Assessing climate change adaptation and mitigation potential of novel protein sources in Europe

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Abstract

It has been estimated that around one third of anthropogenic greenhouse gas (GHG) emissions originates from the way the humanity feeds itself. Current global production and consumption of animal protein account for a significant share of these emissions and associated long-term impacts on health, environment, and climate. While food insecurity persists globally, GHG emissions are likely to rise as more people gain access to adequate nutrition, including sufficient protein. In regions such as Europe, where protein intake is largely adequate and even exceeds recommendations, the majority still comes from animal-based sources (meat, dairy, fish, eggs) causing considerable climate impacts. The European Green Deal and Farm-to-Fork Strategy aim to reduce these impacts, in part by promoting substitution of some animal-based protein with alternative sources. While alternative proteins may play an important role in climate transition, it is not yet clear how their production systems are affected by climate change, to what extent they are able to adapt to these changes, or what their climate mitigation potential is. The paper presents a six-step methodology developed in the GIANT LEAPS Project to assess climate change adaptation and mitigation potential of alternative proteins and apply it to nine European produced sources shortlisted in the project (crickets, cultured meat, fava beans, lentils, microalgae, oats, quinoa, rapeseed, single-cell protein). The application of the methodology that contains climate vulnerability assessment combined with mitigation and adaptation options provides initial, comparable insights into climate vulnerabilities, adaptation capacities, and mitigation potentials of these novel protein production systems and highlights leverage points that can inform policy and investment in Europe's protein transition.

Keywords: alternative proteins; climate change; climate adaptation; climate mitigation; climate vulnerability; food system transition

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1. Introduction

Food systems have become a central focus of climate change mitigation efforts, as they contribute an estimated 19–29% of global GHG emissions and about one-third of all anthropogenic emissions when land-use change is included (Vermeulen et al., 2012; Crippa et al., 2021). A large portion of food-related emissions is attributable to the production of animal-based proteins: rearing of livestock for meat, dairy, and eggs produces significant methane, nitrous oxide, and carbon dioxide emissions and is a major driver of deforestation and land-use change for feed production (Gerber et al., 2013; Poore & Nemecek, 2018). For example, Poore and Nemecek (2018) found that beef cattle can generate on the order of 50–100 kg CO_2-equivalent (CO_2e) per kilogram of protein, whereas many plant-based protein sources emit only a small fraction of that. Beyond climate impacts, heavy reliance on animal proteins has been linked to adverse outcomes for biodiversity loss, water pollution, and public health (Willett et al., 2019). These concerns have prompted calls for a global protein transition, which refers to a shift toward more sustainable protein consumption patterns (Froggatt & Wellesley, 2019; Westhoek et al., 2011).

Global demand for protein is rising due to population growth and increasing incomes, especially in developing regions, exacerbating the challenge of feeding the world sustainably (Tilman & Clark, 2014; Springmann et al., 2018). If current dietary trends continue, food-related GHG emissions could roughly double by 2050, making it virtually impossible to meet international climate targets without significant dietary changes (Springmann et al., 2018). At the same time, climate change itself threatens food production through increasing temperatures, shifting precipitation patterns, and more frequent extreme weather events, which can reduce crop yields and stress livestock systems (IPCC, 2022). Food security thus faces a dual challenge: reducing climate footprint of food systems (mitigation) while coping with climate-induced stresses (adaptation) (Vermeulen et al., 2012). A diversified protein supply that relies less on GHG emissions-intensive animal protein and includes more climate-resilient sources could be a key strategy to address both challenges.

In Europe, per capita protein intake is already high, often above recommended levels, mostly from animal sources (Westhoek et al., 2011). Recognizing the need to curb emissions and improve sustainability, the European Union has incorporated food system transformation into its policy frameworks. The European Green Deal identifies food sustainability and security as integral to achieving climate neutrality by 2050 (European Commission, 2019). Under the Green Deal’s umbrella, the Farm to Fork Strategy (European Commission, 2020) specifically calls for a shift to sustainable diets, including an increase in plant-based and alternative proteins to reduce the environmental impact of food production. This policy push has been accompanied by research and innovation support programs aimed at developing and assessing new protein sources that could complement or replace animal proteins in European diets (European Commission, 2020; GIANT LEAPS, 2022).

