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Global Warming Potential of Organic Strawberry Production under Unheated High Tunnels in Kentucky, USA

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Abstract: The global warming potential (GWP) of organic strawberries (*Fragaria* × *ananassa*) grown under high tunnels in Kentucky, USA, was assessed using life cycle assessment (LCA) methodology. The site, part of the Berea College Farm, had been under organic crop management for two decades. The GWP was calculated as 0.57 kg CO_2-eq per kg of strawberries with the combined impact of the aluminum and plastic manufacturing accounting for 44% of the total and the direct production activities, including labor, accounting for another 28%. The average yields of 18,990 kg/ha of fresh fruit over the two years (2020–2021) were comparable to those typically reported in the southeastern USA for conventional production, but opportunities to increase strawberry yields in high tunnels without increasing inputs should be explored to reduce the GWP. Future research should also measure the GWP of production in controlled-environment agriculture (CEA) systems, particularly plant factories with artificial lighting (PFALs), to compare the greenhouse gas emissions of strawberries grown with these technologies to those produced using the simple, high-tunnel method.

Keywords: strawberry; organic; greenhouse gas emissions; life cycle assessment; high tunnel

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1. Introduction

Strawberries (*Fragaria* × *ananassa*) are among the most popular fresh fruits in the United States (USA), ranking behind only a few others, such as apples and bananas, in annual per capita consumption. Production has steadily increased to meet consumer demand, and the USA leads the world in strawberry production [1]. However, most commercial production is concentrated in California, with Florida a distant second. These two states, along with North Carolina and Oregon, account for about 99% of all domestic production [2], and imports from Mexico supply most of the remaining consumer market demand. Despite this imbalanced production situation, opportunities exist for small-scale producers throughout the USA to grow and sell strawberries as demand for local and organic products continues to rise [3].

The Berea College Farm, the oldest continuously operating student educational farm in the US [4], has produced strawberries on a small scale for decades. The practices and systems used have evolved, just as they have across the entire strawberry industry. While perennial matted row culture was the norm two decades ago, the farm shifted to certified organic, annual hill production with cover-cropped furrows/paths about a decade ago (Figure 1a). This system also used floating row covers and drip-tape irrigation under the plastic mulch. The cover crop was flattened to create mulched paths that minimized muddy conditions for harvesters and kept the fruit cleaner. Nevertheless, harvested amounts and quality were highly dependent upon weather conditions.

Over the past several years, the farm has transitioned to growing certified organic strawberries using annual hill production in unheated high tunnels [5] with woven plastic fabric for weed management (Figure 1b). The plants are "Chandler" and "Ruby June" established from certified organic plugs sourced from North Carolina. This system has generated higher fruit yields with fewer blemishes and longer shelf life. This approach is highly compatible with seasonal direct marketing to consumers interested in fresh, local, organic products. Most of the practices and inputs could also be suitable for and appealing to small-scale conventional operations in the region because of the potential savings in herbicide and fungicide expenses with the polyethylene protection above and the weed barrier on the ground. Of course, the high-tunnel structure is a relatively large investment for a small area that should be used and amortized over many years to justify the investment. Production costs and profitability are critical considerations for any producer, but they are not the only concerns.

(a) (b)

Figure 1. Berea College Farm has produced certified organic strawberries as annuals over the past decade using two systems: (**a**) outdoors on raised beds with black plastic mulch and rye (Secale cereale) as a cover crop and mulch between the beds to protect soil and build organic matter, and more recently, (**b**) on beds in unheated high tunnels with woven weed fabric.

Increasing public interest in the environmental impacts of food, particularly related to climate change, means that producers are giving more attention to assessing, improving, and communicating their performance to consumers [6–8]. In their recent overview of the strawberry industry in the USA, Samtani et al. [3] discussed the various major factors affecting production today, including the loss of methyl bromide as a soil fumigant, restrictions of pesticides, challenges of finding labor, and China's ban on importing used plastics for recycling. They predicted that "[o]rganic berry production is likely to increase in the future with increasing consumer demand and the consumer's willingness to pay a premium price for organically grown produce". This presents opportunities for small producers willing to pursue organic certification. However, the authors also anticipated an expansion of controlled-environment agriculture (CEA) for strawberry where "fruit can be produced close to population centers and transportation costs are low".

