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The Power Behind the Plants: Energy Scenarios in Vertical Farming

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ABSTRACT

Vertical farms are often promoted as environmentally friendly options; however, evidence on the environmental performance of commercial facilities is limited, particularly within Mediterranean climates. This study reports a cradle-to-grave life cycle assessment (LCA) of a large-scale commercial vertical farm producing lettuce in the Lombardy region of northern Italy. The functional unit was defined as 1 kg of edible lettuce. Environmental impacts were assessed applying the Environmental Footprint (EF) 3.1 characterization method across nine impact categories: climate change, acidification, terrestrial ecotoxicity, freshwater eutrophication, marine eutrophication, land use, water use, and abiotic depletion of fossil and mineral resources. The current operational configuration, based on biomethane-fueled combined heat and power (CHP) cogeneration, was evaluated against four alternative energy pathways: the Italian national electricity grid, natural gas cogeneration, renewable electricity procurement, and biomethane production from alternative feedstock compositions. The biomethane CHP scenario yielded a climate change impact of 3.02 kg CO_2-eq per kg of edible lettuce, compared to 6.16 kg CO_2-eq per kg under natural gas cogeneration and 6.06 kg CO_2-eq per kg under the Italian grid mix. Minimum climate change impact was obtained under fully renewable electricity supply, at 1.38 kg CO_2-eq per kg. Biomethane performance showed marked sensitivity to feedstock composition, with climate change impacts ranging from 3.02 to 6.44 kg CO_2-eq per kg depending on organic residue and manure proportions. Although biomethane reduced climate change impacts relative to fossil-based configurations, pronounced trade-offs were identified in freshwater eutrophication and terrestrial ecotoxicity, attributable to upstream feedstock handling and digestate management. Electricity consumption for lighting, cooling, and dehumidification constituted the dominant environmental hotspot across all scenarios, while infrastructure embodied impacts represented a secondary yet substantial contributor to fossil and mineral resource depletion. Collectively, these results establish energy sourcing as the principal determinant of environmental performance in Mediterranean vertical farming, with all evaluated pathways directly actionable under the European Renewable Energy Directive (RED II, Directive (EU) 2018/2001). Direct electrification with verified low-carbon electricity delivered the greatest environmental improvements across impact categories. Where biomethane-based cogeneration is maintained, realizing consistent environmental benefits requires careful feedstock selection, stringent methane-loss control, and robust digestate management practices. Mitigating infrastructure-related burdens additionally demands targeted design optimization, responsible material procurement, and appropriate end-of-life management strategies.

1 | Introduction

The global food sector accounts for nearly one-third of anthropogenic carbon dioxide–equivalent emissions (FAO 2022) and imposes substantial pressures on land and freshwater resources (Pastor et al. 2019). Preserving ecosystems will require either profound shifts in consumption patterns or the adoption of transformative production technologies (Crist et al. 2017). At the same time, meeting rising food demand without further expansion of cropland (FAO 2009) calls for production systems that increase output per unit of resource and remain reliable under climate variability.

Within this context, high-technology production approaches aim to release fertile land for alternative ecosystem services and optimize resource utilization. Indoor vertical farming (VF) is frequently presented as a climate-resilient option. Fully controlled environments enable year-round cultivation, high land-use efficiency, reduced pesticide inputs, and proximity to consumers (Erekath et al. 2024; Kozai and Niu 2019; van Delden et al. 2021). Vertical farming has also been reported to achieve high efficiency in the use of natural resources, particularly land and water, relative to conventional agriculture (Orsini et al. 2020; Pennisi et al. 2025). More precise nutrient management can reduce fertilizer requirements and thereby lower direct on-farm emissions, including nitrous oxide, when compared with open-field systems (Rufí-Salís et al. 2020). Furthermore, VF can reduce the land use compared to traditional farming by allowing more intensive cultivation in a smaller area (Gumisiriza et al. 2022; Kalantari et al. 2018). In recent years, several European countries have seen the emergence of commercial facilities and pilot projects, especially for leafy greens, often supported by public and private initiatives intended to shorten supply chains (Erekath et al. 2024). Conversely, indoor vertical farming has notable drawbacks in terms of energy use: the substantial electricity required for lighting and climate control drives up operating costs and associated carbon emissions (Blom et al. 2022; Kozai and Niu 2019; Martin et al. 2023). Comparative studies frequently report higher electricity demand in vertical farms than in greenhouses across crops and regions, although outcomes are context dependent and relative advantages have been observed in colder climates (Benis et al. 2017a; Harbick and Albright 2016; Kikuchi et al. 2018; Weidner et al. 2021; Zhang and Kacira 2020). In accordance with this context dependence, Pennisi et al. (2025) estimate a transport break-even point of approximately 1100 km for chilled lettuce when contrasting a Swedish VF (low-carbon electricity) with low-tech greenhouse production in Italy. Beyond this distance, proximity benefits can offset VF's higher electricity consumption. Environmental assessments further identify electricity for lighting and the carbon intensity of the supplied grid as dominant contributors to climate-change impact (Martin and Molin 2019; Song et al. 2022). Collectively, the evidence indicates that performance in VF is jointly determined by system configuration, local climate, and electricity sourcing.

Since electricity intensity and supply characteristics largely determine environmental outcomes, the evaluation of alternatives in Europe must reflect the policy environment that enables or constrains those alternatives. In the European Union, the relevant conditions are set by Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (Renewable Energy Directive II, hereafter RED II) and by the corresponding national measures adopted by Member States. Situating the analysis within this framework is necessary to compare energy options that are actually implementable by operators and policymakers. RED II raises the Union's renewable-energy ambition for 2030 and establishes binding provisions for advanced fuels produced from residues and wastes, including biomethane. The directive also recognizes mitigation benefits associated with improved manure management in its greenhouse gas accounting for transport fuels. Italy's transposition (Legislative Decree 199/2021) promotes renewable electricity, biogas, and biomethane, making these vectors directly pertinent to energy-intensive controlled-environment agriculture. Nevertheless, the environmental implications of these options for large-scale VF in Mediterranean settings remain insufficiently quantified.

Previous life cycle assessment (LCA) studies have examined VF in varied settings and with different system configurations. Analyses in the north-eastern United States reported higher impacts for high-yield, high-energy facilities relative to conventional production and distribution (Goldstein et al. 2016). In Japan, container-based production in Kashiwa was contrasted with plastic-tunnel greenhouse cultivation, emphasizing that energy consumption was the primary determinant influencing the overall life-cycle emissions in the plant factory as opposed to the greenhouse (Kikuchi et al. 2018). In Singapore, assessments of lettuce produced in vertical farms and greenhouses, alongside imported alternatives, highlighted the influence of electricity intensity on global warming potential (Song et al. 2022). A complementary line of work has explored the role of electricity sourcing, showing that procuring low-carbon electricity can materially reduce impacts, including wind-powered production in Sweden (Hallikainen 2019), photovoltaic supply with nutrient recovery in Singapore (Li et al. 2020), grid mixes with high wind shares across multiple regions (Casey et al. 2022), facilities operated on fully renewable electricity in the United Kingdom (Sandison et al. 2022), and hydro–wind configurations for both large-scale and modular systems in Sweden (Martin et al. 2023, 2024). Despite these advances, two gaps remain. First, there is no primary-data LCA of a commercial VF in the Mediterranean context, and none for Italy specifically. Second, while renewable electricity pathways have been analyzed, the literature has not yet addressed the role of biofuels, which are indeed central to the European policy environment and, in particular, residue-based biomethane under RED II. Accordingly, the central premise of this study is that energy sourcing, evaluated within the European regulatory context, is the decisive lever for improving the environmental impact of commercial VF in Southern Europe.

This study addresses both gaps. It provides a primary-data LCA of a commercial VF in Italy and evaluates energy options that are actionable under RED II: national grid electricity, natural gas, and biomethane used in combined heat and power, and renewable electricity procurement. The scenario analysis quantifies the effect of energy sourcing on climate-change impact per functional unit in a Mediterranean context and identifies the energy pathway that yields the lowest impact for the commercial vertical farm examined.

2 | Methodology

The following sections present the assessed vertical farm case study, explain the life cycle assessment methodology used, compare it with conventionally sourced lettuce, and describe the additional analyses carried out.

2.1 | Case Study Vertical Farm

The study evaluated a large-scale vertical farm, located in the Lombardia region in the North of Italy. The farm is designed as a dedicated facility for the production of leafy greens, with a primary focus on lettuce, utilizing hydroponic cultivation in substrate-based trays. The facility includes 14 growing chambers, each 10.2 m in height and 261 m^2 in area, corresponding to a total cultivation area of 19,353 m^2. The production cycle consists of sowing, germination in climate-controlled chambers for 48–72 h, transplanting into growing trays, cultivation under controlled conditions for 15–30 days depending on the variety, harvesting by mechanical cutting, packaging in polypropylene (70% bio-based) bags after cooling, and short-term storage prior to delivery. Packaged lettuce is distributed to customers within 24 h of harvest. Advanced automation and climate regulation technologies are integrated to optimize plant growth and resource efficiency, while waste management practices aim to align with circular economy principles. Energy is supplied through a combined heat and power (CHP) system fueled by biomethane, which provides both electricity and heat to the growing chambers, even if the heating of the CHP is not considered in the assessment. The CHP is supplemented by electricity from the national grid (see Section 2.3). In the following sections, all performance data, including yields, resource consumption, and operating parameters, are discussed and analyzed as declared by the company.

Because the present study relies on primary data from a real commercial vertical farm, some production and operational details could not be disclosed in full due to company confidentiality requirements. The methodological description, therefore, reflects the maximum level of disclosure permitted by the data provider while retaining the information necessary for interpreting the LCA framework and results.

