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Towards Life Cycle Assessment and Techno-Economic Analysis of Vertical Farming: Integrating Municipal Wastewater Treatment with Nutrient Recovery and Direct Air Capture[#]

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ABSTRACT

Indoor vertical farming (IVF) offers promising solutions for urban food security but still faces challenges in resource efficiency and economic viability. This study develops a preliminary LCA-TEA framework to evaluate two scenarios for lettuce production in a Swedish urban environment: (1) conventional vertical farming with municipal water and mineral/synthetic fertilizer, and (2) an integrated IVF system coupling wastewater nutrient recovery with Direct Air Capture (DAC)[1] for CO_2 fertilization.

The conventional IVF shows considerable environmental impacts resulting from high energy consumption of LED lighting, water use, and synthetic fertilizer production. Regardless of Sweden's low-carbon electricity grid, the high energy intensity remains the main challenge to achieve economic viability. The integrated IVF system aims to transform the conventional linear model into a circular one, where municipal wastewater undergoes advanced treatment to recover N and P, while a modular DAC unit captures atmospheric CO_2 that is delivered to crops.

The literature review indicates that such an integrated approach could substantially reduce freshwater consumption, eliminate synthetic fertilizer requirements, and enable potential carbon-negative production through atmospheric CO_2 removal. Economic benefits may arise from avoided input costs and potential revenue including water treatment services and eventually carbon credits. Sensitivity analysis can further explore critical parameters such as electricity prices, nutrient recovery efficiency, and CO_2 recovery efficiency.

In addition, we link the framework to energy resilience, referring to the ability to sustain production during periods of electricity price volatility and interruptions. This is achieved by considering demand flexibility, on-site storage and backup systems, and a substituted CO_2 supply via DAC.

Overall, the work demonstrates that there are promising conditions for developing integrated IVF systems that represent the water-energy-food-carbon nexus which could enhance sustainability and resilience in urban environment and better align with Sweden's 2045 climate policy goals.

Keywords: vertical farming, nutrient recovery, direct air capture, CO_2 fertilization, Life Cycle Assessment, Techno-Economic Analysis.

energy resilience

NOMENCLATURE

Abbreviations	
AS	Air stripping
BACF	Biological activated carbon filtration
CDR	Carbon dioxide removal
COP	Coefficient of performance for cooling/dehumidification
DLI	Day light integral
EBCT	Empty bed contact time
EF	Environmental footprint
ELCD	European Reference Life Cycle Database
FU	Functional unit
FW	Fresh weight
GH	Greenhouse
GWP	Global warming potential
HVAC	Heating, ventilation and air conditioning
IVF	Indoor vertical farming
LCA	Life-cycle assessment
LCIA	Life cycle impact assessment

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[1] Direct Air Capture (DAC) is a technology that removes CO_2 directly from ambient air for storage or reuse.

NPV	Net present value
IRR	Internal rate of return
KPI	Key performance indicator
SEC	Specific electricity consumption
TEA	Techno-Economic Analysis
UDF	Urine-derived fertilizer

1. INTRODUCTION

Indoor vertical farming (IVF) promises resilient and high-quality production of leafy greens locally. However, many reviewed life-cycle assessment (LCA) studies show that electricity for lighting and Heating, ventilation and air conditioning (HVAC) is the main contributor to environmental impact. Techno-economic analysis (TEA) similarly confirms that energy use plays most significant role in operating cost and profitability. Recent studies from various countries further show how sensitive results are to local energy mix as well as to operational conditions such as photon flux density (PPFD), daily light integral (DLI), temperature and relative humidity (RH) [1–4].

Sweden provides relevant context due to net-zero policy targets by 2045 [5] with low carbon intensity electricity grids compared to other European countries allowing for reduced climate impact of electricity intensive systems although operating expenses still largely depend on electricity prices. From a resilience perspective, Sweden’s electricity price volatility, winter peaks and occasional capacity constraints also motivate evaluating flexible IVF operations that can shift demand away from peak hours without compromising biomass yield.