These expected trends raise some interesting and important questions about the environmental performance of different strawberry production systems, particularly with respect to carbon emissions. Tabatabaie and Murthy [2] used life cycle assessment (LCA) methodology to compare the environmental performance of strawberry production in California, Florida, Oregon, and North Carolina and found that strawberries produced in California had the lowest impacts according to most metrics due to the extremely high yields relative to other regions. More specifically, they reported that the global warming potential (GWP) of strawberries produced in California, Oregon, Florida, and North Carolina was 1.75, 2.21, 2.50, and 5.48 kg CO_2-eq per kilogram of strawberry, respectively. Transportation impacts were not included, but a widely cited study by Weber and Matthews [9] reported that "food miles" for delivery to the consumer account for only 11% of greenhouse gas (GHG) emissions for fruits and vegetables in the US food system. Most of the impact results from actual production—specifically the material inputs and production practices used.

A better understanding is needed of the environmental impacts of strawberries grown using different management practices and inputs, such as organic production in high tunnels as well as large-scale CEA systems. A very wide range of strawberry yields per unit area has been reported in the literature from around the world (Table 1), suggesting the potential for substantial yield increases that could result not only in higher productivity but also reductions in land use. However, questions remain about the net GHG emissions associated with these high yields generated from protected systems, such as plant factories with artificial lighting (PFALs) and tunnels.

Table 1. Strawberry yields reported in the literature from various geographic locations and under different production methods.

Open Field or Protected	Conventional or Organic	Location	Source	Yield (kg/ha)
Greenhouse—in peat	Conventional	Western Germany	Soode-Schimonsky et al. [10]	100,000
Open field	Conventional	California, USA	Samtani et al. [3]	96,047
Greenhouse	Conventional	Turkey	Yildizhan [11]	75,063
Poly-Tunnel—in peat	Conventional	Western Germany	Soode-Schimonsky et al. [10]	75,000
Open field	Conventional	California, USA	Tabatabaie and Murthy [2]	74,000
Greenhouse	Conventional	Iran	Khoshnevisan et al. [12]	72,512
Open field	Conventional	USA	Wu et al. [1]	46,558
Open field	Conventional	Spain	Mordini et al. [13]	32,802
Greenhouse	Organic	Italy	Tittarelli et al. [14]	30,000
Open field	Conventional	Florida, USA	Samtani et al. [3]	28,249
Open field	Conventional	Italy	Valianate et al. [15]	26,500
"Protected"—in coir	Conventional	United Kingdom	Mordini et al. [13]	22,900
Open field	Conventional	Western Germany	Soode-Schimonsky et al. [10]	22,000
Open field	Conventional	South Carolina, USA	Samtani et al. [3]	21,299
"Protected"—in peat	Conventional	United Kingdom	Mordini et al. [13]	20,450
"Protected"—in soil	Conventional	United Kingdom	Mordini et al. [13]	19,318
Open field	Conventional	Switzerland	Valianate et al. [15]	18,400
Open field	Conventional	Virginia, USA	Samtani et al. [3]	16,142
Open field	Conventional	United Kingdom	Mordini et al. [13]	15,117
Open field	Conventional	North Carolina, USA	Samtani et al. [3]	13,452
Open field	Conventional	Alabama, USA	Samtani et al. [3]	11,787
Open field	Conventional	Northeast, USA	Samtani et al. [3]	11,210
Open field	Conventional	Upper Midwest, USA	Samtani et al. [3]	7847
Open field—in peat	Conventional	United Kingdom	Mordini et al. [13]	7100
Open field	Conventional	Southern Estonia	Soode-Schimonsky et al. [10]	7000
Open field	Conventional	Southern Estonia	Soode-Schimonsky et al. [10]	5500
Open field	Conventional	Iran	Khoshnevisan et al. [12]	5476
Open field	Organic	Western Estonia	Soode-Schimonsky et al. [10]	5000
Open field	Organic	Southern Estonia	Soode-Schimonsky et al. [10]	3000

Clearly, the results from Tabatabaie and Murthy [2] suggest that high yields from open-field production systems in California have superior performance over other commercial production systems. However, when yields like these are obtained using greenhouses and tunnels, what are the GHG emissions per unit of output and how do they compare with other productions systems? Table 2 presents a summary of findings about the GWP of strawberry production, presented as the GHG emissions (kg CO_2-eq) per kg of strawberries produced. The lowest rates of GHG emissions are from countries in the Mediterranean region, such as Spain, Italy, and Turkey, using either open-field or tunnel production systems. By contrast, the highest emissions are from open-field and greenhouse production systems in the USA, Germany, United Kingdom, and Japan. The objective of this research was to provide a transparent assessment of the GWP of small-scale, organic strawberry production using unheated high tunnels in central Kentucky, USA.