Alternative proteins refer broadly to protein-rich foods and ingredients that serve as alternatives to conventional animal products. These include plant-derived proteins (e.g. pulses, oilseeds, cereals), proteins from insects and other invertebrates, microbial proteins (such as algae or fermentation-derived biomass like single-cell fungi/bacteria), and cell-cultured meat grown in vitro. In recent years, numerous studies have highlighted the potential of such alternatives to significantly reduce GHG emissions, land use, and water use relative to animal products (Parodi et al., 2018; Mazác et al., 2022). For instance, replacing a portion of European diets' animal foods with novel plant-based or cultured alternatives could cut diet-related GHG emissions by over 80% while staying nutritionally adequate (Mazác et al., 2022).

Studies on edible insects suggest that cricket or mealworm farming emits far fewer GHGs and uses less land and water per unit of protein than beef or pork production (Oonincx, et al., 2010; van Huis et al., 2013). Cultured meat has also been projected to yield major environmental benefits: one early analysis estimated 78–96% lower GHG emissions, 99% lower land use, and 82–96% lower water use for cultured meat compared to conventionally produced European beef, assuming renewable energy is used in production (Tuomisto & Teixeira de Mattos, 2011). Plant-based protein crops such as legumes and grains inherently produce less emissions than animal proteins and can even enhance environmental sustainability by improving soil health and requiring lower inputs (Jensen et al., 2012; Searchinger et al., 2019).

While the climate change mitigation potential of alternative proteins is well recognized in the literature, much less attention has been given to their adaptation potential and vulnerabilities. Climate change adaptation in the food system context involves ensuring that production of food (including novel proteins) can withstand or adjust to changing climate conditions. Different protein sources will be affected by climate change in varying ways. For example, insect farming operations are typically indoor or in sheltered facilities, which may buffer them against weather extremes (suggesting high adaptive capacity) though they still depend on agricultural feed inputs that could be disrupted by climate stress on crops. In contrast, cultivation of plant protein sources (like fava beans, lentils, oats, quinoa, rapeseed) is subjected directly to climatic influences; yields may decline under higher temperatures, droughts, or increased pests and diseases, unless adaptive measures (such as breeding climate-resilient crop varieties, irrigation, or shifting planting zones) are implemented (Myers et al., 2017; Webber et al., 2018).

To date, most assessments of alternative proteins have focused on sustainability metrics and consumer acceptance, with relatively few examining how climate change might impact the production of these novel proteins or how integrating them into the food system could enhance climate resilience. The EU-funded GIANT LEAPS Project (2022-2026) is an interdisciplinary research project aims to fill some of the gaps in nutritional, safety, allergenicity and environmental assessments to promote alternative protein utilization and the dietary shift towards more sustainable and healthy diets. Through interdisciplinary research, it seeks to address and accelerate the shift to alternative proteins in line with EU climate and health objectives (GIANT LEAPS, 2022).

Within this broad initiative, a methodology was developed to assess both climate change mitigation and adaptation dimensions for alternative proteins. Here this methodology is presented and applied to nine promising novel protein sources in the European context, chosen from those shortlisted by GIANT LEAPS as emerging alternatives: *crickets, cultured meat, fava beans, lentils, microalgae, oats, quinoa, rapeseed*, *and single-cell protein*. These sources span three major categories of alternatives – plant-based proteins, microbial proteins, and non-conventional animal-based proteins – allowing a comparative analysis across different production systems.

In the following sections, the assessment methodology is described, and preliminary results based on literature and project insights presented, highlighting climate vulnerabilities, adaptation capacities, and GHG mitigation potentials of each of the nine protein sources. The findings' implications for climate change adaptation and mitigation strategies in the food sector are then discussed, and recommendations for policy and future research to harness these novel proteins for climate transition in Europe and beyond are presented.

2. Methods

The six-step climate vulnerability assessment framework for novel protein sources, adapting the risk/opportunity assessment-based method of Pham et al. (2021) that was originally designed for fisheries and aquaculture to the selected protein production systems. The adapted framework, illustrated in Figure 1, follows a logical sequence: from identifying climate exposure and sensitivity of each protein production chain (Steps 1-2), to determining specific risks and opportunities (Step 3), evaluating adaptive capacity (Step 4), synthesizing these into an overall vulnerability rating (Step 5), and an extra step to quantify mitigation potential in terms of GHG emissions (Step 6), given the emphasis of these novel protein producers on climate change mitigation potential. The assessment is informed by multiple sources of data: downscaled climate projections from the IPCC Sixth Assessment Report (AR6) for Europe (IPCC, 2022), scientific literature on each protein source's production constraints, and insights from industry producers obtained via semi-structured interviews in the GIANT LEAPS project. Figure 1 depicts the details of the framework and its application.