2.2 | Life Cycle Assessment and Life Cycle Inventory

A life cycle assessment (LCA) was conducted to evaluate the environmental impacts of lettuce production, following the guidelines ISO 14040:2006 and ISO 14044:2006. The functional unit (FU) was defined as 1 kg of edible lettuce, a standard metric widely used in assessments of controlled environment agriculture. The study adopted a cradle-to-grave perspective, covering all stages from the construction of farm infrastructure to cultivation inputs, packaging materials, energy consumption, transportation of inputs and products, and waste management at the consumer stage. A simplified representation of the system boundaries and processes included in the assessment is provided in Figure 1. The LCA was performed using OpenLCA version 2.3.1 (GreenDelta 2024) with supplementary data analysis on Microsoft Excel. Environmental impacts were calculated using the Environmental Footprint (EF) v.3.1 method (Zampori and Pant 2019), which is widely

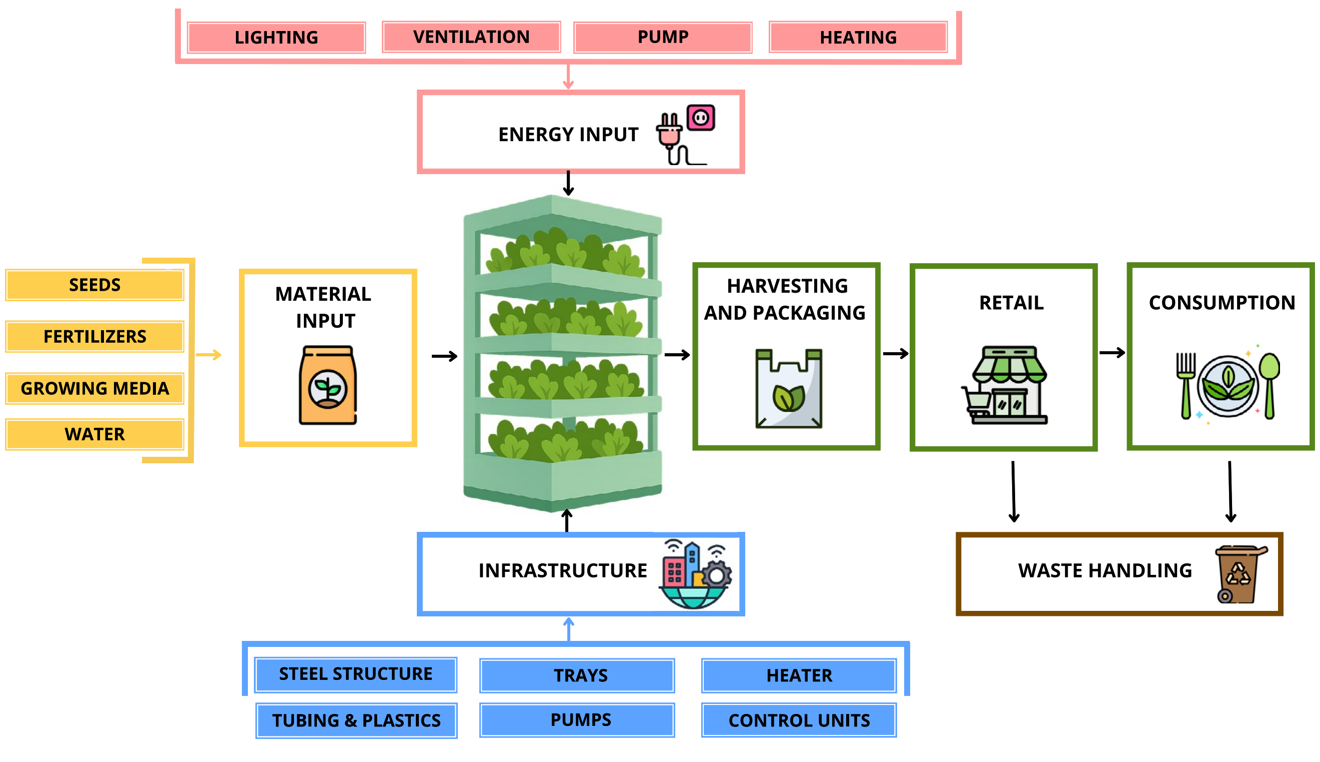

FIGURE 1 | Simplified system boundaries and processes included in the life cycle assessment.

applied and recognized for its robustness in evaluating products marketed within the European Union. The impact categories considered include Climate Change (CC, kg CO_2 eq), Acidification accumulated exceedance (AE, mol H^+ eq), Terrestrial Ecotoxicity (ET, in Comparative Toxic Units for ecosystems, CTUe), Freshwater Eutrophication (FE, kg P eq), Marine Eutrophication (ME, kg N eq), Land Use (LU, Pt), Water Use (WU, m^3 deprived), Abiotic Depletion Potential—fossil resources (ADP-f, MJ), and Abiotic Depletion Potential—mineral elements (ADP-e, kg Sb eq). These particular impact categories were selected for the main text as they highlight important global, regional, and resource implications for food systems. In line with previous applications of LCA to vertical farming in Sweden (Martin et al. 2023; Martin and Molin 2019), these categories allow us to ensure comparability with existing studies in contexts where energy sourcing and infrastructure burdens are key drivers. To our knowledge, no LCA studies of vertical farming have yet been carried out in Italy. Therefore, the reference to Swedish case studies provides a useful benchmark. Moreover, these categories are also widely used in LCA studies of vertical farming and other agricultural systems, allowing for broader comparisons (Gargaro et al. 2024; Joensuu et al. 2024; Rufí-Salís et al. 2021).

The life cycle inventory (LCI) covered all material and energy inputs, cultivation processes, infrastructure components, and waste flows. Primary data were obtained directly from company operators and tech manufacturers, while secondary datasets were sourced from the Ecoinvent v 3.8 database (Wernet et al. 2016). Infrastructure burdens were distributed across expected service lifetimes, and transport distances were included for consumables, infrastructure, and distribution. The annual production goal of lettuce in the facility is approximately 1,800,000 kg, which serves as the reference basis for allocating inventory flows to the FU of 1 kg. An overview of the annual material and energy inputs, infrastructure, and waste outputs for the VF-Lettuce scenario is provided in Table 1, while further details on assumptions and datasets are included in the Supporting Information.

2.2.1 | Inventory Structure and Process Grouping

To ensure transparent interpretation, foreground processes are grouped into inventory categories that reflect materials, energy flows, and operations. Process inputs are parameterized using Ecoinvent market datasets, which represent regional supply mixes and upstream processes up to delivery at the market. End-of-life is not embedded in these datasets; disposal and recovery are modeled separately under the waste handling categories when they fall within the system boundary.

Growing media consists solely of peat, which is the only substrate used. Fertilizers include all nutrients for the hydroponic solution along with nitric acid for pH adjustment. The application of fertilizers is based on the farm's measured dosing rates. The category labeled 'other materials' contains corrugated cardboard boxes and seeds; for both, the inventory covers upstream production and distribution to market. Packaging refers to the primary plastic bags used for packing lettuce for sale; their upstream production and market distribution are included here, while their end-of-life at retail or consumer stage is addressed under waste handling of the product system. The process of cleaning and protective covering involves the use of water and detergents to sanitize growing rooms and irrigation lines. Upstream supply is included via market datasets, while wastewater from these activities is managed at the farm level according to the modeled treatment routes. Carbon dioxide supplementation accounts for the CO_2 used for enrichment. Energy data reflect electricity purchased from the national grid, not supplied by the CHP unit. Cogenerator inputs include auxiliary consumables such as glycol, urea, and oil required for CHP operation. Fuel and biofuel supply are modeled in a separate category covering the upstream chains for biomethane (by feedstock mix) or fossil natural gas and their delivery to the site. Combustion is treated separately, representing on-site oxidation of these fuels in the CHP, including stack emissions. Maintenance includes routine spare parts and technician travel directly related to maintenance activities recorded in the inventory. Infrastructure encompasses long-lived assets, such as structural steel racks and benches, tanks, piping, pumps, lighting and control systems, HVAC and dehumidification units, insulation panels, electrical panels, and the CHP housing and ancillary equipment. Their embodied impacts are amortized to the functional unit based on expected lifetime and throughput. Transportation-in refers to inbound logistics for materials, inputs, and spare parts, while transportation-out pertains to outbound distribution of packaged products to retailers or wholesalers.

Waste handling at the farm on-site, as well as wastewater sent for treatment, and recyclable materials such as cardboard and polyethylene, along with their transportation. Waste handling at the end of the product's life includes collecting, treating, and transporting postretail food biowaste and packaging materials introduced upstream. End-of-life management of infrastructure involves decommissioning capital goods through metal recovery and recycling, treating plastics and composites, and specialized treatment of electronic components from lighting and control equipment, with associated transportation. This structure provides a clear, nonoverlapping view of the cradle-to-grave system, aligning with market-based datasets and supporting robust hotspot analysis and comparability across scenarios.

2.3 | Scenarios and Sensitivity Analyses

The environmental performance was assessed under multiple energy supply scenarios. While the farm currently operates with a CHP unit fueled by biomethane and supplemented by electricity from the grid, additional configurations were modeled to provide comparative insights. These included reliance on the Italian grid alone, natural gas-based cogeneration, alternative biomethane feedstock mixes, and renewable electricity sourcing. More specifically, three groups of alternative scenarios were considered, as summarized in Figure 2. The first group comprised the "CHP + renewable grid" scenarios, in which the baseline biomethane-fired CHP unit was maintained while grid electricity was replaced by alternative electricity mixes predominantly based on renewable sources, including hydropower reservoir, run-of-river hydropower, wind, photovoltaic electricity, and a renewable electricity mix. The second group consisted of a biomethane sensitivity

TABLE 1 | Material and energy inputs and outputs for the production of 1 kg of edible lettuce in the Biomethane scenario; the highlighted section undergoes changes across different scenarios (grey-shaded rows correspond to the Energy input category, while bold values refer to the total energy demand calculated for each input group. Transport inputs are expressed in tonne-kilometers [tonne-km], representing the product of mass [metric tonnes] and distance [km] transported).