Table 2. Greenhouse gas emissions reported for strawberry production (per kg of fruit produced) reported in the literature from various geographic locations and under different production methods.

Production System	Location	GHG Emissions (kg CO_2-eq)	Source	Scope
Open field	N. Carolina	5.48	Tabatabaie and Murthy [2]	Cradle-to-gate
Greenhouse	Japan	3.99	Mordini et al. [13]	Cradle-to-gate
Open field	Florida	2.50	Tabatabaie and Murthy [2]	Cradle-to-gate
Greenhouse, peat bag	Germany	2.50	Soode et al. [16]	Cradle-to-grave
Open field	Oregon	2.21	Tabatabaie and Murthy [2]	Cradle-to-gate
Open field	Germany	1.87	Valianate et al. [15]	Cradle-to-gate
Open field	California	1.75	Tabatabaie and Murthy [2]	Cradle-to-gate
Open field	United Kingdom	1.20	Mordini et al. [13]	Cradle-to-gate
Open field	Spain	0.88	Mordini et al. [13]	Cradle-to-grave
High tunnel—integrated, soilless	Spain	0.87	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
Open field—conv.	Spain	0.83	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
Greenhouse	Iran	0.70	Khoshnevisan et al. [12]	Cradle-to-gate
Open field	Iran	0.59	Khoshnevisan et al. [12]	Cradle-to-gate
Greenhouse	Turkey	0.51	Yildizhan [11]	Cradle-to-gate
Open field	Germany	0.40	Soode et al. [16]	Cradle-to-grave
Open field	Turkey	0.24	Yildizhan [11]	Cradle-to-gate
High tunnel—conv.	Spain	0.23	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
High tunnel—integrated	Spain	0.22	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
Open field	Italy	0.21	Valianate et al. [15]	Cradle-to-gate
Low-tunnel—conv.	Spain	0.21	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
Low tunnel—integrated	Spain	0.21	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
High tunnel—conv., soilless	Spain	0.12	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate
High tunnel—organic	Spain	0.11	Romero-Gámez and Suárez-Rey [17]	Cradle-to-gate

2. Materials and Methods

2.1. Production System

This study consisted of a cradle-to-farmgate LCA of certified organic strawberries produced in an unheated high tunnel. The LCA was conducted by following the ISO 14040 and ISO 14044 standards [18,19]. The functional unit was considered to be 1 kg of strawberry fruit, and the system boundaries were defined as presented in Figure 2. The input and output data used to generate the inventory were collected from organic strawberry production in high tunnels at the Berea College Farm in Berea, Kentucky, USA, using management and harvest records from the 2020 and 2021 production years, interviews with the farm manager responsible for the enterprise, and field measurements.

The site had been managed using organic practices according to USDA National Organic Program for 20 years and produced a wide range of vegetables and fruits annually using high tunnels [20,21]. Each high tunnel measured 30 by 6 m (95 by 20 ft) and consisted of an aluminum frame covered with attached clear polyethylene sheeting. Plants were grown directly in the soil, which was routinely amended with composts and commercial organic fertilizers. All of the high tunnels were equipped with drip irrigation and were opened and closed manually for ventilation as needed.

Strawberries occupied one or two of the eight high tunnels at the farm in any given year and required 10–11 months to complete a cycle, from transplanting to clean-up after the harvest. Woven, plastic landscaping fabric was used to cover the entire ground surface within a high tunnel before transplanting. Prior to putting the fabric down in the high tunnel for the first time, holes were burned into it with a propane torch with spacings of 30 cm (12 in) between each row on a bed and 35 cm (14 in) between plants within a row. Certified organic strawberry plugs were purchased and shipped from a nursery in North Carolina in September of each year and planted into three rows on each of three beds in each high tunnel (Figure 1b). Two lines of irrigation drip tape were positioned on each bed between the rows. During the winter, the beds were covered with floating row cover for additional protection. Harvests began in late April and continued through early June in both years. In 2020, the strawberry cultivar "Chandler" was grown; in 2021, "Ruby June" was grown.