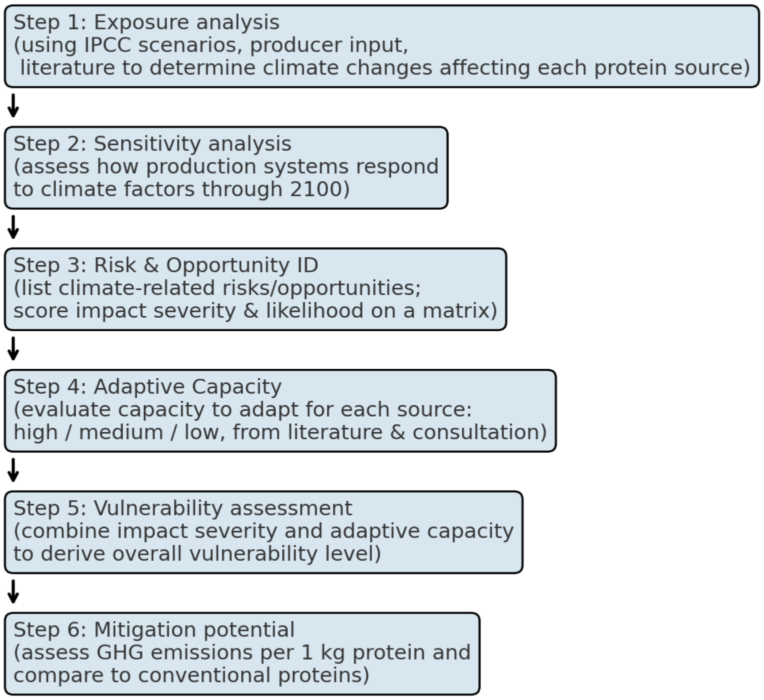

Figure 1. Schematic of the climate vulnerability assessment framework applied in this study. The process consists of six key steps: (1) evaluating the protein source's exposure to climate change, (2) analyzing its sensitivity, (3) identifying and scoring climate-related risks and opportunities, (4) assessing its adaptive capacity, (5) determining overall climate vulnerability, and (6) estimating its climate change mitigation potential (GHG emissions per unit protein). Arrows indicate the flow from understanding climate impacts (Steps 1-3) and adaptive capacity (Step 4) to evaluating vulnerability (Step 5), alongside a parallel estimation of mitigation benefits (Step 6).

This early version of the assessment relies largely on existing literature and datasets for environmental impacts. Key sources included meta-analyses of food system emissions (e.g. Poore & Nemecek, 2018), specific LCA studies for novel proteins (Tuomisto & Teixeira de Mattos, 2011; Smetana et al., 2015), and climate impact studies on agriculture (IPCC, 2022; Webber et al., 2018). The methodology provides a framework to compile and interpret secondary data in a climate adaptation-mitigation context. Wherever possible, data for European production systems was used (for example, emission factors for European-grown fava beans, or energy grid mixes for cultured meat production in Europe) to improve relevance. The qualitative judgments on vulnerability and adaptive capacity were informed by literature and expert consultations. This combined approach ensures that our results are grounded in the best available evidence while highlighting areas of uncertainty and further research needs.

Step 1: Exposure Analysis. In the first step, we characterized the exposure of each protein source's production system to relevant climate change factors over the 21st century. "Exposure" here refers to the extent and magnitude of climatic changes that the system will experience. Using IPCC AR6 regional climate projections for Europe (IPCC, 2022), we extracted climate variables pertinent to each protein production system. For field crops (fava beans, lentils, oats, quinoa, rapeseed), key exposure metrics included changes in average temperature and precipitation across growing seasons, frequency of heatwaves (>35 °C) and droughts, and shifts in suitable growing zones. For example, it was noted that southern Europe is projected to see increased heat and drought stress by mid-to-late century, while northern Europe may experience longer growing seasons and greater precipitation extremes (IPCC, 2022). More controlled indoor systems (crickets, cultured meat, microalgae, single-cell) experience less direct weather exposure, but may be susceptible to indirect exposures such as rising ambient temperatures (which could affect cooling requirements), potential water scarcity (for systems requiring water cooling or cultivation), and extreme weather events that might disrupt supply chains or infrastructure (e.g. storms affecting power grids).