The purpose of this pre-study is to review published literature and define plan for LCA-TEA comparing (1) conventional IVF that uses municipal drinking water, with mineral/synthetic fertilizers and (2) integrated IVF system with nutrient recovery from wastewater and CO_2 fertilization from direct air capture (DAC) system. In this paper we define the scope, system boundaries, data inventory, allocation and sensitivity tests for credible comparison. Where relevant, we also propose simple metrics to capture energy resilience in both scenarios.

2. ENVIRONMENTAL IMPACT IN RECENT STUDIES

A recent review [6] focuses on energy-use efficiency and water use efficiency for lettuce in IVFs. It compares IVFs with greenhouses (GH) and open-field systems and quantifies how transport distance and refrigerated distribution influence cradle-to-retail impacts. Commercial IVF commonly report lettuce yield approx. 60-105 kg FW m^{-2} $year^{-1}$ [6,7]. As noted above, electricity demand is high, but water-use efficiency is higher compared to greenhouses and open fields, and the advantage of local and year-around production is greatest in the winter. The specific electricity consumption (SEC) in optimized IVF growing lettuce is about 10-18 kWh kg^{-1} with expected advances (LEDs and HVAC) reaching 3.1-7.4 kWh kg^{-1} in future [8].

The LCA study performed in Netherlands (Tab. 1) showed that IVF showed higher GHG emissions compared to field production and GH systems, with electricity as dominant factor [1]. In the study from Sweden [3] on cabinet IVF authors found that electricity dominates and that environmental impact can be comparable to imported lettuce depending on assumptions. Another study from Sweden [2] on container farm case supplying an IKEA cafeteria reports climate impact of about 1,24 kg CO_2e kg^{-1}. A study from Finland (farm-gate) shows strong dependence on energy scenarios and reuse of waste heat [4]. The consistent conclusion over the studies is that electricity is the main factor influencing environmental impact, a low-carbon electricity grid lowers the climate impact. At cradle-to-retails scope, packaging and transport (refrigerated products) plays also important role.

3. TECHNOECONOMIC ANALYSIS IN RECENT STUDIES

Parametric modelling of energy costs demonstrates that demand varies greatly with climate and chosen set points [9]. Adjusting lighting (PPFD), photoperiod and

Tab. 1 Recent LCA studies in Europe on IVF and lettuce

Coutry, system and scope	FU	Result	Ref.
Netherlands, IVF vs GH/field; crandle-to-grave	1 kg retail	IVF impact > GH/field in baseline, electricity dominates	[1]
Sweden, IVF on-site modular cabinet	1 kg at point of use	Electricity dominates, competitive to import with assumptions	[3]
Sweden, IVF container IVF (IKEA)	1 kg delivered	Approx. 1,24 kg CO_2e kg^{-1}; LEDs and ventilation dominates, impact of energy mix	[2]
Finland, IVF vs GH; farm-gate	1 kg	Strong sensitivity to electricity and heat/lighting strategy.	[4]

Tab. 2 Nutrient recovery and reclaimed water optios for IVF

Method	Product	LCA/TEA impact	Notes	Ref.
Air stripping (WWTP side stream)	N fertilizer	0,2-0,5 kg CO_2e kg^{-1} AS; break-even at approx. 0,046 USD kg^{-1}	N source. Manage NH_4^+/NO_3^- balance in the recipe.	[10]
Struvite precipitation	P source (some N and Mg)	Additional value WWTP benefits are credited	Use as P; suplemental K; manage solubility.	[11,12]
Advanced treatment O_3, BACF ,UV on secondary effluent	Reclaimed water	Feasible for lettuce with micropollutant control	Include barrier set points and monitoring.	[13]
Urine-derived fertilizers UDFs (nitrified urine)	N rich solution	Comparable biomass yields if salinity/N-form is managed	Partial substitution is beneficial, Na/Cl to be tracked.	[14,15]

humidity (RH) can reduce latent heat load and therefore the electricity needed for dehumidification. Technoeconomic analyses (TEAs) on IVF typically identify electricity for lighting and dehumidification as dominant operating expense (OPEX) and the main driver for profit margins [16]. The SEC presented above aligns with several models and field reports [8,9].