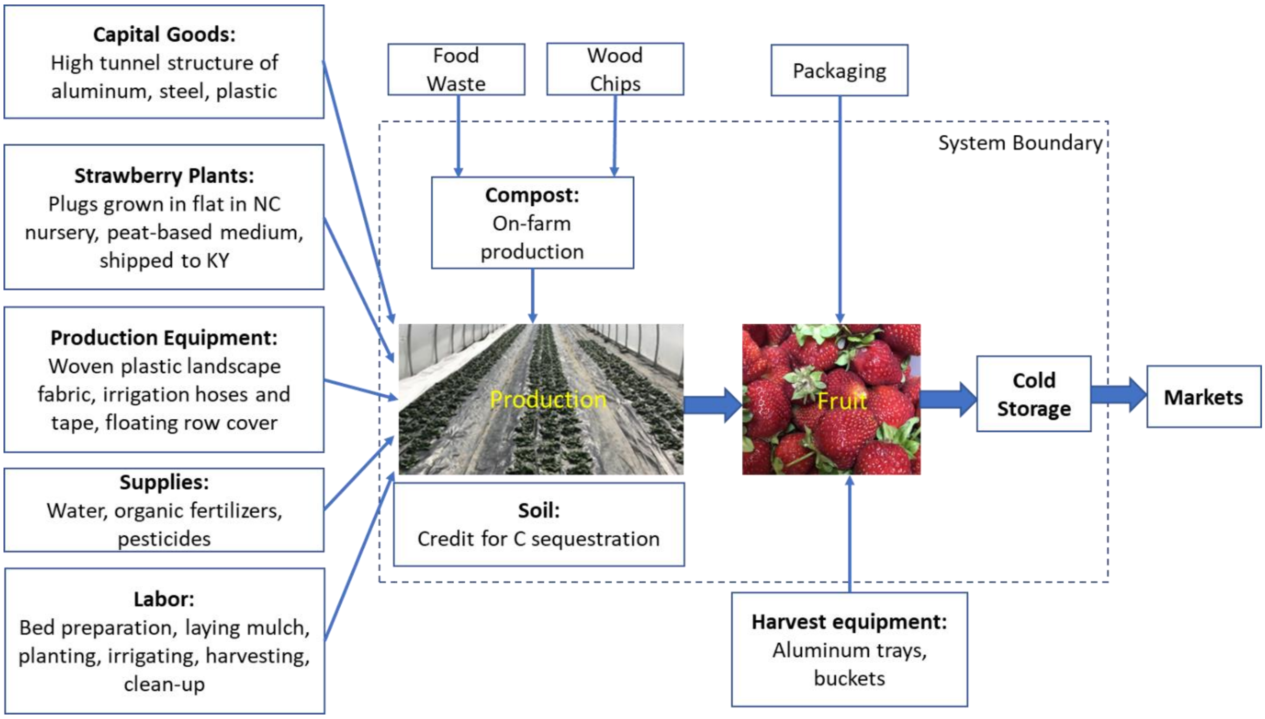

Figure 2. A flow-chart diagram illustrating the inputs and outputs of organic, high-tunnel strawberry production on the Berea College Farm.

2.2. Life Cycle Assessment

The life cycle inventory data consisted of all materials consumed, energy inputs, equipment and facilities used, direct emissions associated with the production, harvest and post-harvest operations, as well as the yields of strawberries harvested and sold during the two years. The amount of carbon annually sequestered in the soil was estimated from soil test data collected in the top 15 cm over a 20-year period. All soil analyses were performed by A&L Western Agricultural Laboratories (Modesto, CA, USA). Direct emissions associated with the production, harvest, and post-harvest were estimated by following the method suggested by the Intergovernmental Panel on Climate Change (IPCC) [22].

