Intersection of Agri-Genomics and Agriculture 5.0 Technologies

Role for life cycle assessment

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Summary

Agriculture 5.0 technologies such as alternative proteins, vertical farming, and cellular agriculture, are increasingly presented as solutions for addressing food security and environmental sustainability. The introduction of agri-genomics into these emerging food production techniques offers potential for scalable ways to improve food production efficiency.

To assess the environmental benefits of these innovations, life cycle assessments (LCA) are essential but still underdeveloped. LCA's capture embodied and operational environmental outcomes, presenting a holistic view of a production process' impacts. As agri-genomics techniques and tools are applied to emerging agri-food innovations, life cycle techniques afford novel opportunities to discuss their potential tradeoffs with greater transparency and robust data.

This report provides a backgrounder and overview of LCA methodology within mushroom cultivation, cellular agriculture, and vertical farming production systems, highlighting considerations for agri-genomics applications. It also provides recommendations for integrating LCA thinking into accessible decision-support tools to evaluate novel agri-food technologies.

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1. Background

Scholars and policy makers increasingly recognize agri-tech innovations as promising strategies to address the challenge of feeding a growing global population sustainably. Conventional agricultural practices contribute significantly to greenhouse gas (GHG) emissions, land use change, water consumption, and biodiversity loss, with estimates suggesting that the food system is responsible for approximately 21% to 37% of global GHG emissions (Mbow et al., 2019). Accordingly, exploring methods for reducing the environmental footprint and impact of agriculture is essential for achieving a sustainable and resilient food system. Agriculture 5.0 technologies – a suite of digital tools, novel food technologies, and decision-support software and hardware, powered by artificial intelligence and big data – is one such method (Fraser & Campbell, 2019). For example, vertical farming, alternative proteins, and cellular agriculture offer methods to produce food with reduced land use and water consumption, potentially lowering emissions compared to conventional farming (Smetana et al., 2015; Kalantari et al., 2017).

Agri-genomic technologies are a particularly promising approach to address food security and environmental sustainability issues, as they provide a means to produce food more efficiently across a variety of techniques (e.g., conventional or controlled environment or cellular agriculture), and offer scalable solutions for reducing the environmental footprint of food production (Poore & Nemecek, 2018). Genomic technologies can be applied to a variety of agriculture 5.0 technologies to improve yields and create sustainable food products. Given the breadth of agriculture 5.0 technologies, this report focuses on only three emerging industries/technologies commonly registered under the Agriculture 5.0 umbrella: mushroom-based proteins (alternative proteins), vertical agriculture, and cellular fish products. The application of agri-genomics technologies to cellular agriculture can increase yields and production efficiency in tissue culture (Chandrababu & Puthumana, 2024). In addition, genomics techniques can be used to optimize controlled environment production systems, such as using functional genomics to identify best lighting conditions for indoor growing of different crop varieties (SharathKumar et al., 2020) .

Quantifying the environmental benefits of these technologies to understand their ‘promise’ requires the use of comparative life cycle assessments (LCA). LCAs are used to evaluate the total environmental impact of a product or process across its entire lifecycle, from production to disposal. The application of this method in the development and scaling of agri-genomic solutions is critical for understanding how these technologies contribute (or fail to contribute) to improving the environmental sustainability of the food system (Clune et al., 2017). Yet, use of LCA in cutting-edge agri-genomics applications within cellular agriculture, alternative proteins, and vertical agriculture is still in early stages (Glaros et al., 2022).

This report provides a methodological summary for LCA studies in agri-genomics as a backgrounder for future studies. The report concludes with recommendations to guide the development of a decision-support tool that incorporates LCA methods in the evaluation and potential deployment of emerging agri-food innovations.

2. Literature Review

2.1 Lifecycle Assessments and Agri-Genomics

Goals, Scope, and Inventory

An LCA project begins by defining the purpose of the assessment (e.g., estimating GHG emissions from controlled environment production of a crop vis-à-vis conventional production of the same crop, Blom et al., 2022) and associated relevant research questions. Then, the researchers must establish system boundaries (e.g, farm-to-fork, cradle-to-grave analysis) often including the entire production system from extraction of raw material inputs (e.g., growth substrates, nutrients) to energy use (e.g, artificial lighting, temperature control, bioreactor operation), and finally waste disposal. Studies such as Smetana et al. (2015) and Poore and Nemecek (2018) note the importance of clearly defining system boundaries to ensure that all environmental aspects are considered and assumptions clarified when conducting an LCA.