Input/ Output		Type	Detail	Amount per FU	Unit	Lifetime (years)	Transport distance
Material inputs	Growing media	Growing media	Peat	1.26E+00	Liters		253
	Seeds	Lettuce		1.29E-05	kg		30
	Fertigation	Water	Water	1.05E+01	Liters		
		Fertilizers	N Fertilizers	9.67E-03	kg		30
			K Fertilizers	3.30E-03	kg		30
			Micronutrients	3.36E-03	kg		30
	CO_2 supplemental		Carbon dioxide	9.72E-02	kg		30
	pH Adjust	Acid	Nitric acid (52.8%)	1.89E-05	Liters		30
	Detergents	Detergents	Various	4.06E-03	liters		30
		Water cleaning	Water	0.00E+00			30
	Packaging	Plastic bag	Polyethylene	6.06E-02	kg		30
		Cardboard	Cardboard	2.89E-01	kg		30
	Disposable materials	Gloves	Nitril	8.33E-06	kg		30
		One piece suits	PE (Polyethylene)	1.67E-05	kg		30
		Disposable shoes covers	PE (Polyethylene)	3.33E-06	kg		30
		Disposable beard covers	Nylon	8.33E-06	kg		30
	Cogenerator input	Cogenerator urea		1.11E-02	L	5	30
		Glycol		3.33E-04	L	5	30
		Biomethane		2.61E+00	m^3	5	30
		Oil		1.11E-03	L	5	30
	Other	Water for cleaning		4.54E+00	L		30
Energy		**Grid**		1.22E+00	kWh		
		Energy consumed by the cogenerator		8.67E-01			
		Energy produced from the cogenerator		1.08E+01			
		Total		1.21E+01			
		LEDs (Light emitting diode)		5.18E+00			
		Irrigation		2.41E-01			
		Refrigerators		1.33E+00			
		HVAC (Heating, ventilation and air conditioning)		3.38E+00			
		Machines (e.g., Packaging)		1.93E+00			

(Continues)

Input/ Output		Type	Detail	Amount per FU	Unit	Lifetime (years)	Transport distance
Infrastrucure		Machines		1.07E-03	kg	20	30
		Structure	Emaco (cement mortar)	6.81E-02	kg	10	30
				0.00E+00			
			Steel	2.07E-01	kg	20	30
				0.00E+00			
		Irrigation	Plastics	1.13E-02	kg	10	30
				0.00E+00			
			Steel	6.36E-03	kg	20	30
				0.00E+00			
			Sensors	8.45E-06	kg	10	30
			Electronic component	2.22E-06	kg	10	30
			Pump	1.50E-04	kg	10	30
			Wires	5.52E-04	kg	8	30
		Trays	Plastic	1.31E-02	kg	1	30
				0.00E+00			
		LEDs	Aluminum	1.52E-02	kg	8	30
				0.00E+00			
			HDPE (High-density polyethylene)	1.08E+00	kg	8	30
				0.00E+00			
			Steel	7.78E-02	kg	8	30
				0.00E+00			
			Diodes	2.75E-03	kg	8	30
			Wire	2.00E-03	kg	8	30
		Machines/Electronics	Computers	5.56E-05	kg	10	30
	Transfer	Air compressor (2 kW)	—	4.44E-05	kg	10	30
		Engine	—	2.22E-05	kg	10	30
		Rollers	Polyurethane	2.01E-03	kg	10	30
				0.00E+00			
		Hydraulic pistons—steel	Steel	2.01E-03	kg	20	30
				0.00E+00			
		PE Piping	—	6.70E-05	kg	10	30
				0.00E+00			
	Packaging	Machines	Sorting	1.50E-02	kg	30	30
			Bagging	1.11E-03	kg	20	30
			Electronics	1.39E-04	kg	20	30
	Cleaning/ Hygiene Room	Pressure washer		3.78E-05	kg	10	30
	Air treatment unit (UTA)	Ventilation		3.11E-05	item	30	30
	Cogenerator	Machine		7.83E-03	kg	20	30

(Continues)

Input/Output		Type	Detail	Amount per FU	Unit	Lifetime (years)	Transport distance
Maintenance		Fixing equipment	Travel	1.39E-04	km		
		Parts	Plastics	8.33E-06	kg	5	30
			Steel	2.22E-05	kg	30	30
			Control units	2.78E-06	kg	10	30
Main output	Plants/Edible	Lettuce		1.00E+00	kg		30
		Biowaste	Farm waste to farmer—Lettuce	1.00E-02	kg		30
			Substrate	0.00E+00			
			Sorted plants	0.00E+00			30
Waste	Farm-based	Packaging waste/Other	Disposable germination trays	0.00E+00	kg		30
			Plastic packaging	1.44E-04	kg		30
			Other packaging	0.00E+00	#		30
			Other	0.00E+00			30
		Cardboard	Paper/Cardboard waste	2.89E-01	kg		30
		Waste water	Waste water	1.15E-02	m^3		30
	End of life	Product	Plant Waste (Consumer)	3.00E-02	kg		30
			Packaging (Consumer)	6.06E-02	kg		30
		Infrastructure-structures/Materials	Machines and electronics	1.38E-02	kg		30
			Steel	7.17E-04	kg		30
			Plastic	1.26E-02	kg		30
			Electronics	7.96E-05	kg		30
			Other	0.00E+00			30
			Compost	1.00E-02			30
Transport			Consumables	4.70E-01	Tonne-km		
			Infrastructure	5.42E-03	Tonne-km		
			Distribution	1.42E-01	Tonne-km		
			Other/Maintenance	1.39E-04	km		
			Waste handling (Farm)	9.01E-03	Tonne-km		
			Waste handling (EOL)	3.83E-03	Tonne-km		

analysis based on five datasets: the default ecoinvent biomethane representation and four feedstock-specific pathways, namely S1 (50% cattle manure + 50% organic waste), S2 (50% cattle manure + 50% sorghum residues), S3 (50% cattle manure + 50% organic waste, transport-only variant), and S4 (100% organic waste). The third group included the "grid-only" electricity scenarios, in which the farm was supplied entirely by electricity, either from the conventional Italian grid or from renewable electricity configurations based on hydropower reservoir, run-of-river hydropower, wind, photovoltaic electricity, or a renewable electricity mix. The baseline configuration, comprising a biomethane-fired CHP unit supplemented by grid electricity, was used as the reference case for comparison across all scenarios.

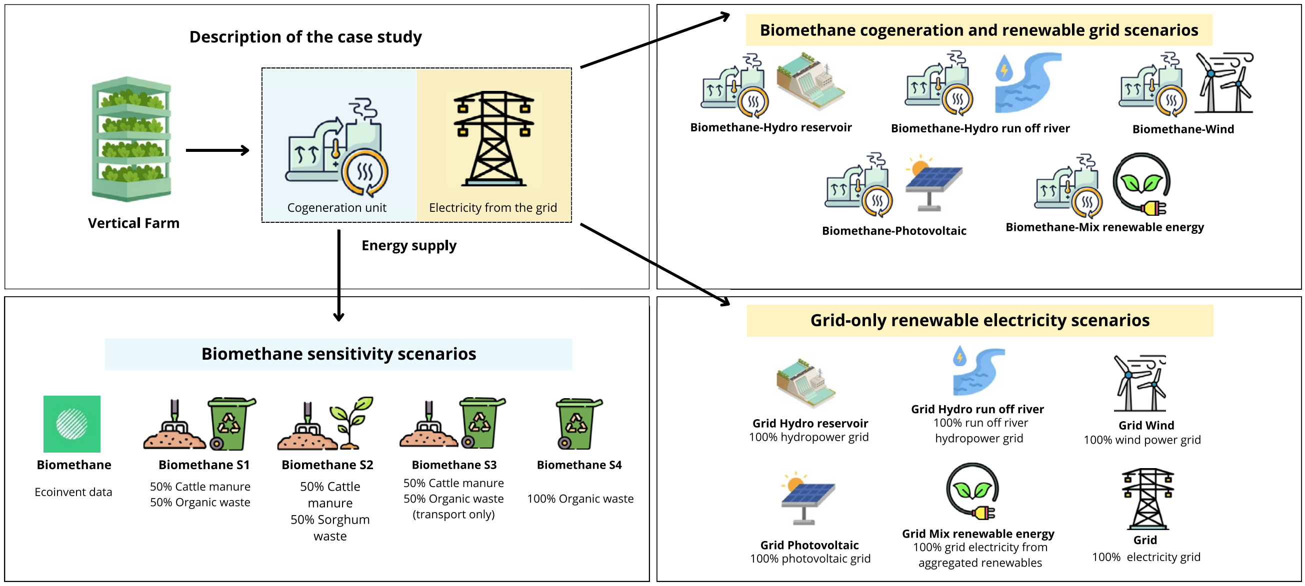

FIGURE 2 | Representation of the case study and the energy scenarios evaluated within the Life Cycle Assessment, including the baseline biomethane CHP configuration, the CHP + renewable grid scenarios, the biomethane feedstock sensitivity scenarios, and the grid-only electricity scenarios.

2.3.1 | Biomethane Cogeneration

The Biomethane scenario reflects current operation, in which the CHP unit is fueled by biomethane and supplemented by electricity from the Italian grid. Biomethane was modeled using the default ecoinvent v3.8 representation. Under this representation, biomethane is assumed to be produced domestically, upgraded and purified, and to leave the purification plant before being directly fed into the high-pressure distribution network. This choice reflects the actual configuration of the case study, as the vertical farm does not produce biomethane onsite but sources it from a nearby company operating in the same regional context. Therefore, the baseline scenario was intended to represent biomethane as supplied to and used by the farm under current operating conditions. Within the attributional scope of this study, cattle manure was treated as a residual feedstock entering the biomethane supply chain; consequently, enteric methane emissions from the originating cattle system were not allocated to the lettuce functional unit. While this configuration includes biomethane production and delivery within the default market-based supply representation, it does not resolve a unique upstream feedstock composition. For this reason, the influence of feedstock origin was assessed separately through sensitivity analysis, in which alternative upstream biomethane production chains were explicitly reconstructed. This scenario aligns with the regulatory framework of the Renewable Energy Directive (RED II, Directive (EU) 2018/2001), under which biomethane is classified as a renewable energy carrier. In Italy, biomethane development is supported by national and European incentive schemes, with a production target of 4 billion m^3 annually by 2026 (Buffi et al. 2024; European Commission 2022).

2.3.2 | Grid

The *Grid* scenario represents the vertical farm operating without cogeneration, powered entirely by the Italian electricity grid. This provides a reference point for evaluating the potential benefits of cogeneration technologies. In 2024, the Italian electricity mix consisted of natural gas (37.6%), oil and petroleum products (35.7%), renewables (18.5%), coal (5.0%), imported electricity (2.5%), and nonrenewable waste (0.8%) (International Energy Agency 2024; Ministero dell'Ambiente e della Sicurezza Energetica (Italian Ministry of Environment and Energy Security) 2023).