The inventory data were subjected to SimaPro 9.1.1 modeling software [23] using the DataSmart database [24], which effectively represents the USA in processes for energy, materials, and wastes. The Tools for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) impact category method [25] was used for environmental impact assessment. The GWP, which is a standardized index of the overall amount of heat absorbed as a result of the direct and indirect GHG emissions of an action or product, is presented as kg CO_2-eq per kg of marketable strawberry fruit harvested and sold.

3. Results and Discussion

3.1. Crop Yield

An inventory of inputs for high-tunnel strawberry production on the Berea College Farm is presented in Table 3. This inventory was generated using farm production and harvest records, a physical inventory, and published enterprise budgets produced by land-grant universities to verify and confirm values. A single season of strawberry production utilizes the space of a high tunnel for nearly one year (10–11 months) when pre-planting soil preparation and post-harvest clean-up are included. Thus, the season typically begins in early September and ends in early July of the following year. A flow-chart diagram illustrates the process, system boundaries, inputs, and outputs in Figure 2.

Table 3. Inventory of inputs and outputs for a life cycle assessment of high-tunnel strawberry production (outer footprint = 176.5 m^2 or 1900 ft^2) on the Berea College Farm.

Category	Material/Activities	Quantity/High Tunnel	Unit	Lifespan (Years)
Capital Goods	Aluminum structure	1036	kg	30
	Steel screws, wire, and hydrant	20	kg	30
	Plastic (6 mil poly plastic)	47	kg	5
	Plastic (PVC water line to tunnel)	14	kg	20
Strawberry Plants	Plastic trays with cells	4	kg	3
	Peat-based potting medium	6	kg	1
	Plants	14	kg	1
	Transportation from NC	470	km	1
Production Equipment	Woven plastic landscape fabric	9	kg	5
	Irrigation header line (plastic)	7	kg	5
	Irrigation drip tape (plastic)	2	kg	2
	Irrigation valves	1	kg	2
	Spun polyester row-cover fabric (row cover)	10	kg	4
	Steel ground staples (to pin landscape fabric)	1	kg	5
	Two-wheel tractor with rotary plow	2	hour	1
	Propane burner	3	hour	1
Supplies	Water	60,567	l	1
	Organic fertilizer—Nature Safe 13-0-0	14	kg	1
	Gasoline (two-wheel tractor with rotary plow)	4	l	1
	Propane (burner)	4	l	1
Labor	Bed preparation (two-wheel tractor)	2	hour	1
	Compost application	3	hour	1
	Burning holes in landscape fabric	1	hour	1
	Laying and pinning landscaping fabric	2	hour	1
	Planting	32	hour	1
	Irrigating	4	hour	1
	Harvesting	90	hour	1
	Clean-up	16	hour	1
Harvest Equipment	Aluminum trays	3	kg	10
	Plastic buckets	2	kg	2
Packaging	Plastic retail container	19	kg	1
Compost	Compost—from food waste and wood chips	91	kg	1
Cold Storage	Cold storage (electricity to operate air conditioner)	12	hour	1
Soil	Carbon sequestration (CO_2-eq in lbs)	(15)	kg	1
Output	Strawberry yield "Chandler" (2020)	327	kg	1
	Strawberry yield "Ruby June" (2021)	343	kg	1

The strawberry fruit harvested per high tunnel in 2020 ("Chandler") was 327 kg and in 2021 ("Ruby June") was 343 kg, for an average output of 335 kg. This is equivalent to 18,990 kg/ha for comparison with other studies. There is a more than a 30-fold difference between the highest and lowest strawberry yields reported in the literature (Table 1). The average yield in this study was lower than the average reported for the USA and the world

(Figure 3). However, it is comparable to typical yields reported for adjacent states in the southeastern USA, such as Virginia and North Carolina (Table 1).