LCA assessments of agri-genomics technologies as applied in alternative protein, cellular agriculture, and vertical agriculture production requires material inventory data from real or hypothetical operations, aligned with the previously defined system boundaries. Such LCAs should track, for example, energy consumption from LED lighting, material requirements for growth media production, extraction of raw minerals and materials for electrical and/or infrastructure design, and bioreactor design materials. In mushroom-based production systems, energy for heat and moisture management as well as materials as grow substrate are monitored (Shahid et al., 2024). In vertical farming systems, electricity for LED lighting and HVAC are often reported, including raw materials for vertical grow shelves and automated control units (see Blom et al., 2022). For cellular agriculture production, materials as grow inputs and for scaffolding, in addition to bioreactor design materials are commonly reported as inventory (see e.g., Tuomisto et al., 2022).

Impact Assessment

The purpose of the LCA is to produce data and understanding on environmental impacts and (when conducting comparative LCAs) relative benefits, such as those related to GHG emissions, water depletion, and land use compared to conventional agri-food production. When conducting LCAs on agri-genomic technologies to determine their climate change mitigation potential, functional unit (i.e. impact per mass of product, or unit of product nutrition) is important to consider, as it can be used to compare with conventional food production methods. For example, in a meta-review of cellular fish production LCAs, Telesetsky (2023) found that cell-based production is likely to address many environmental and social concerns pertinent to fisheries, but at the cost of higher emissions.

In the literature on LCAs and agri-genomics, Shahid et al (2024) measure the carbon footprint of mushroom-based protein is comparable to or better than plant-based protein sources. With respect to vertical farming, Kalantari et al. (2017) indicate that while vertical farms use more energy-intensive that conventional agriculture, reduced land and water usage may offset some of the GHG emissions produced through the higher energy consumption. In terms of cellular agriculture, Smetana et al (2015) identify concerns around high energy use; however, these studies also emphasize future potential for reducing GHG emissions as biotechnologies evolve and energy systems transition to sustainable, renewable sources.

Interpretation

The final stage of an agri-genomic LCA involves interpreting the results to identify opportunities for impact mitigation and improving environmental performance. Such areas of improvement can include switching to renewable energy sources in vertical farms or optimizing bioreactor efficiency in cellular fish production. Findings from LCA work provide insights into how agri-tech can reduce GHG emissions and resource use, which in term, can be use to guide industry practices and policy-making. Interpretation should be conducted carefully, reflecting a recognition of uncertainties and unintended tradeoffs with respect to new technologies. By way of example, the adoption of cleantech and clean energy to address high operational carbon emissions from controlled environment growing can increase demand for critical mineral resources (El Wali et al., 2024).

2.2 Key Impact Measurements in Agri-Genomic Life Cycle Assessments

Energy

Energy use presents a potentially significant environment trade-off in terms of GHG emissions within controlled environment production systems (Newman et al., 2023). Energy consumption, particularly electricity use, is one of the primary sources of GHG emissions in vertical agriculture and cellular agriculture. Transitioning to renewable energy could significantly reduce the GHG emissions of these technologies for food production. When deploying agri-tech innovations and methods, the energy efficiency of lighting, climate control, and bioreactor operation, along with the source of that energy (renewable versus fossil fuels), greatly affects the carbon footprint of these technologies. For example, vertical farms in regions with a high proportion of renewable energy will have a lower GHG impact compared to those relying on fossil fuel-based grids (Newell et al., 2021).

Yield

Yield is a critical variable affecting the per-unit emissions in agricultural systems, reflecting production by land area. Higher yields generally reduce emissions intensity, while lower yields increase it. Reliable yield data from field studies or experimental settings are necessary to ensure accurate modeling of GHG emissions. In the case of vertical farming or cellular agriculture, where experimental or industry data may still be limited, using ranges or sensitivity analysis can be crucial to account for uncertainties in yield.

The application of agri-genomics to farming can in improve crop yields, which in turn increasing output per unit of input and space (Kalantari et al., 2017). Such technologies can be coupled with other emerging food production approaches to increase their environmental benefits and potentially offset trade-offs. For example, higher yields per square meter in vertical farming systems demonstrates higher land use efficiency and possible biodiversity benefits (i.e. land-sparing) as compared to horizontal soil-based produciton. Agri-genomic technologies, such as cellular fish and mushroom proteins, are still evolving in terms of biological and technological efficiency. For instance, advancements in bioreactor technology for cellular fish or substrate optimization for fungal proteins could lead to significant improvements in energy use and yield, thereby reducing the overall GHG emissions (Shahid et al., 2024; Tuomisto et al., 2022).

