load of vines and/or growing media with less than 20% contamination. If so, the fee at time of writing is CAD 45 per tonne from January to August and CAD 66 per tonne from September to December. If the load is contaminated by plastics, fruits, vegetables, irrigation lines, etc., a rate of CAD 66 per tonne is applied. The landfill does not accept any odiferous plant material, such as that from cannabis production [85]. The landfill reports a strain on resources and significant influxes of material coming at the end of the growing seasons, with a peak in August and a larger peak in November. This timing aligns with the end of greenhouse crop-growing cycles [49].

Land application was practiced historically in Leamington with all types of greenhouse biowaste but resulted in concerns about pest and disease transfer [6]. This practice continues to occur to some extent within Essex County and other countries, such as the United States [6,13].

Seth estimated that the biowaste supply break down in Essex County was approximately as follows: two thirds of in-season biowaste are sent to landfills while one third is land-applied. Approximately 90% of end-of-season biowaste is sent to landfills [40]. A 2023 survey of Ontario fruit and vegetable growers included data from greenhouse growers covering 37% of Ontario greenhouse acreage and 19 greenhouse respondents, with most greenhouse growers being from the Essex County area. Table 4 shows the reported greenhouse waste management practices by greenhouse growers [52]:

Table 4. Ontario greenhouse biowaste practice participation [52].

Practice	Percentage of Growers That Use This Practice
Landfilling of green waste (leaf, vine)	69%
Spreading organic waste on field of outdoor farm	47%
Landfilling crop grade-outs	42%
Managed composting system (incl. turning for aeration, blending with other organic material)	21%
Rockwool repurposing	16%
Conversion of organic waste into value added products (e.g., vinegar, growing media)	11%
Unmanaged organic decomposition (material is left to decompose outside, no active management)	11%
Biodigester	5%

As the EWRL is rapidly filling and greenhouse biowaste production has increaseed in recent years, landfill tipping costs have increased. Some stakeholders believe that within a few years, the option to landfill waste will no longer be available to greenhouse growers. This could occur through significant price increases or through specific material restrictions at the landfill [24,31,40]. As the majority of farms in Essex County rely on landfilling for at least some portion of disposal, this would impact nearly the entire local greenhouse industry. Regulations or other factors restricting landfill disposal of greenhouse waste would impact farms differently depending on their size. Small farms (<24 hectares or 60 acres) are currently the ones more likely to be land-applying their waste and may not be impacted. Larger growers may be able to find and afford work-arounds. For example, if a large grower has greenhouse locations in both Canada and the United States, they may be inclined to transport their waste to their American locations and dispose of it as if it were waste from their American site. Although regulations restricting local landfilling would be created to prevent rapid landfill filling and reduce environmental impact, this response would potentially create more emissions due to the increased trucking of greenhouse waste. Large growers (>61 hectares or 150 acres) are also likely to have the funds and waste volumes needed to deal with their waste without collaborating with other farms. Medium-sized farms will likely be the most impacted by restrictions on landfilling and growers of this size are reportedly most active in searching for biowaste disposal solutions including collaborations with other growers [31].

2.3.2. Local Motivations and Barriers to Sustainable Practice Adoption

Each grower may have unique motivations and challenges related to waste disposal. The actual adoption of more sustainable practices will be significantly influenced by these reasons, making it important to understand the relationship between research and industry when trying to approach scaling, implementation, and adoption in the industry. The 2023

Ontario Fruit and Vegetable Growers Association (OFVGA) survey asked respondents about sustainability on their farms, including information on waste management practices, and found that economic considerations appear to be a driving factor in management practice decision-making [52,86]. To encourage more adoption of more sustainable practices in industry, this will need to be a key area of focus for future research.

Separately, a 2022 report about horticultural waste management in Ontario indicated that farmers and processors, including greenhouse growers, had an interest in composting but that they did not have the knowledge about how to move forward [6]. Gaining a true picture of the motivations and interests is challenging, as suggested by notably different responses in the 2023 OFVGA survey (Tables 5–7) where no local growers cited a lack of knowledge as reasoning for not advancing their sustainability [52].

Table 5. Results from OFVGA 2023 grower survey. Motivations to adopt sustainable greenhouse practices [52].