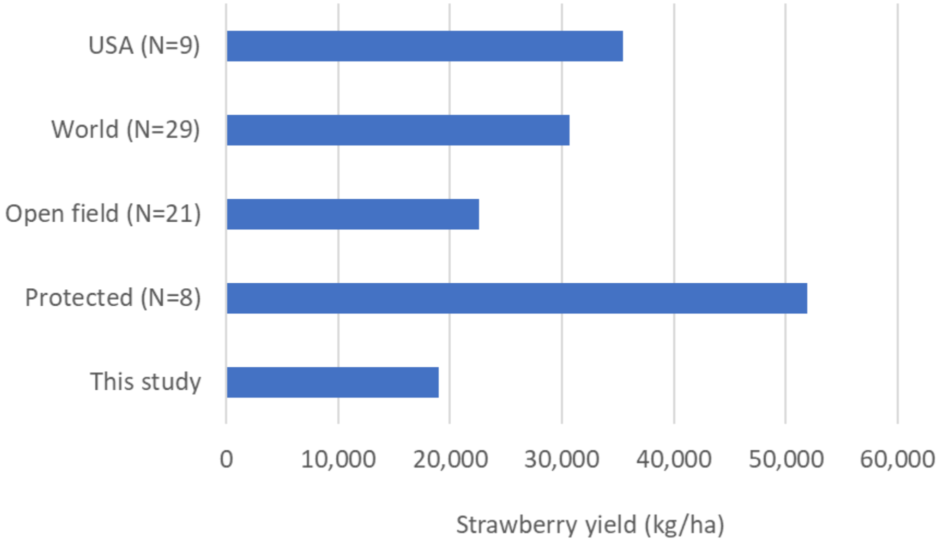

Figure 3. Comparison of the average strawberry yield in this study to yields (kg/ha) reported in the USA, world, open-field systems, and protected systems using the data reported in Table 1.

3.2. Global Warming Potential

The GWP, estimated using the average yield over the two years, was 0.57 kg CO_2-eq per kg of strawberry fruit (Table 4). Aluminum manufacturing for the frame of the high tunnel accounted for the largest fraction of the total GWP, followed by the actual production activities (including human labor, assessed at 0.7 kg CO_2-eq per hour) and plastic manufacturing. The labor activities accounting for the largest fraction of production were harvesting and planting. Combined, these three factors accounted for over 70% of the total GWP. Adding in compost production, use of municipal tap water, and the purchased strawberry plugs (seedlings) brings the fraction of the GWP accounted for up to 90% of the total.

Table 4. Breakdown of the components contributing to the GWP of strawberry production for the defined functional unit.

Inputs/Emissions	**GWP (kg CO_2-eq)**	**% of Total**
Aluminum product manufacturing	0.1714	30.03
Production—direct activities, including labor	0.1611	28.23
Plastics manufacturing	0.0808	14.16
Compost, at plant	0.0421	7.37
Municipal tap water, at user	0.0320	5.61
Strawberry seedlings, for planting	0.0255	4.46
Gasoline produced and combusted, at equipment	0.0153	2.69
Manure, fertilizer, as applied N, at field	0.0149	2.61
Transport, light commercial truck, diesel-powered	0.0107	1.87
Extrusion, plastic pipes	0.0041	0.72
Agricultural machinery, general, production	0.0031	0.54
PVC pipe	0.0030	0.52
Compost, nutrient supply from compost	0.0024	0.42
Propane/ butane, at refinery	0.0019	0.33
Cooling operation, reefer	0.0015	0.26
Plastic tunnel construction	0.0004	0.07
Wire drawing, steel	0.0004	0.07
Peat production	0.0002	0.03
Total	0.5706	100.0

There is an even greater range of values reported for GHG emissions than for yields in strawberry production (Table 2). In comparison to the values reported in the literature, the system studied here generated lower levels of GHG emissions than might be expected. They were comparable to many of the values reported from the Mediterranean region, regardless of whether they were open-field or protected systems, and lower than those reported for the USA. Thus, despite having yields that were lower than average, this system performed reasonably well compared to the GWP of many other production systems in the USA and around the world (Figure 4).