2.3.3 | Natural Gas Cogeneration

The *Natural gas* scenario assumes electricity and heat supplied by a CHP unit powered by natural gas, supplemented by electricity from the Italian grid. This was selected as a comparative baseline, reflecting the central role of natural gas in Italy's energy system, where it accounted for more than one-third of total energy supply in 2024 (International Energy Agency 2024).

2.3.4 | Biomethane Sensitivity Scenarios

To capture the variability of biomethane production, four sensitivity scenarios were modeled based on different feedstock compositions for anaerobic digestion. In all these scenarios, the energy demand of the vertical farm is kept constant and only the sourcing of the biogas changes, so that the effect of different feedstock pathways can be isolated without altering the underlying energy values. These reflect realistic conditions in agricultural biogas production and highlight the trade-offs between manure, organic residues, and crop-based pathways (Rana et al. 2016; Valli et al. 2017; Ardolino and Arena 2019). The full set of biomethane configurations is summarized in Table 2.

2.3.5 | Biomethane Cogeneration and Renewable Grid

In these scenarios, the CHP remains in operation (fueled by biomethane), but all electricity purchased from the grid is assumed to be renewable. This reflects procurement practices where companies purchase certified renewable electricity. Five configurations were modeled: hydropower reservoir, hydropower run-of-river, wind power, photovoltaic, and a renewable mix. An overview is provided in Table 3.

2.3.6 | Grid-Only Renewable Electricity Scenarios

Finally, a set of renewable grid-only scenarios was defined and reported in Table 4, in which the CHP is excluded, and the vertical farm is supplied entirely by renewable electricity. These represent fully decarbonized configurations and align with Italy's PNIEC, which forecasts that renewables will cover 65% of electricity consumption by 2030 (International Energy Agency 2024).

TABLE 2 | Biomethane scenarios.

Scenario	Feedstock composition	Energy supply configuration
Biomethane	Average biomethane (Ecoinvent default)	CHP powered by biomethane + Italian grid
Biomethane S1	50% cattle manure +50% organic waste	CHP powered by biomethane + Italian grid
Biomethane S2	50% cattle manure +50% sorghum waste	CHP powered by biomethane + Italian grid
Biomethane S3	50% cattle manure +50% organic waste (transport only)	CHP powered by biomethane + Italian grid
Biomethane S4	100% organic waste	CHP powered by biomethane + Italian grid

Note: Overview of the baseline biomethane scenario and four sensitivity cases (S1–S4) reflecting alternative feedstock mixes for anaerobic digestion. All scenarios include CHP operation and supplementary electricity from the Italian grid.

3 | Results and Analysis

The following sections present the results of the environmental life cycle assessment of lettuce production. The analysis begins with the impacts of the company's actual configuration, that is, cogeneration powered by biomethane supplemented with electricity from the Italian grid, compared with a grid-only reference and a natural gas-based cogeneration scenario. Subsequent sections evaluate the influence of alternative biomethane feedstocks and renewable electricity sourcing.

3.1 | Company and Reference Scenarios

The contribution of various processes to the Biomethane cogeneration scenario is illustrated in Figure 3. Cogeneration is a primary hotspot for climate change, acidification, and freshwater eutrophication, reflecting upstream processes related to biomethane production and supply. Marine eutrophication exhibits contributions from both cogeneration and other consumables, whereas terrestrial ecotoxicity is shared among cogeneration, infrastructure, and transport. Infrastructure dominates abiotic depletion of fossil resources due to the embodied impacts of steel and other construction materials and also contributes to land use. Abiotic depletion of elements is primarily associated with consumables, such as fertilizers and electronic components, which collectively account for the majority of this category. Water use under the Biomethane scenario amounts to 0.93 m^3 deprived per kilogram of edible

TABLE 3 | Biomethane cogeneration with renewable grid electricity.

Scenario	Electricity supply configuration
Biomethane Hydro reservoir	CHP powered by biomethane +100% hydro grid
Biomethane Hydro run off river	CHP powered by biomethane +100% run-of-river hydro grid
Biomethane Wind	CHP powered by biomethane +100% wind grid
Biomethane Photovoltaic	CHP powered by biomethane +100% PV grid
Biomethane Mix renewable energy	CHP fueled by biomethane, grid electricity from aggregated renewables

Note: CHP powered by biomethane supplemented with renewable grid electricity.

TABLE 4 | Grid-only renewable electricity scenarios.

Scenario	Electricity supply configuration
Grid Hydro reservoir	100% hydropower grid supply
Grid Hydro run off river	100% run-of-river hydropower grid
Grid Wind	100% wind power grid supply
Grid Photovoltaic	100% photovoltaic grid supply
Grid Mix renewable energy	Grid electricity from aggregated renewables
Grid	Italian electricity grid (without CHP)

Note: Vertical farm powered exclusively by renewable grid electricity, including a grid reference case.

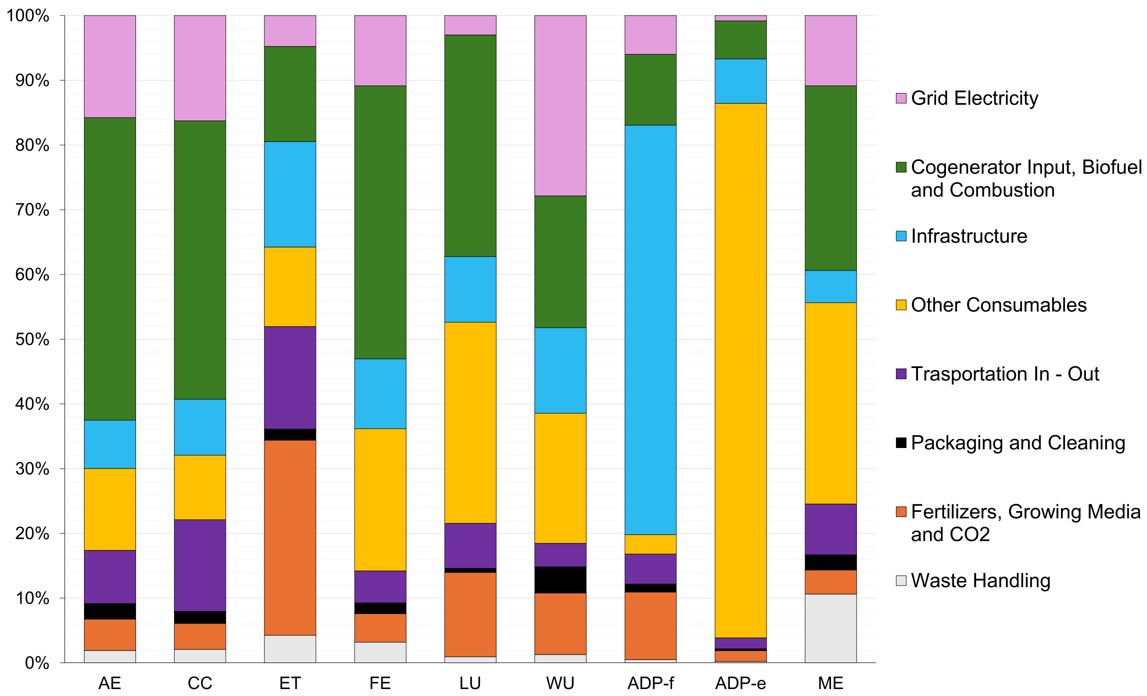

FIGURE 3 | Summary of contribution analysis of different processes and inputs to the cradle-to-grave life cycle impacts of 1 kg of edible lettuce for the Biomethane scenario. ADP-e, Abiotic Depletion Potential—elements, in kg Sb eq; ADP-f, Abiotic Depletion Potential—fossil resources, in MJ of net calorific value; AE, Acidification, in mol H^+ eq; CC, Climate Change, in kg CO_2-eq; ET, Terrestrial Ecotoxicity CTUe; FE, Freshwater Eutrophication, in kg P eq; LU, Land Use, in Pt; ME, Marine Eutrophication, in kg N eq; WU, Water Use, in m^3 deprived. In this graph, some categories are aggregated: Cogenerator includes inputs, biofuel and combustion; Transportation includes both inbound and outbound flows; Packaging and cleaning are grouped together, as are fertilizers, growing media and CO_2; and Waste handling includes waste management processes, farm operations and infrastructure.

lettuce. This is largely associated with energy demand, including both cogeneration and grid electricity. Although the Italian electricity mix contains a relatively modest share of hydropower (approximately 19% in the International Energy Agency 2024), the EF 3.1 method attributes a high-water deprivation factor to hydro-based electricity. As a result, even a limited share of hydropower in the mix leads to significant impacts in the water use category. Land use is mainly influenced by consumables, particularly substrates and fertilizers and, to a lesser extent, fertilizers and infrastructure. Transport processes, both inbound and outbound, significantly contribute to freshwater ecotoxicity, highlighting the role of logistics in peri-urban production systems. Packaging and waste handling remain minor contributors, generally accounting for less than 5%, although they are more pronounced in freshwater and marine eutrophication. As summarized in Table 5, the results show that cogeneration, infrastructure, and consumables are the key processes shaping the environmental performance of the Biomethane scenario across categories beyond climate change.

3.2 | Comparison With Conventional Energy Supply

The contributions of different processes to the climate change impact are reported in Figure 4. Energy supply is scenario-specific: in the Grid configuration it consists only of electricity purchased from the national mix and used on site; in the Natural gas and Biomethane cogeneration configurations it consists of four components: grid electricity purchased for loads not covered by the CHP, fuel/biofuel used in the CHP, on-site combustion in the CHP (stack emissions), and cogenerator inputs. Consistent with these definitions, the three configurations exhibit different emission profiles as summarized in Table 6, with electricity supply having the largest contribution across all scenarios. The Natural gas cogeneration scenario has the highest impact, with 6.16 kg CO_2 eq per kg of lettuce. The dominant contribution comes from combustion, followed by upstream fuel supply. The Grid scenario, supplied entirely by the Italian electricity mix, results in a slightly lower footprint of 6.06 kg CO_2 eq per kg, with electricity use accounting for almost 80% of the total. The Biomethane cogeneration scenario, which reflects the current configuration at the case study, achieves a footprint of 3.02 kg CO_2 eq per kg. This corresponds to a 51% reduction compared with the natural gas scenario and nearly a 50% reduction compared with the grid scenario. In this case, the main contribution is associated with biofuel supply, while the impact from combustion is nearly negligible.