What Were the Top Three Reasons That Most Often Motivated Your Farm to Adopt Sustainable Practices?	% of Growers (n = 18)
Economic (cost savings)	100%
Desire to be environmentally sustainable	44%
Labour productivity	44%
Improved product quality	33%
Keeping up with changing farm practices being adopted by my peers	33%
Health and safety of staff and family	28%
Personal interest in science and technology	6%
Public perception	6%

Table 6. Results from OFVGA 2023 grower survey. Challenges to adopting sustainable greenhouse practices [52].

What Are Your Top Three Greatest Challenges to Adopting More Sustainable Production Practices?	% of Growers (n = 18)
Cost of sustainable practices, technology, or equipment vs. return on investment	83%
Cost of operating a farm (minimal margin available for adopting new practices or technologies)	67%
Regulatory hurdles (permitting and approvals)	67%
Lack of time and capacity (i.e., labour) to experiment with new practices and technologies	44%
Concerns over risk to yield	22%
Availability of equipment/technology	6%
Access to technical resources, lack of knowledge	0%

Table 7. Results from OFVGA 2023 grower survey. Resources for adopting sustainable greenhouse practices [52].

What Were the Top Three Reasons That Most Often Motivated Your Farm to Adopt Sustainable Practices?	% of Growers (n = 19)
Networking with peers (farm tours, farm meetings, conferences, industry events, grower association)	74%
Government funding programs	58%
Private consultants	58%
Business success (more funds available for sustainability goals)	42%
Researchers or research studies	26%
Internet resources (searching independently)	16%
OMAFA resources	5%

Other industry stakeholders reported that the current major challenges to widely adopting new biowaste management solutions are the seasonality of waste, increasing transportation costs, education and awareness barriers, and challenges relating to consistent and continual inputs [6,22].

2.3.3. European Practices

While looking for solutions to greenhouse biowaste disposal issues in Essex County, it may be relevant to consider techniques used elsewhere in the world. Globally, Spain and the Netherlands also have large regions of high greenhouse density [3,63,87].

Disposal prices of tomato biomass in Netherlands have reached EUR 1050/ha (over 1500 CAD/ha) per year [59]. Overall, a portion of greenhouse biowaste in the Netherlands is converted to low-grade compost but faces similar challenges to Canada with plastic contamination [88]. The business case for biomass composting is not very profitable for both the grower and the composter, but may be improved with the reduction of contamination by plastic strings and clips [59].

Spanish growers, which are typically located in the Almería region, appear to have similar waste-management practices to their Canadian and Dutch counterparts, even though hydroponic growing is far less common. This mainly includes landfilling practices, but also involves exploring the ideas of incineration and composting to produce organic fertilizer [3,25,89]. Significant work has gone into waste management in the region, where, as of 2020, ten central plants collected plant residues from most of the greenhouses. In total, 98% of this is used as a fertilizer for organic greenhouse-growing media and small portions are composted or used in animal feed [3]. A high amount of illegal dumping, mainly consisting of plastics from greenhouses, is also an issue in this region [89].

Like Spain, growers in Turkey do not commonly use hydroponics [90]. However, an understanding of practices amongst Turkish greenhouse farmers may also be informative. In Turkey, dumping in a sanitary landfill with methane capture (33.7%), open field burning (32.7%), recycling (27.7%), and landfilling in a local dump with no methane capture (5.9%) comprise the most common practices [90].

2.3.4. Social and Policy Considerations

Policy makers around the world have begun to increase their focus on agricultural waste. To promote a circular economy, European Union regulations require that agricultural waste is transformed into usable by-products such as bioenergy, organic amendments, or plastics when possible [3]. Historically, producers rarely faced the environmental burden associated with waste disposal [91]. Moving forward, waste management policies will continue to play an essential role in the adoption and implementation of new and sustainable technologies in this field [3,6].

The Netherlands has produced several sets of documents and research articles that indicate work towards a more circular greenhouse farming approach [92,93]. For example, "Strategic Biomass Vision for the Netherlands towards 2030" includes references to the use of horticultural biomass in the country's plan to increase circularity of the economy. Although limited language discusses greenhouse biowaste uses, it is suggested that greenhouses should be heated with biomass boilers or bio-combined heat and power systems [93]. Further, the sector aims to be climate-neutral by 2040, 10 years before this goal in the Paris Agreement [94].