4. NUTRIENT RECOVERY AND USE OF RECLAIMED WATER

Ammonia air stripping producing ammonium sulfate (AS) at a municipal WWTP has been evaluated in LCA-TEA in the US resulting in 0,2-0,5 kg CO_2e kg^{-1} AS with break-even price of 0,046 USD (Tab. 2). Struvite recovery has also been reviewed and assessed in Flanders, where WWTP benefit are credited (i.e. improved sludge dewatering and lower coagulation polymer use) [11,12]. A study on combining ozonation and biologically activated carbon filtration (BACF) followed by ultraviolet (UV) disinfection showed that reclaimed water can be used for hydroponic lettuce if micropollutants are adequately removed; otherwise they will accumulate in lettuce [13]. Urine derived fertilizers (UDF) have been tested, enhancing lettuce yield comparable to mineral fertilizer when salinity and N form were managed. Observed changes in in root microbes did not lead to yield losses [14]. From a resilience angle, local nutrient recovery may reduce dependency on potentially volatile fertilizer markets and supply chains, stabilizing OPEX during high-cost periods.

5. CARBON DIOXIDE ENRICHMENT AND DIRECT AIR CAPTURE

It is reported that in IVF controlled environments, CO_2 enrichment 800-1000 ppm can increase lettuce growth and can improve light-use efficiency when air exchange is adequate [21]. The supply options for CO_2 enrichment for IVF are summarized in Tab. 3. The environmental impact of Direct Air Capture (DAC) depends strongly on electricity and heat used. With low-carbon electricity grids adsorption based DAC can be even carbon net-negative [17,18]. Operationally, DAC can improve resilience switching from CO_2 supply from combustion-based sources or deliveries to reduce the risk of supply interruptions.

6. FRAMEWORK AND RESEARCH QUESTIONS

The intended LCA-CEA will focus on two Swedish scenarios. The conventional IVF (1), that uses municipal drinking water, mineral/synthetic fertilizer and the integrated one (2), that connects IVF with WWTP e.g. through technology when secondary effluent receives treatment with O_3, BACF and UV, with N and P recovered

Tab. 3 CO_2 supply options for IVF

Method	Note	Impact on growth	Accounting	Ref.
DAC sourced CO_2	Can be low-carbon source if powered by clean energy	Lettuce typically responds between 800-1000+ ppm under adequate light and air speed	No CDR credit unless stored (DACCS).	[17–19]
CO_2 from combustion or commercially purchased	Typically, higher inherent emissions	Lettuce typically responds between 800-1000+ ppm under adequate light and air speed	Can be used as baseline comparison	[20]

as ammonium sulfate (AS) to substitute for part of the mineral/synthetic fertilizers. CO_2 enrichment is then supplied by DAC as food-grade gas.

The research questions for the LCA-TEA in Swedish conditions can be defined as follows:

1. How much can the integrated IVF (2) reduce freshwater use and demand for mineral/synthetic fertilizers at cradle-to-retail scale?
2. When comparing with commercially purchased CO_2 source, under what conditions does DAC-sources CO_2 improve both the environmental impact as well as economic indicators of the IVF?
3. Which benefits are created at WWTP and how should they be allocated and credited?
4. Which operational parameters of IVF (e.g. LED efficacy, coefficient of performance for cooling/dehumidification (COP) for latent heat removal, CO_2 leakage rate, efficiency and quality of recovered nutrients) impact the most uncertainty in LCA-TEA?
5. How does each scenario affect energy resilience?