3.3 | Environmental Trade-Offs

The comparative assessment using the Biomethane scenario as baseline highlights differentiated responses across the impact categories, as illustrated in Table 6. As shown above, Biomethane achieves the lowest climate change values, whereas both Natural gas and Grid scenarios exceed it by more than a

TABLE 5 | Contribution of inputs and processes to the impacts of producing 1 kg of edible lettuce for the Biomethane Lettuce scenario.

	AE	CC	ET	FE	LU	WU	ADP-f	ADP-e	ME
	mol H+ eq	kg CO_2 eq	CTUe	kg P eq	dimensionless	m3 depriv.	MJ. net calorific value	kg Sb eq	kg N eq
Growing Media	6.40E-05	1.80E-02	4.31E+00	2.24E-06	1.32E-01	4.38E-02	1.25E+01	8.51E-08	2.34E-05
Fertilizer	2.81E-04	3.13E-02	1.47E+00	8.28E-06	4.82E+00	2.56E-02	3.91E-01	8.83E-07	3.48E-05
Other Consumables	1.40E-03	3.00E-01	2.44E+00	1.56E-04	1.22E+01	1.86E-01	3.90E+00	8.95E-05	8.40E-04
Cleaning/Protection	9.66E-05	1.43E-02	2.35E-01	4.80E-06	1.87E-01	2.39E-02	2.22E-01	1.68E-07	3.11E-05
Cogenerator input-Biofuel-Combustion	5.18E-03	1.30E+00	2.92E+00	2.99E-04	1.34E+01	1.89E-01	1.43E+01	6.37E-06	7.71E-04
Other (CO2)	1.91E-04	7.17E-02	2.06E-01	2.07E-05	1.71E-01	1.86E-02	7.48E-01	8.16E-07	4.25E-05
Packaging	1.72E-04	4.18E-02	1.10E-01	7.09E-06	5.58E-02	1.37E-02	1.39E+00	1.65E-07	3.27E-05
Energy	1.75E-03	4.90E-01	9.47E-01	7.70E-05	1.17E+00	2.58E-01	7.82E+00	8.90E-07	2.93E-04
Transportation-In	7.42E-04	3.48E-01	2.55E+00	2.83E-05	2.27E+00	2.72E-02	4.94E+00	1.46E-06	1.74E-04
Transportation-Out	1.68E-04	7.94E-02	5.90E-01	6.71E-06	4.63E-01	6.38E-03	1.12E+00	3.55E-07	3.85E-05
Waste Handling-Farm	1.24E-04	3.17E-02	6.81E-01	1.77E-05	1.28E-01	4.05E-03	3.37E-01	1.23E-07	2.52E-04
Waste Handling-EOL Product	7.20E-05	2.62E-02	1.38E-01	4.14E-06	1.83E-01	6.80E-03	2.66E-01	9.37E-08	2.95E-05
Maintenance	3.53E-07	3.53E-07	7.59E-08	1.53E-08	3.62E-06	4.62E-07	9.47E-05	1.00E-09	1.53E-08
Infrastructure	8.23E-04	2.60E-01	3.24E+00	7.64E-05	3.98E+00	1.22E-01	8.27E+01	7.43E-06	1.35E-04
Waste Handling-EOL (Infrastructure)	1.53E-05	4.63E-03	2.44E-02	8.03E-07	5.18E-02	1.04E-03	5.48E-02	2.38E-08	5.91E-06
Total	**1.11E-02**	**3.02E+00**	**1.99E+01**	**7.09E-04**	**3.92E+01**	**9.25E-01**	**1.31E+02**	**1.08E-04**	**2.70E-03**

Note: Bold values indicate refer to the total for each impact category.
Abbreviations: ADP-e, Abiotic Depletion Potential—elements, in kg Sb eq; ADP-f, Abiotic Depletion Potential—fossil resources, in MJ of net calorific value; AE, Acidification, in mol H^+ eq; CC, Climate Change, in kg CO_2 eq; ET, Terrestrial Ecotoxicity CTUe; FE, Freshwater Eutrophication, in kg P eq; LU, Land Use, in Pt; ME, Marine Eutrophication, in kg N eq; WU, Water Use, in m^3 deprived.

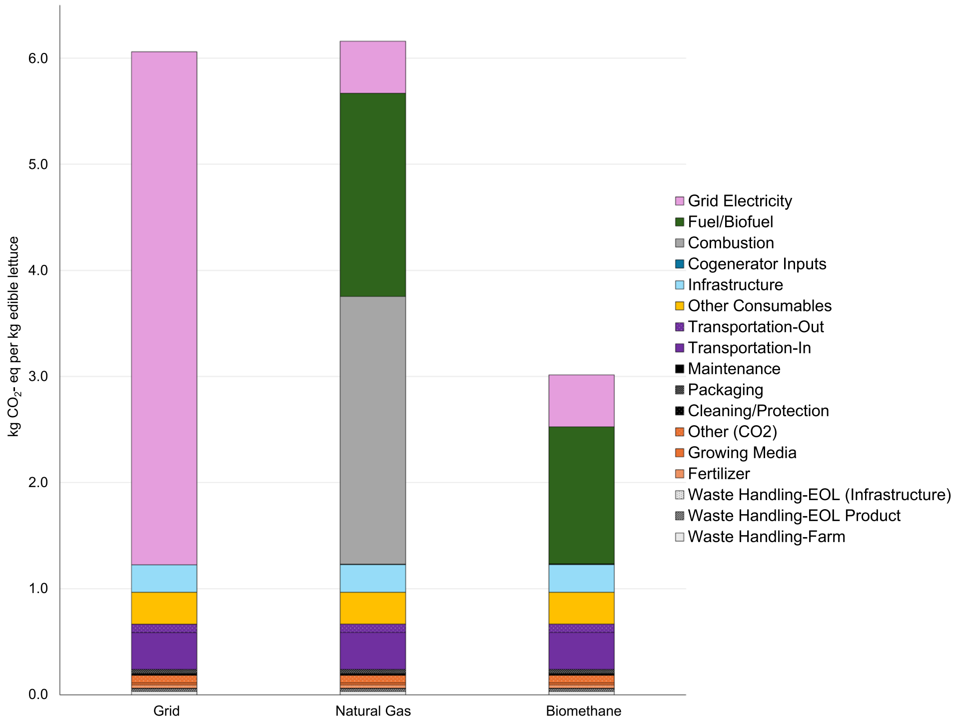

FIGURE 4 | Climate change impact of 1 kg of edible lettuce under three scenarios (Grid, Natural gas cogeneration, Biomethane cogeneration), disaggregated by life cycle stage.

TABLE 6 | Environmental impacts of the Biomethane, Natural Gas, and Grid scenarios.

	AE	CC	ET	FE	LU	WU	ADP-f	ADP-e	ME
Biomethane	100%	100%	100%	100%	100%	100%	100%	100%	100%
Natural Gas	89%	204%	85%	71%	70%	97%	170%	96%	114%
Grid	193%	201%	127%	154%	92%	326%	142%	101%	168%

Abbreviations: ADP-e, Abiotic Depletion Potential—elements, in kg Sb eq; ADP-f, Abiotic Depletion Potential—fossil resources, in MJ of net calorific value; AE, Acidification, in mol H^+ eq; CC, Climate Change , in kg CO_2 eq; ET, Terrestrial Ecotoxicity CTUe; FE, Freshwater Eutrophication, in kg P eq; LU, Land Use, in Pt; ME, Marine Eutrophication, in kg N eq; WU, Water Use, in m^3 deprived.

factor of two. However, this advantage does not extend uniformly to other categories. The acidification potential and freshwater eutrophication are moderately higher for biomethane than for natural gas, although still below the levels observed in the Grid configuration. The most significant distinction is observed in terrestrial ecotoxicity, which records lower values than Biomethane, while the Grid shows higher impacts, likely reflecting upstream burdens associated with the electricity mix. Land use is higher in the biomethane case, reflecting the influence of additional infrastructure and substrate requirements. Water use exhibits a distinct pattern: the Grid scenario is dominant, with values more than three times higher than those of Biomethane, while Natural gas is closer to the reference case.

3.4 | Comparative Environmental Performance: Sensitivity of Biomethane Scenarios' Carbon Footprint to Feedstock Selection

The findings from the life cycle assessment of various biomethane production scenarios reveal significant variability in the associated climate change impacts, primarily influenced by the type and origin of feedstock used for biogas generation. As illustrated in Figure 5, the quantified climate change impacts range from 3.02 to 6.44 kg CO_2-eq per kg of edible lettuce. The baseline biomethane scenario, modeled using life cycle inventory data from the Ecoinvent database, representing average European anaerobic digestion and biogas upgrading conditions, yields the lowest total emissions at 3.02 kg CO_2-eq per kg. Scenario 1, which combines 50% manure and 50% organic waste, records the highest impact at 6.44 kg CO_2-eq per kg, more than double the baseline. This increase is primarily attributed to the biofuel stage, where emissions rise substantially due to the higher methane emission potential of untreated manure and the additional burdens associated with organic waste handling. Scenario 2, using 50% manure and 50% sorghum residues, yields 3.43 kg CO_2-eq per kg, closer to the baseline thanks to the higher methane yield efficiency of sorghum. Scenarios 3 and 4 yield intermediate values, at 4.55 and 4.28 kg CO_2-eq per kg, respectively, reflecting the influence of transport and waste-stream characteristics. Feedstock composition also affected impact categories beyond climate change. Freshwater ecotoxicity increased from 1.99E+01 CTUe per kg in the baseline to 2.63E+01 CTUe per kg in Scenario 3, with all feedstock configurations exceeding the