In 2018, the province of Ontario released a policy statement on food and organic waste [95]. This mandates municipalities to implement organic waste separation based on the size of the community. This requirement also expands into industrial and commercial centers to include facilities such as retail shopping establishments and office buildings.

This creates an interesting opportunity because Essex County has recently been required to consider how to deal with local organic waste as a separate waste stream for the first time. Notably, since greenhouses fall under an agricultural designation, they are not required to complete organic waste separation under this policy [95].

To implement an organic waste program and accommodate for future increases in organic waste from the community, many communities require new infrastructure. As of 2012, the estimated amount of total residential organic waste from the city of Windsor and Essex County was over 63,000 tonnes [96]. If a new organic waste facility is going to be built, the large volume of greenhouse waste produced in the region that could potentially contribute to the facility would impact the sizing requirements. Even with increases in population and waste volumes since 2012, the greenhouse waste produced in Essex County is likely larger than the total volume of residential organic produced per year. Other sources such as food processing likely also have significant volumes of organic waste to contribute, but are out of the scope of this study.

For the broader Essex County community experiencing the burden of the filling landfill and environmentally damaging impacts of landfill disposal, this research is economically and environmentally relevant [65]. The broader community could benefit from improved greenhouse waste processing due to the avoidance of landfill emissions, reduced burdens on local natural gas and electricity grids, and increased production of co-products like compost, digestate, char, etc. that could contribute to soil health. As tax dollars will be required to build a new landfill or organic waste facility, it is important that decision-makers have access to information about the environmental impacts of the various methods of disposal and can understand the challenges farmers face when considering their options for biowaste disposal. Research exploring the current state of greenhouse biowaste disposal may be a useful resource as future decisions are made about regional landfilling or other potential organic waste disposal facilities [2].

3. Feasibility Summary

This section aims to review the feasibility of different future greenhouse waste management options for Essex County. Multiple options may be feasible or desirable, because the scale, crops, growing methods, and disposal needs of greenhouses vary substantially. The following considerations are noted as important to prioritize for growers and logistical purposes:

- Seasonal timing: Some solutions, such as AD, require a continuous supply of feed material. This may be appropriate for dealing with in-season waste, but might be less appealing as an end-of-season waste solution due to lack of a steady supply of nutrients [97];
- Waste stream composition: Farmers may not have time to manually sort waste to decrease contamination [31];
- Time: Farmers are on a set schedule to remove the crop post-harvest to prepare for the next crop to be planted [40].
- Cost: Labour and transport costs will influence a farmer’s decision on management practices [52].
- Space: Some solutions, such as composting, would require significantly more space for storage and processing. This space may not be available to farmers or may be costly to purchase [31].

A summary of the above methods of disposal for greenhouse biowaste is used to demonstrate the feasibility of each option in Table 8.

Table 8. Summary of various greenhouse biowaste disposal methods in the context of Essex County.

Disposal Method	**Environmental Considerations and Feasibility Depending on Scale of Solution**			
	Community Level	**Individual Grower Level**	**In-Season Waste**	**End-of-Season Waste**
Land Application	Pest and disease issues likely prevent this solution from scaling up at a community level for all crops.	This is currently practiced to some extent. It is unclear how much more this could be scaled up. Contamination issues related to strings and clips are a concern.	This solution seems to be more suited to only portions of the waste, such as the fruit of certain crops, which is found in the in-season waste.	Large volumes of waste that may be contaminated with plastics and pest and disease issues make this an impractical solution for significantly increased adoption.
Incineration/Waste-to-Energy	Significant infrastructure, including storage facilities, would be required to set up a facility. Thus, for economic reasons, it should be implemented at a community-wide scale. Biosecurity issues would be eliminated. Trucking would be comparable to current landfilling.	Due to economic constraints, it is unlikely that this would be feasible at a grower level. Volumes of waste required are not likely produced from a single grower.	A continuous waste supply would be necessary for economic feasibility of an incineration or waste-to-energy facility.	For economic reasons, a communal facility would have to accept in-season waste, but is also well suited to handling post-harvest waste. Additional storage space may be required. Various materials including plastics and all types of organics would be suited to incineration or waste-to-energy and not require sorting, but it is likely pretreatment would be needed.
Anaerobic Digestion	Anaerobic digestion has proven successful in the area. For increased capacity, buy-in from other industries may be essential. Outputs would provide an alternate revenue source. It may be possible to accept feedstocks beyond greenhouse waste from the greater community. Trucking may be reduced if a digestor is built in a more central location than the landfill location.	Volumes of waste required are not likely produced from a single grower.	Strings and clips pose contamination issues that may be overcome with additional research or industry adoption of new practices. Pretreatment would likely be needed.	Continuous, non-variable supply of feedstock is required which is not possible with end-of-season waste. Vines are not ideal or the anaerobic digestion process.
Char Production	This method may provide many environmental benefits and additional revenue opportunities, but has thus far been challenging to scale and make cost effective. Research so far suggests that it may be more suited economically to be implemented at the community level and be able to accept all greenhouse waste. Additional storage may be necessary for end-of-season waste. In-season waste would be needed to maintain char production year-round. Char would provide an additional revenue source.			