7. GUIDELINES FOR LCA-TEA

The aim is an attributional LCA together with a TEA that compares the baseline conventional IVF (1) with integrated IVF (2). However, selected consequential questions can be explored e.g. effect of avoiding mineral/synthetic fertilizers, the value of WWTP benefits or the implication of switching CO_2 supply to DAC-based CO_2. The primary functional unit (FU) should be defined preferably as 1 kg of market-ready lettuce at store exit, with clearly defined packaging. A supplementary FU of 1 $m^2\ yr^{-1}$ of cultivated area will help to compare capital intensity and productivity. The study should follow principles and requirements of ISO 14040 and ISO 14044, to ensure transparency, reproducibility and consistency across system boundaries and impact categories. Additionally, the alignment with the EU ILCD Handbook and Product Environmental Footprint (PEF) guidance should be applied when relevant to comply with EU policy frameworks and with other EU LCA studies. Specific methodological references and data quality criteria should follow EU guidance for carbon capture and utilization (CCU) systems.

System boundaries for the conventional IVF system (1) should include infrastructure i.e. growth racks, LEDs, HVAC for sensible and latent heat loads, fertigation, seedlings, packaging, distribution (as refrigerated) and waste. The integrated IVF system (2) boundaries should in addition include advanced water treatment for reclaimed water, nutrient recovery units and DAC with its electricity and heat and sorbet needed. Mass and energy balances, water use, N, P and CO_2 need to be accurately measured (Tab. 4) so that flows and substitutions are traceable. Multifunctionality of the integrated system needs to be handled with care, when e.g. ammonium sulfite displaces mineral N and P, avoided product use may be credited. Benefits at the WWTP such as reduced coagulation polymer use and improved sludge dewatering should be recorded and credited consistently [12]. In accounting, the CO_2 fertilization should be considered as carbon capture and utilization (CCU), not CO_2 removal (CDR). To be able to claim negative emissions, the CO_2 must be stored

Tab. 4 Parameters to be measured

Module	Measurements	Notes	Ref.
LEDs with controls	Efficacy (µmol J^{-1}); PPFD/DLI; kWh by rack/zone	Impacts LCA and OPEX; interacts with CO_2 response.	[21]
HVAC/dehumidification	Sensible vs latent heat load; COP; condensate volume; set points	Latent heat removal is commonly second highest load; condensate reuse saves water.	[22]
CO_2 enrichment	Set-point; dosing mass; leakage/vent %; purity	Yield/light use efficiency vs CO_2 cost and footprint	[21]
Water recovery	O_3 concentration/time; BACF Empty bed contact time (EBCT)/media; UV dose; micropollutants and pathogens before/after	Safety and ecotoxicity outcomes	[13]
Nutrient recovery	Air stripping concentration/impurities; struvite purity; mass yields; WWTP coagulation polymer use, energy changes	Avoided credits for mineral/syntetic fertilizer, proven recipe feasibility.	[10,12]
Packaging and logistics	Packaging, refrigeration, transportation distance	Important when crandle-to-retail	[6]

permanently (DACSS) [19]. For resilience, on-site storage/backup should be included if present (e.g. batteries) and any demand-response control logic within system boundaries.

The inventory should include measured electricity on each subsystem. For lighting, record LED efficacy in μmol·J^{-1}, PPFD (μmol·m^{-2}·s^{-1}) and DLI (mol·m^{-2}·d^{-1}). For HVAC, separate sensible and latent heat loads should be recorded together with COP and condensate volume and operation set points. For CO_2 fertilization, dosing schedule and quantity, eventual leakage and total mass CO_2 used, this should be linked to measured biomass yield and light use efficiency. For the water reclamation, ozonation dose-time, empty bed contact time (EBCT) and media for BACF and UV should be measured. Micropollutants and pathogens before and after treatment should be measured. For nutrient recovery concentration and impurities of ammonium sulfate, purity and solubility of struvite and mass yield (g·kg^{-1}) from sludge should be recorded. Furthermore, any changes in energy use and chemicals from the recovery unit at WWTP should be recorded [10,12]. For materials and packaging the list of materials and end-of-life assumptions should be compiled, distribution should account transport distance and type (also considering potential refrigeration) with food appropriate emission factors [6]. If resilience should be evaluated the high-resolution electricity data should be recorded during price spikes or load reduction requests.