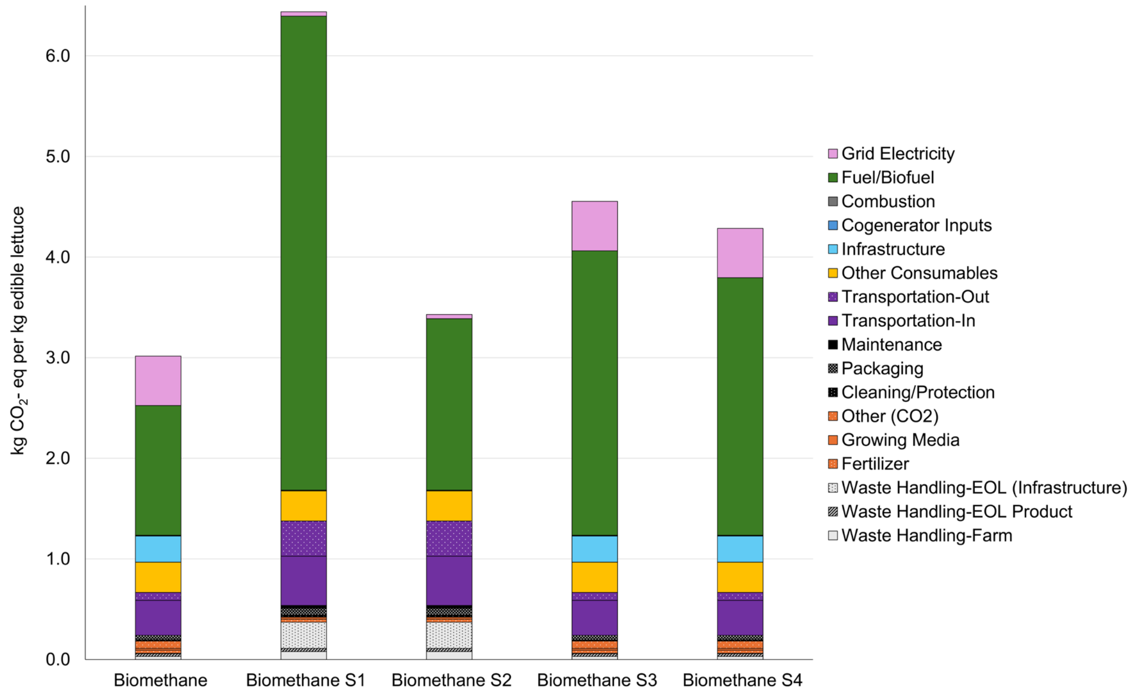

FIGURE 5 | Climate change impact (kg CO_2-eq per kg of edible lettuce) for the different biomethane scenarios, disaggregated by categories. Scenario codes: S0 = Baseline biomethane (average EU anaerobic digestion + upgrading, Ecoinvent); S1 = 50% manure + 50% organic waste; S2 = 50% manure + 50% sorghum residues; S3 = as S1 with transport burdens varied only; S4 = 100% organic waste. Functional unit: 1 kg edible lettuce.

baseline value. Freshwater eutrophication was highest under Scenario 4, reaching 1.35E-03 kg P-eq per kg, while marine eutrophication followed a similar pattern, peaking at 3.88E-03 kg N-eq per kg. Land use was also highest in Scenario 3, at 4.33E+01 dimensionless per kg. By contrast, Scenarios 1 and 2 remained comparatively close to the baseline across these categories.

3.5 | Comparative Environmental Performance: Sensitivity of Biomethane Cogeneration Scenarios to Renewable Electricity Sourcing

In this set of scenarios, the Italian grid mix was replaced with various renewable electricity sources, while maintaining a cogeneration system based on biomethane. The aim was to assess the extent to which renewable electricity procurement could influence the overall climate change impact of edible lettuce production. As shown in Figure 6, the climate-change impact associated with producing 1 kg of edible lettuce under biomethane-fueled cogeneration is evaluated across renewable electricity options (hydro reservoir, run-of-river hydro, wind, photovoltaic, and other renewables). The results suggest that all configurations cluster in a narrow range between 2.53 and 2.62 kg CO_2-eq per kg. The lowest value corresponds to the hydro reservoir and run-of-river options (2.53 kg CO_2-eq per kg), while photovoltaic reaches the upper bound (2.62 kg CO_2-eq per kg). Wind (2.55 kg CO_2-eq per kg) and the renewable energy mix (2.54 kg CO_2-eq per kg) are placed in between. The limited spread of results confirms that the dominant hotspot for the scenarios is related to the energy produced from cogeneration, with renewable electricity supply providing only marginal differences, as electricity from the grid is only supplemental. Nonetheless, the comparison shows that replacing the Italian grid mix with renewables reduces the sensitivity of results to electricity sourcing and contributes to lowering the carbon footprint relative to fossil-based scenarios. Across impact categories other than climate change, variation among renewable electricity configurations was generally limited. Freshwater ecotoxicity ranged from 1.89E+01 to 1.97E+01 CTUe per kg, with the photovoltaic configuration recording the highest value. Water use ranged from 6.98E-01 to 1.47E+00 m^3 per kg. Land use was highest under the photovoltaic configuration, at 5.17E+01 dimensionless per kg, compared with 3.80E+01–3.86E+01 dimensionless per kg for the hydropower- and wind-based alternatives.

3.6 | Comparative Environmental Performance: Sensitivity of Grid-Only Scenarios to Renewable Electricity Sourcing

In a further set of scenarios, the cogeneration unit was excluded and the electricity required for the vertical farm was assumed to be supplied entirely by renewable electricity from the national grid. Figure 7.

Climate change impacts range from 1.38 to 2.04 kg CO_2-eq per kg of edible lettuce, substantially lower than results for the Italian grid reference (6.06 kg CO_2-eq per kg). The lowest value is obtained for the mixed renewable case (1.38 kg CO_2-eq per kg), wind and photovoltaic configurations both report values around 1.46 kg CO_2-eq per kg, while hydropower-based supply results in slightly higher values, 2.04 kg CO_2-eq per kg for reservoir plants and 2.01 kg CO_2-eq per kg for run-of-river plants. These renewable scenarios were defined using country-specific datasets from Ecoinvent for Italy, which model grid-connected electricity

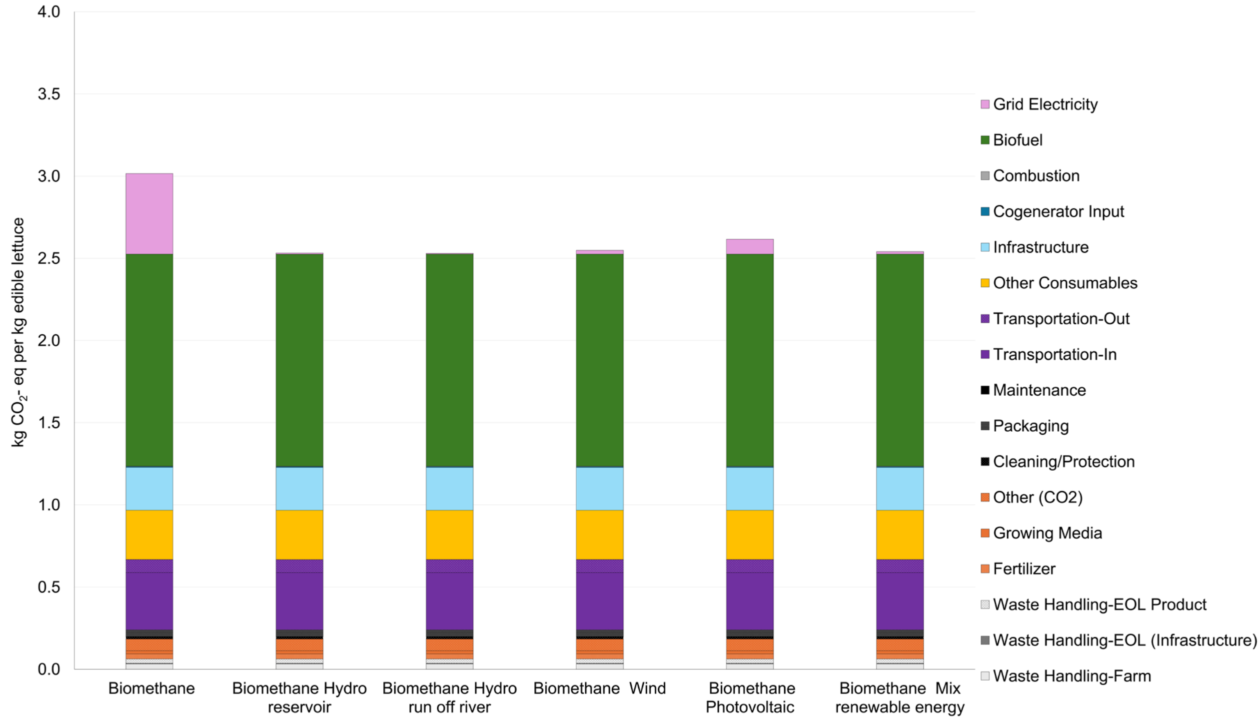

FIGURE 6 | Climate change impact of 1 kg of edible lettuce under biomethane cogeneration with renewable electricity supply (biomethane baseline, hydro reservoir, hydro run-of-river, wind, photovoltaic, and a renewable mix).

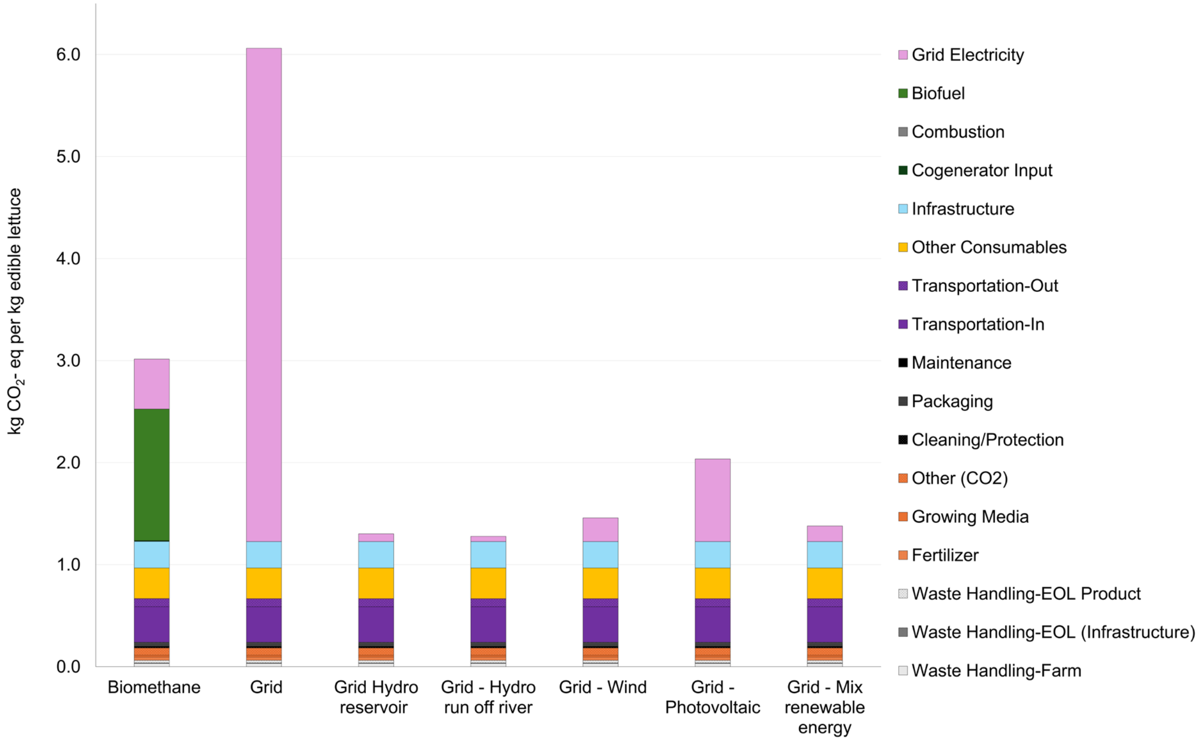

FIGURE 7 | Climate change impact of 1 kg of edible lettuce for grid-only renewable electricity configurations (hydro reservoir, hydro run-of-river, wind, photovoltaic, and mixed renewables), compared with the Biomethane baseline and Italian grid mix.