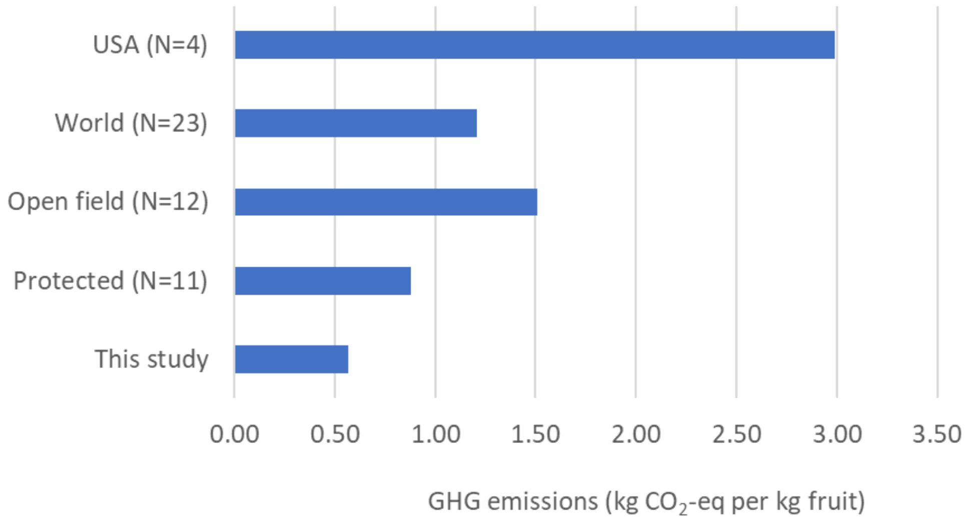

Figure 4. Comparison of the greenhouse gas emissions from strawberry production (kg CO_2-eq per kg fruit) in this study to those reported in the USA, world, open-field systems, and protected systems using the data reported in Table 2.

3.3. Discussion

In summary, the average strawberry yield in this study over the two-year period (2020–2021) was much lower than the highest yields reported for commercial production (for example, California) but comparable to those reported for the southeastern USA. The GWP of 0.57 kg CO_2-eq per kg of strawberry fruit was lower than the values reported by Tabatabaie and Murthy [2] for four other states in the USA and more similar to those reported for various types of open-field and protected production in Spain, Italy, Turkey, and Iran (Table 2). Factors that may account for this situation include the use of an *unheated* high tunnel, the limited use of machinery and fossil fuels, and the absence of synthetic fertilizers.

A breakdown of the components contributing to the GWP of strawberry production in this study (Table 4) suggests that there is not much opportunity to reduce GHG emissions further, beyond obtaining higher yields with the same inputs. For example, eliminating the brief post-harvest refrigeration or sourcing plugs closer to the farm would do relatively little to reduce the overall GWP.

A recent comprehensive review of the environmental impacts of protected vegetable cultivation by Gruda et al. [26] drew from over 100 studies published globally since 1990 and summarized the findings of dozens of LCAs. They included simple plastic high tunnels [21], on the one hand, such as those found on the Berea College Farm, to high-tech PFALs, usually soilless culture systems with active climate control. The authors concluded that based upon current literature, PFALs have many advantages, but a reduction in GWP is not among them. In fact, they wrote the following about such systems: "A distinguishing feature . . . is the large amount of energy consumption for heating during the cold season [and for] artificial lighting", and " . . . high amounts of GHG are produced and emitted from such protected cultivation systems".

The construction of the facility itself contributes significantly to the overall GHG emissions, which must be included in the carbon footprint of the crops grown. The authors wrote that during "the production of the structure itself (using steel and concrete) high CO_2 emissions are delivered into the atmosphere". This situation raises serious questions about the environmental costs and benefits of protected crop production, in particular, which practices and technologies can yield larger amounts of food without contributing more GHG emissions and exacerbating the climate crisis. As Gruda et al. [26] concluded, innovative adaptations are needed because currently "protected cultivation has some negative impacts on climate change".

4. Conclusions

This study evaluated the GWP of organic strawberry production under unheated high tunnels using LCA. Data were collected from two years of certified organic strawberry production in Kentucky, USA. The average strawberry yield was estimated to be 18,990 kg/ha, which is lower than yields reported for some commercial production but typical of conventional outdoor production in the region. This is an important consideration because the lower crop yields typically derived from organic production can often result in higher GHG emissions per unit product [27]. GWP was estimated to be ~0.57 kg CO_2-eq per kg of strawberries, which mainly resulted from the aluminum and plastic structure comprising the high tunnel and direct emissions associated with crop production activities. However, the GWP was lower than values reported in similar studies, likely due to limited use of fossil fuels, as well as the absence of manufactured synthetic fertilizers. Future research should document and assess the GWP of strawberries produced in large-scale CEA or PFAL systems in the USA. This will permit comparisons to determine if the performance of such systems is an improvement over strawberry production in high tunnels and open fields with respect to GWP.

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Conflicts of Interest: The authors declare no conflict of interest.

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