Table 8. *Cont.*

Disposal Method	**Environmental Considerations and Feasibility Depending on Scale of Solution**			
	Community Level	**Individual Grower Level**	**In-Season Waste**	**End-of-Season Waste**
Compost/Organic Fertilizer Production	This would require significant additional space but would be able to accept feedstock beyond greenhouse waste to serve the greater community. Compost would provide a revenue source. Trucking may be reduced if a composting facility is built in a more central location than the landfill is currently at. Pathogens and viruses may not be killed in the composting process and may cause issues.	This would require additional space and equipment, but is likely feasible at an individual grower level. String and clip contamination may require additional labour or costs. This is already being practiced on some area organic farms and can reduce required inputs such as fertilizer that the grower must purchase. This could be targeted to growers with crops that have decreased viral concerns.	Continuous waste supplies the necessary inputs to maintain a composting process year-round.	With sufficient space, this would be possible. However, it may not be economically feasible to deal with large volumes of waste as certain times of the year, rather than a continuous supply.
Insect Digestion	Can be completed in a large-scale controlled environment. As alternative proteins become increasingly popular, this will become more economically viable. Insects would provide an additional revenue source.	Can be completed in a greenhouse and would not require significant additional space. As alternate proteins become increasingly popular, insects will act as an additional revenue source to growers.	Continuous supply is necessary to sustain populations. Multiple populations may be used during the growing season. Insects may be used to target discarded fruits or fed leaf mash.	It is unknown how suitable vines are as insect food.

Note on table coloring: Red represents poor feasibility potential, yellow indicates moderate feasibility potential, green indicates high feasibility potential. Grey indicates that further research would need to be performed to assess the feasibility of the alternative.

4. Future Work

Greenhouse plant matter and discarded fruit are a known source of significant waste in Essex County and other greenhouse-dense areas around the world. Several potential solutions exist to reduce the volume of waste that is sent to the landfill, the most common disposal method for greenhouse waste in Essex County. However, most of these solutions have yet to become common practice in the industry. Through interview discussions with local growers, the opportunities, knowledge level, and barriers to these technologies were assessed against those found in the research to identify gaps in the scaling and adoption of sustainable disposal methods. AD, char production, waste-to-energy, and composting are solutions with the highest potential for wide-spread adoption. Through pretreatment, the impacts of these technologies have even greater potential. Policy will also play a critical role in incentivising the adoption of sustainable industry-wide practices. The scale of the technology will also have an impact on its implementation and resulting emissions.

A full-scale economic analysis for each waste disposal method was out of the scope of this research but would likely be of significant interest to the industry and presents a unique future opportunity for research. It is also unclear what the exact environmental impacts of each of these methods of disposal for greenhouse biowaste are and how they compare to landfilling, which poses potential for an area for future research. Using life cycle assessment methods, the environmental impacts of various waste management methods could be considered on large and small scales within the Essex County area. The resulting environmental impacts would be useful for researchers, industry, and policy makers to better understand the opportunities in the sector and what a sustainable path forward may look like in the local context. Alternatively, more technical studies may be completed to further improve the technical or economic feasibility of more sustainable disposal methods to increase adoption rates.

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