generation for photovoltaic (ground-mounted multi-Si modules), wind (onshore, 2 MW turbines), and hydropower (reservoir and run-of-river). The choice of technologies reflects their actual contribution to the Italian renewable electricity mix, where in 2023 hydropower represented 40.4%, photovoltaic 30.7%, and wind 23.3% of total renewable electricity generation (Ministero dell'Ambiente e della Sicurezza Energetica (Italian Ministry of Environment and Energy Security) 2023). Grid-only renewable configurations achieve a reduction of over 70% compared to the Italian grid mix, highlighting the significant potential of decarbonized electricity sourcing for vertical farming. For impact categories other than climate change, grid-only renewable configurations generally recorded lower values than the Italian grid reference across several indicators. Freshwater ecotoxicity ranged from 1.89E+01 to 1.97E+01 CTUe per kg across renewable configurations, compared with 2.53E+01 CTUe per kg under the conventional grid. Fossil resource depletion decreased from 1.86E+02 MJ per kg under the Italian grid to values comparable to the biomethane baseline, and water use similarly declined relative to the conventional grid reference (3.02E+00 m^3 per kg). Mineral resource depletion changed only marginally across electricity sourcing configurations, whereas land use remained more sensitive to the choice of renewable source, with higher values under the photovoltaic configuration.

4 | Discussion

The following sections provide further discussion of the results in relation to other studies, the limitations and sensitivity of the modeling, and potential improvements and suggestions for future research, while also highlighting the main challenges associated with policy implications.

4.1 | Product Environmental Impact

4.1.1 | Literature Benchmarking and Energy Context

The results indicate that the case study vertical farm has a climate change impact of 3.02 kg CO_2-eq per kilogram of edible lettuce under the biomethane-powered cogeneration scenario, which reflects the farm's current configuration. This value is substantially lower than the nonrenewable energy scenarios, where impacts reach 6.16 kg CO_2-eq per kg in the natural gas cogeneration case and 6.06 kg CO_2-eq per kg under the Italian grid mix. When compared with the literature, the climate change impacts are within the observed range of other large-scale VF and GH systems but remain positioned toward the upper end (Martin et al. 2023; Pennisi et al. 2025). Environmental performance in vertical farming systems is known to exhibit wide variability, with Pennisi et al. (2025) reporting average values of 2.87 kg CO_2-eq per kilogram of edible lettuce (median: 0.83 kg CO_2-eq per kg edible lettuce; $n = 121$) for VF and 2.38 kg CO_2-eq per kg edible lettuce (median: 1.98 kg CO_2-eq per kg edible lettuce; $n = 36$). This variability across case studies is strongly driven by technological choices and by local energy contexts, which determine whether vertical farms align with low- or high-carbon production systems (Casey et al. 2022; Martin et al. 2023; Pennisi et al. 2025). In Italy, the national energy context remains heavily reliant on fossil fuels, with natural gas accounting for approximately 40% of the total energy supply and oil products for 36%, while biofuels and waste contribute only 11% (International Energy Agency 2024). This dependence on fossil sources is reflected in the high climate impacts observed under the Italian grid scenario. By contrast, domestic energy production shows a different structure, with biofuels and waste representing roughly 36%, and solar, wind, and other renewables contributing around 30% (International Energy Agency 2024). Situating the vertical farm within this national context highlights the potential and necessity of integrating renewable energy procurement to further reduce the climate footprint of vertical farming.

4.1.2 | Fuel-Type Effects on Impact Categories

In the Biomethane scenario, climate change impacts were reduced by approximately 51% compared to natural gas. Indeed, the combustion of natural gas is a primary contributor, with 2.52 kg CO_2-eq per kg. This correlates with the direct release of fossil carbon during combustion, consistent with the emission factor of 53.06 kg CO_2 per MMBtu for natural gas, as reported by the Intergovernmental Panel on Climate Change (IPCC 2025). In the Biomethane scenario, emissions from combustion are minimal (0.003 kg CO_2-eq per kg), as the released carbon dioxide is of biogenic origin. As stated in Annex II of the IPCC Fifth Assessment Report (Krey et al. 2014), biogenic CO_2 is generally excluded from the climate change impact category in life cycle assessment, since it is assumed to be reabsorbed during biomass regrowth over short timeframes. This methodological approach accounts for a significant share of the observed difference in total emissions between the two scenarios. Upstream emissions related to fuel production and supply also differ substantially. In the Natural Gas scenario, these contribute to a measure of 1.92 kg CO_2-eq per kg, reflecting the energy intensity of extraction and refining, long-distance transport, and fugitive methane emissions. In the Biomethane scenario, upstream emissions are lower (1.29 kg CO_2-eq per kg), although not negligible. These impacts are mainly related to the energy required for gas upgrading, the handling of digestate, and methane slip during purification. According to Ardolino et al. (2021), air emissions during the upgrading phase are primarily linked to the efficiency of biogenic CO_2 removal and methane losses from the residual gas stream. Yet, the biofuel production remained a critical contributor, reflecting upstream processes such as anaerobic digestion, digestate management, and upgrading (Ardolino and Arena 2019; Rana et al. 2016). These stages also explain the higher burdens recorded for acidification potential and freshwater eutrophication compared with natural gas, consistent with findings by Valli et al. (2017), who documented nutrient-rich digestate flows as a key driver of eutrophication in biogas systems. Although central to the circular energy model, the cogeneration input remains the dominant hotspot across multiple categories, reflecting both direct emissions and upstream burdens. Electricity consumption, primarily driven by LED lighting and HVAC systems, continues to play a key role in water use and fossil resource depletion. This pattern is consistent with prior studies on vertical farming systems, which highlight the important influence of energy demand on environmental performance (Casey et al. 2022; Stanghellini and Katzin 2024; Martin et al. 2023). For terrestrial ecotoxicity, both natural gas and biomethane cogeneration scenarios showed higher impacts than the grid scenario, indicating the combined effects of methane slip, nutrient losses, and infrastructure requirements. This trend aligns with previous Italian LCA studies of biogas supply chains, which also reported elevated ecotoxicity categories (Fusi et al. 2016). Conversely, the grid scenario was dominant in water use, due to the EF 3.1 characterization of hydro-based electricity. Although hydropower accounts for only about 19% of Italy's electricity mix (International Energy Agency 2024), its high-water deprivation factor results in comparatively elevated burdens in this category. Infrastructure also emerged as a structural hotspot across categories. In particular, it accounted for over 60% of fossil resource depletion and nearly 70% of mineral depletion, reflecting the steel- and electronics-intensive nature of vertical farm construction. This is consistent with findings by (Sari and Sopha 2023), who showed that infrastructure and cultivation equipment can dominate mineral resource depletion in vertical farming systems, contributing up to 92% of total burdens.

4.2 | Energy Supply Alternatives

4.2.1 | Biomethane Feedstock Sensitivity

The comparative assessment of biomethane feedstock scenarios revealed a marked variability in climate change impacts, ranging from 3.02 to 6.44 kg CO_2-eq per kg of edible lettuce. The baseline scenario achieved the lowest footprint. This result should not be read as evidence that all biomethane pathways are intrinsically low-impact. Rather, it reflects the baseline as the reference representation of the farm's current biomethane procurement, whereas the sensitivity scenarios explicitly address alternative upstream feedstock pathways and their associated burdens. This is confirmed by the biofuel contribution, which is lowest in the baseline scenario (1.29 kg CO_2-eq per kg edible lettuce) and increases substantially when specific feedstock chains are modeled in greater detail, reaching 4.71 kg CO_2-eq per kg edible lettuce in Scenario 1. In this sense, the baseline acts as the lowest-burden reference within the biomethane family, while the sensitivity scenarios show how strongly climate change performance can deteriorate when manure-rich or waste-intensive pathways are introduced. These results should be interpreted within the attributional system boundary adopted in this study, in which manure enters the biomethane chain as a residual feedstock and enteric methane emissions from the livestock system are not allocated to the lettuce functional unit. The contrast between Scenarios 1 and 2 further confirms that feedstock composition is a key determinant of results, as the use of sorghum residues reduced both the feedstock requirement and the associated digestate burdens compared with the manure–organic waste configuration. The highest impact was recorded in Scenario 1, with a 50:50 mixture of cattle manure and organic waste, with 6.44 kg CO_2-eq per kg, corresponding to a 113% increase compared to the baseline. Emissions from the biofuel stage increased from 1.29 to 4.71 kg CO_2-eq per kg, driven by the high methane emission potential of untreated manure during storage and handling, as well as the additional burdens associated with biowaste management. Ravina and Genon (2015) demonstrated that climate benefits depend critically on methane slip, with systems remaining beneficial only when losses are limited to 0.05%, while a slip of 4% renders them unsustainable. It should be noted that among currently available upgrading technologies, chemical absorption with amine solvents can achieve methane slip values as low as 0.04%, which falls below this critical threshold (Ardolino et al. 2021), whereas water scrubbing and pressure swing adsorption typically show higher slip values of 1%–2% and 1.8%–2%, respectively. This further reinforces the critical importance of stringent process monitoring and continuous minimization of methane losses in biomethane-based cogeneration systems. The comparison between Scenario 1 and Scenario 2 highlights the importance of selecting the appropriate co-substrate. Although both scenarios incorporated 50% cattle manure, Scenario 2, which used sorghum residues as the complementary feedstock, resulted in 3.43 kg CO_2-eq per kg, only 13.6% higher than the baseline. This improvement is explained by the higher biochemical methane potential of sorghum residues, which enabled the same biomethane output with 73% less feedstock. Digestate generation was consequently reduced by 75%, lowering downstream burdens associated with transport, storage, and field application. These findings are consistent with de Rojas et al. (2025), who demonstrated that co-digestion with agro-residues enhances methane yields, balances nutrient ratios, and improves process stability. Intermediate results were observed for Scenarios 3 and 4, both of which were significantly lower than Scenario 1 but still 42%–50% above the baseline, reflecting the heterogeneity of waste streams and the importance of collection and treatment logistics.