Waste

Waste generation and its management play a significant role in the overall environmental impact. Closed-loop systems that recycle nutrients or repurpose waste can drastically lower GHG emissions in the food production life cycle. Such systems have promise for cellular agriculture and mushroom-based proteins (Skinner & Ülkü, 2024; Grimm & Wösten, 2018). In vertical agriculture production systems, local material inputs can be used to substitute for grow media and substrates (Molari et al., 2024). District heat systems can also be leveraged to reduce heat energy requirements for vertical farming systems (Gentry, 2019).

2.3 Specific LCA Considerations for Agri-Genomics in Mushroom Cultivation, Vertical Farming, and Cellular Agriculture

In this section, the report reviews key considerations affecting the environmental performance and resource demands for agri-genomics as applied to mushroom production, vertical farming, and cellular agriculture. Specific attention is driven toward fungal, plant, and cell line varieties for mushroom, vertical, and cellular-based cultivation methods, respectively. A table summarizing key performance indicators of relevant literature for each production approach is also included.

Mushroom Production

Mushroom variety and substrate composition are key factors driving differences in environmental performance, across the reviewed LCA literature. Different mushroom species (e.g., button mushrooms, oyster mushrooms, shiitake, etc.) vary in their requirements for growth conditions, substrates, and growing times. The type of substrate (compost, wood chips, agricultural residues) can also impact resource use and emissions. Some mushrooms can utilize waste byproducts, reducing the overall environmental footprint. In contrast, if the substrate has high embodied emissions (from fertilizers, energy use in production), the impact will be higher. For instance, many mushrooms grow on lignocellulosic substrates (such as straw or wood chips), which has different environmental impact and yield production impacts than other substrates (Suwannarach et al., 2022). Additionally, some mushroom varieties may require higher energy inputs for temperature and humidity control, which influences the amount of GHG emissions produced per mass of product.

Vertical Agriculture

Different types of crops produced through vertical farms have varying resource needs. For example, leafy greens like lettuce have a relatively short growing cycle, therefore producing higher yields over a year timeframe as compared to fruiting crops like tomatoes or peppers. This can potentially lower the resource intensity of vertical leafy greens production as compared to other crops, per unit produced. Additionally, some crops are more efficient at converting light energy into biomass (Kalantari et al., 2017), requiring less energy input for growth. For instance, lettuce grows well under low-intensity LED lights, whereas more light-demanding crops would require higher energy inputs. Understanding the response curves of different cultivars of crops to vertical production systems (considering hydroponic growth and light) allows for greater potential resource efficiencies and yield gains (de Carbonnel et al., 2022).

Cellular Fish Production

The (represented) species of fish being cultured (e.g., salmon, tuna, tilapia, etc.) using cellular fish technologies influences the environmental footprint[9] of the food production process. Such considerations include the efficiency of bioreactors and the type of growth media used for culturing tissues of different fish species affect. For example, bi-products from conventional seafood industry and mushroom production already present promising materials for cell-based fish production (Rubio et al., 2019).

3. Recommendations and Future Directions

3.1 Key Considerations Informing an LCA-Based Decision-Support Tool

LCAs can generate useful insights into the climate change mitigation potential of agri-genomic technologies; however, they can be difficult to conduct and interpret, requiring specialized skills and training. A user-friendly decision-support tool based on the LCA process would be valuable for practitioners and policymakers, as it would allow them to design and guide the development of agri-genomic food production in ways that best contribute to climate action and broad sustainability objectives. A tool that provides baseline assumptions regarding environmental impacts for diverse production systems utilizing agri-genomic technologies, based upon a limited set of user inputs (e.g., potential site location and desired production volume) could serve to guide food systems planning and decision-making. Such a tool can help drive innovation in food production while guiding decisions toward lower carbon emissions in agriculture. Below are several recommendations for developing the tool in ways that optimize its accuracy, relevance, and user accessibility.

Modularity for Different Systems

The tool should be modular, adaptable for different agri-genomic production systems, such as mushroom-base proteins, agri-genomically enhanced vertical farms, and cellular agriculture. Each system has unique life cycle phases and GHG emissions profiles, and users of the tool need to be able to input variables specific to each technology. Where possible, the tool should allow for automated inventory generation for each unique production approach; however, the tool should also include opportunities to manually enter detailed inventories pertinent to each production method, allowing for tailored results per individual production systems. The ability to customize to production type is rare among existing calculators (Murlow et al., 2019).

Life Cycle Stages and Boundaries

The tool should incorporate all stages of the product life cycles. Such phases include the production and acquisition of inputs (e.g., substrate for mushroom fermentation, cell media for cellular fish) and production (e.g., energy for bioreactors, vertical farm lighting), in addition to processing and packaging (e.g., processing mycoprotein or cultured fish, packaging materials), distribution (e.g., transportation distances and modes), as well as waste (e.g., waste handling, packaging, disposal). Including these components ensures that tool is based on LCA methodologies and comprehensive GHG emissions accounting. Recognizing that users will use the tool with varying potential site locations and business models, ranges and assumptions regarding distances for distribution and input supplies will need to be clarified and specified.