The impact assessment should cover climate change, eutrophication by N and P, acidification, terrestrial and aquatic ecotoxicity and land occupation. The TEA should include capital cost (CAPEX) for LEDs and racks, HVAC and dehumidification, water treatment, nutrient recovery units and DAC. Operating costs (OPEX) should include electricity consumption by subsystem, chemicals and sorbents, labour costs and maintenance, packaging and losses. Revenues should include production sales and any fertilizer products or service fees associated with WWTP. Financial metrics should include levelized cost of lettuce (€/kg), revenues from production and products and service fees, Net present value (NPV), Internal rate of return (IRR) and discounted payback period (yr), as well as an abatement cost (€/tCO_2e) calculated from the change in cost divided by the change in GWP100 versus the baseline. Operational KPIs should include yield (kg·m^{-2}·yr^{-1}), light use efficiency (g FW·mol^{-1}), crop turns per year (yr^{-1}), specific latent and sensible heat removal (kWh·kg^{-1}) and the condensate reuse fraction. Resilience KPIs should include load-shifting potential (kW), fraction of curtailable load (%), islanding duration how long critical systems can operate independently during outages (h), and the production cost under low, average and high electricity price conditions.

For the FU in both cases EF 3.1 midpoint indicators (GWP100) should be reported together with contribution analysis by subsystem and life-cycle stage. Results should include substitution/credit inventory that accounts for avoided mineral N and P via ammonium sulfate and struvite and for documented WWTP benefits. Electricity consumption should be reported in (kWh·kg^{-1}), water consumption in (L·kg^{-1}), N and P related flows in (g Neq and g Peq·kg^{-1}), and CO_2 used for enrichment in (g·kg^{-1}).

Databases used, LCIA method and versions should be documented for reproducibility. The inventories data should be primarily taken from Ecoinvent database (v3.x, allocation cut-off by classification) for electricity, chemicals, packaging, transport, WWTP and waste management. Agribalyse database (v3.x) should be used for agriculture related datasets where applicable. Furthemore, European Environmental Footprint database (EF v3.1) should be used to ensure EU alignment consistent with EF 3.1. Where datasets overlap, Agribalyse should be prioritized. Selected consequential questions may be explored using the corresponding consequential system model in sensitivity analyses. Furthermore, European Reference Life Cycle Database (ELCD) datasets may be consulted where appropriate, it has been however discontinued with last data from 2019. All results should state database name, version and system model, the LCIA method and version, and any dataset substitutions. Swedish electricity mixes and scenarios for different years (i.e. 2025, 2030 and 2045 should be taken from national databases.

Integral to the LCA-TEA is sensitivity and uncertainty analysis. Key factors include the price (€·MWh^{-1}) and carbon intensity of electricity (g CO_2e·kWh^{-1}) in Sweden today with prognoses to 2030 and 2045. LED efficacy and DLI (μmol·J^{-1}; mol·m^{-2}·d^{-1}), COP for latent heat load removal and the reuse of condensate, CO_2 set-point and dosing efficiency, the yield and quality of recovered nutrients, reclaimed water, and food waste. Resilience sensitivities should evaluate peak price scenarios, demand-response availability (h·wk^{-1}), and the backup duration for critical loads required to maintain essential IVF systems.

8. CONCLUSION

The literature review shows that across EU IVF LCAs and engineering analyses, electricity remains the main factor of both environmental and economic performance. Although Sweden's low-carbon electricity mix inherently reduces GHG emissions, IVF energy consumption remains main factor for the overall cost. Recovering nutrients such as ammonium sulfate and struvite, together with reclaiming water, can lower environmental impacts and enhance circularity. However, this depends on water advanced treatment technologies and how effectively micropollutants can be managed. Under Swedish conditions, DAC can supply low-carbon CO_2, while carbon removal claims require permanent storage.

The pre-study further defines functional units, system boundaries, inventory needs, allocation rules, and sensitivity tests for a robust LCA-TEA of both conventional and integrated IVF systems. By incorporating compact, measurable energy-resilience KPIs and inventory items, the framework also allows evaluate each scenario's ability to maintain production during price spikes and grid disruptions.

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