4.2.2 | Sensitivity to Renewable Electricity Configurations

When the Italian grid mix was replaced with renewable electricity while maintaining biomethane cogeneration, impacts ranged narrowly from 2.53 to 2.62 kg CO_2-eq per kg. The limited spread indicates that the biofuel stage remained the primary focus, and that renewable procurement under CHP has only a minor impact on overall results. Excluding cogeneration and relying entirely on renewable electricity achieved the greatest reductions, with values more than 70% lower than the Italian grid baseline. Comparable trends were identified by Blom et al. (2022) and by Joensuu et al. (2024), who demonstrated that sourcing renewable electricity results in significant performance improvements. Pennisi et al. (2025) further showed that some low-carbon vertical farming configurations can approach the range reported for high-tech greenhouses, although both systems remain highly context-dependent and greenhouse systems can also be substantially improved through low-carbon energy supply. This study demonstrates that methane slip control, digestate management, and co-substrate selection are crucial for mitigating the burdens of biomethane-based systems, while renewable electricity procurement is essential in fully electric configurations. In CHP scenarios, upstream biofuel processes dominate regardless of electricity sourcing, whereas grid-only renewables achieve the largest reductions and shift the hotspot almost entirely to electricity demand. This evidence is consistent with previous studies identifying energy sourcing as the primary driver of vertical farming performance (Benis et al. 2017b; Li et al. 2020) and stressing the necessity of coupling decarbonised electricity with efficiency improvements in energy use (Blom et al. 2022; Martin et al. 2019; Romeo et al. 2018).

4.3 | RED II-Based Sustainability Indicators: Methodological and Policy Implications

The assessment of biomethane use in the cogeneration system also required a regulatory interpretation consistent with the certification framework applied to the energy supply. For this reason, the climate change impact of the certified biomethane was additionally evaluated following the Renewable Energy Directive (RED II, Directive (EU) 2018/2001) methodology.

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \tag{1}$$

The RED II expresses the total impact in g CO_2-eq MJ^{-1} of the fuel, calculated as shown in Equation (1), where the direct emission components correspond to cultivation (E_{EC}), processing (E_P), transport and distribution (E_{TD}), and combustion (E_U). Certified deduction terms, such as credits for emission savings from soil carbon accumulation via improved agricultural management (E_{SCA}), carbon capture and storage (E_{CCS}), carbon capture and replacement (E_{CCR}), and excess electricity export (E_{EE}) can then be subtracted when evidence is provided under an approved voluntary scheme (Buffi et al. 2024; European Commission 2018). The objective of this calculation is regulatory rather than analytical; it serves to verify whether a biofuel or biogas pathway meets the minimum CC-reduction thresholds (typically 65%–80%) required for market eligibility within the European Union. In contrast, attributional LCA, as outlined in ISO 14040/44 (ISO 14040:2006, ISO 14044:2006), aims to quantify the overall environmental performance of a system across multiple impact categories, without relying on preset default values or policy-driven boundaries (Fabiani and Bonati 2019). In the context of this work, applying the RED II framework allows a direct comparison between policy-driven carbon accounting and the attributional LCA approach used for environmental impact evaluation. While the two methodologies share the objective of quantifying greenhouse-gas performance, they differ substantially in scope and boundary definition. RED II focuses on compliance with regulated thresholds through simplified and standardized assumptions, whereas ISO-based LCA aims to comprehensively quantify all life-cycle impacts across multiple environmental categories, without policy-driven cut-offs.

In this study, the RED II calculation was applied to the biomethane supplied by "Energia Verde Truccazzano," which is documented under the International Sustainability and Carbon Certification (ISCC) voluntary scheme and used in the facility's combined heat and power unit. Two alternative configurations were analyzed to reflect the real operational setup of the vertical farming system: one excluding and one hypothetically including the certified E_{SCA} credit for avoided methane emissions from upstream manure management. If the certified E_{SCA} value of $-90.2\,g\,CO_2\text{-eq}\,MJ^{-1}$ were included according to RED II rules, the resulting climate change impact of the system would be reversed, shifting from a positive to a markedly negative balance. Because all other life-cycle contributions remain constant, this inversion would depend solely on the accounting of certified avoided emissions. Such a result would comply with RED II rules but would not align with attributional LCA principles, since avoided upstream emissions represent consequential effects rather than direct system outputs (Brandão et al. 2022). To prevent misinterpretation by secondary users, we emphasize that a negative RED II value for certified biomethane is a fuel-level compliance result obtained by applying certified credits to the per-MJ greenhouse gas intensity of the fuel against a regulatory baseline. It is not a product-level outcome and consequently should not be extrapolated. The product LCA employs a per kg functional unit and cradle-to-grave boundaries that encompass nonenergy processes, including cultivation inputs, packaging, logistics, and infrastructure, which are outside the scope of RED II. Additionally, E_{SCA} credits represent avoided methane in upstream manure management; these avoided emissions do not occur within the lettuce system and would only be attributed under a consequential framework with explicit system expansion, which is not adopted here.

This methodological divergence reveals a fundamental tension between regulatory and scientific approaches. RED II offers a transparent and standardized framework for verifying CC-reduction compliance, but it simplifies system boundaries and overlooks broader environmental dimensions such as eutrophication, water depletion, or ecotoxicity (Calero et al. 2023; Fabiani and Bonati 2019; Lehtoranta et al. 2024). Therefore, while RED II results are informative in policy and certification contexts, they should not be directly incorporated into multi-indicator LCA frameworks without appropriate methodological alignment.

5 | Conclusion

This study applied a cradle-to-grave life cycle assessment to a large-scale vertical farm in Lombardia region, Italy, using 1 kg of edible lettuce as the functional unit. The analysis shows that energy configuration is the principal determinant of environmental performance. Under biomethane cogeneration, the climate change impact was 3.02 kg CO_2-eq per kg of edible lettuce, whereas procurement of renewable electricity without cogeneration reduced the value to 1.38 kg CO_2-eq per kg. Electricity use for lighting and climate control was the dominant hotspot across scenarios, with cogeneration operation further shaping results; infrastructure contributed substantially to mineral and fossil resource use due to material- and energy-intensive components. These findings are consistent with previous evidence and confirm that energy sourcing and system design largely determine outcomes in indoor vertical farming.

Sensitivity analysis revealed that the selection of biomethane feedstock has a large influence on performance, with blends based on organic residues and sorghum performing better than those based on livestock manure. Using locally available residual materials for biomethane can enhance resilience by reducing dependence on fossil natural gas and grid electricity while supporting waste valorization and nutrient recycling. Beyond energy, targeted improvements in infrastructure design, procurement, and end-of-life management are needed to limit resource-use burdens.

A supplementary assessment, using the methodology of Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (Renewable Energy Directive II), provided an additional perspective on certified biomethane performance but highlighted methodological inconsistencies. Policy indicators developed for compliance and communication are not directly comparable with attributional life cycle results because of differences in system boundaries, allocation, and impact coverage. Integrating such metrics, therefore, requires careful interpretation to avoid misleading conclusions.

Overall, the results indicate that cogeneration with residue-based biomethane lowers climate-change impact relative to fossil comparators, and that verified low-carbon electricity procurement delivers the largest improvement among the options evaluated. A practical pathway for sustainable production and consumption in Mediterranean contexts is to prioritize direct electrification with certified low-carbon supply where feasible; where cogeneration is used, to pair residue-based biomethane with stringent control of methane losses and robust digestate management; and, in parallel, to reduce infrastructure-related burdens through design optimization, responsible sourcing, and appropriate end-of-life strategies. Although this work reports primary data from a single commercial facility, further studies across multiple sites and crop portfolios in the Mediterranean region would help test the breadth of applicability. Future research should also track operational changes over time, incorporate temporally resolved and marginal electricity modeling, assess technical and economic feasibility, and explore ways to align attributional life-cycle assessment with policy metrics to support consistent and decision-useful evaluations. Beyond energy sourcing, reducing the intrinsic energy intensity of vertical farming through advances in LED efficiency, dynamic climate control, and system design optimization remains a critical priority, particularly when benchmarking VF against high-tech greenhouse systems that can exploit natural daylight and passive ventilation in many climate zones (Stanghellini and Katzin 2024).

Author Contributions

T.P.: writing – original draft, data analysis and curation, writing – review and editing, investigation, conceptualization. V.A.-P.: writing – review and editing, data analysis, supervision. G.P.: writing – review and editing. G.G.: writing – review and editing. M.M.: writing – review and editing, methodology, supervision, funding acquisition, conceptualization. F.O.: writing – review and editing, supervision, funding acquisition, conceptualization.

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Conflicts of Interest

The present manuscript contains information stemming from a consultancy activity between the University of Bologna (UNIBO), through the Department of Agricultural Sciences and Technologies, as well as IVL and a Contractor operating in the field of commercial vertical farming on the basis of the elaboration of an environmental assessment of leafy green production. The relationship and grounds of collaboration are based on the activity of consulting from the involved researcher institutions in the matters of life cycle analysis for plant production. The results have not been modified to benefit the businesses' interests. Since this business does not want to disclose any information including its name or exact location, no mention has been made in the present manuscript and declaration.

Data Availability Statement

The data that support the findings of this study are available from the contractor operating the commercial vertical farm. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the contractor operating the commercial vertical farm.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** fes370234-sup-0001-Supinfo.xlsx.