Energy Source and Emissions Factors

The tool should allow users to input the different energy sources (e.g., electricity grid mix, renewable energy) used to power individual food production operations. Energy use is a significant contributor to GHG emissions, especially in energy-intensive systems such as vertical agriculture or cellular fish. To this end, the tool development process can involve the use of GHG emissions databases such as Ecoinvent, EPA's GHG Emission Factors Hub, and International Energy Agency (IEA) for up-to-date emissions data. Region-specific information should be included within the tool to automatically account for variations in energy grid composition, making it more user-friendly and locationally accurate (following Murlow et al., 2019).

Water and Nutrient Efficiency Calculations

In addition to carbon and greenhouse gas emissions, it is recommended that the tool include a diverse array of potential environmental impacts and performance dimensions (e.g., water use, nutrient management, yield).

Water and nutrient efficiencies are key metrics in sustainable agriculture. For vertical farming, water recycling and efficient nutrient delivery reduces the environmental footprint of food production as compared to conventionally grown products. The tool could be used to understand (for example) the volume of water used per mass of product to examine the potential resources and environmental benefits of a particular food production method.

Waste and Circular Economy

There is opportunity to include circular waste management scenarios that assesses the impacts of food waste, packaging disposal, and waste-to-energy conversion processes. Waste management, recycling, and circular economy principles influence the life cycle GHG emissions of agri-genomic systems. Many emerging food production systems, such as vertical farming, have the potential to minimize waste by developing them as closed-loop systems through, for example, circular grow media and substrate production (see Molari et al., 2024).

User-Defined Inputs and Default Values

To increase user-friendliness, the tool can provide default values for some inventory data and variables based on scientific literature, while also allowing users to input custom data. While some users may have access to specific data for their unique operation, providing some default values retrieved from the literature allows for a broader user base. Such values and data can be retrieved from publicly available models and inventories (e.g., Martin et al., 2023; Tuomisto et al., 2011).

Benchmarking and Scenario Analysis

The tool should include an ability to benchmark against conventional systems (e.g., traditional livestock farming, open-field agriculture, greenhouse production, wild-caught fish). The benchmarking feature provides an ability to compare environmental indicators from agri-genomic food production methods with conventional systems, allowing for evaluations of the environmental advantages and drawbacks (as done in LCA assessments such as Graamans et al., 2018). Such a feature can be used to reveal the potential GHG emissions reductions and other resource efficiencies gained from transitioning to novel food systems.

Dynamic Visualization of Results

The tool should provide visualizations of GHG emissions outcomes from implementing agri-genomic technologies, such as comparative graphs and charts. Visual representations make the tool and its outputs easier to use, as they improve the tool’s ability to convey the results of its calculations more effectively to broad and diverse groups, including policymakers, researchers, and stakeholders.

Such visualizations could include graphs that breakdown GHG emissions by life cycle stage (e.g., production, packaging, transport), and compare the magnitude of these emissions to conventional food production methods (e.g., cellular fish compared to farmed fish).

Data Export and Reporting

The tool should enable data exports in formats suitable for reporting, such as CSV, Excel, or PDF summaries. Data export functions are valuable for industry users, government staff, and researchers, who wish to share insights from the tool in presentations and meetings. Customizable downloads that allow users to select the data/outputs and presentation formats can help businesses and other organizations with their sustainability reporting needs.

3.2 Illustrative Tools

Examples of existing models can serve as references for a developing a tool for calculating GHG emissions calculator from agri-genomic food production methods. These examples include modelling tools for performing LCA and assessing GHG emissions from agricultural production. Table 2 provides a list of the examples, with descriptions and links.

Tool Name	Description
Holos	HOLOS is a whole-farm model designed to estimate GHG emissions from agricultural activities, including livestock, crops, and management practices. It provides customizable inputs for users to model different agricultural systems and could serve as a framework for incorporating agri-genomic technologies.
SimaPro	SimaPro is a leading LCA software tool that helps to assess the environmental impact of products and systems. It can model agriculture-based LCAs, including novel food systems like mycoproteins, vertical farms, and cellular agriculture.

Tool Name	Description
OpenLCA	OpenLCA is a free, open-source LCA software that offers comprehensive modeling capabilities for assessing environmental impacts. It allows users to create customized GHG calculators with relevant agricultural data.
Sphera	Sphera software provides tools for Life Cycle Assessment, helping industries to evaluate their products' environmental performance. It is often used in agricultural LCAs and can be tailored for agri-genomic technologies.

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