Step 2: Sensitivity Analysis. "Sensitivity" here denotes how responsive or susceptible the production system is to a given climate stimulus. Where crop sensitivity model results are available, projections of yield changes under climate scenarios were used as a proxy for sensitivity. If no direct model was available (e.g. for quinoa, which has fewer long-term studies in Europe), it was extrapolated based on the crop's known climate niche (e.g., quinoa is adapted to cool, semi-arid highland climates, suggesting sensitivity to very high humidity or extreme heat). For crickets, sensitivity was evaluated in terms of biological tolerance ranges (optimal vs. lethal temperatures, humidity needs) and feedstock sensitivity (since cricket farming's success partly depends on feed availability, which are climate-sensitive). Cultured meat sensitivity was considered mainly in terms of inputs: for instance, cell culture operations are sensitive to temperature only insofar as maintaining bioreactor conditions, but highly sensitive to power outages or supply interruptions for growth media. Microalgae systems' sensitivity depends on cultivation mode: open-pond algae are quite sensitive to weather (algae growth rates drop in suboptimal temperatures and can collapse in extreme heat or if heavy rain dilutes culture), whereas closed photobioreactors have buffered sensitivity but still rely on consistent energy and CO_2 supply. Single-cell protein fermentation (e.g. yeast, fungal or bacterial fermentation) is similarly sensitive to feedstock consistency and energy supply, and certain strains may have optimal temperature ranges for fermentation efficiency. Each sensitivity was scored qualitatively (low, moderate, or high) based on how strongly negative outcomes (e.g. yield loss, production decline, mortality, or system failure) occur under the projected climate stress.

Step 3: Risk and Opportunity Identification. Building on exposure and sensitivity, specific climate change risks (negative impacts) and opportunities (beneficial effects) for each protein source were identified. A list of plausible impact scenarios for mid- and late-century were identified, e.g., “increased drought frequency causing lentil yield reductions” (risk) or “warmer temperatures enabling double-cropping in some regions” (opportunity). Each impact was then evaluated by assigning two scores: impact severity and likelihood, following a matrix-based risk assessment approach similar to that used by Pham et al. (2021). We used a five-point scale for severity of impacts, from 1 (negligible impact) to 5 (extreme or transformative impact), and a three-point scale for likelihood (1 = unlikely, 2 = possible, 3 = likely under the climate scenario). These judgments were informed by literature and producer surveys. We then combined the scores in a risk matrix to assign each item an overall risk or opportunity level. This step allowed to highlight which climate factors pose the greatest threats or benefits to each protein source.

Step 4: Adaptive Capacity Evaluation. In parallel with identifying impacts, we evaluated the adaptive capacity of each protein source’s production system. Adaptive capacity refers to the ability of the system to adjust, evolve, or otherwise cope with climate impacts, thereby reducing potential damages or exploiting opportunities (Pham et al., 2021). We qualitatively rated adaptive capacity as High, Moderate, or Low for each protein source, based on factors such as available adaptation options, flexibility of the production system, human and financial resources, and institutional support. The question asked in this step was: How easily can producers access resources or strategies to adapt to climate stress?

Step 5: Vulnerability Assessment. We derived an overall climate change vulnerability level for each protein source by integrating the results of the previous steps, essentially combining the potential impact (exposure × sensitivity, as reflected in the severity of risks identified) with the adaptive capacity (Pham et al., 2021). For this a vulnerability matrix approach was applied: if a protein’s expected climate impact was ranked major or extreme and its adaptive capacity low, it would be deemed highly vulnerable; conversely, minor impacts with high adaptive capacity yield low vulnerability. Intermediate cases were judged as moderate vulnerability. This qualitative synthesis was informed by the stakeholder input and scenario analysis. We assigned each protein source an overall vulnerability rating (Low, Moderate, or High) for the European context by 2100 (under medium and high-emission scenarios). These ratings are reported in the Results section for each source. It should be noted that high vulnerability indicates the climate impacts have a potential to significantly impede or alter production without major adaptation efforts, whereas low vulnerability means the source is relatively robust or can adjust with minimal disruption. Moderate vulnerability implies some noticeable impacts that require concerted adaptation measures but are not existential threats to production.

Step 6: Mitigation Potential (GHG emissions analysis). Finally, the climate change mitigation potential of each protein source is estimated by analyzing its life cycle GHG emissions intensity and comparing it to conventional animal protein sources. For this initial assessment, literature was searched forvstudies focused on GHG emissions, if possible, per 1 kg of dry protein produced (CO_2-e per 1kg protein). This functional unit allows fair comparison across diverse products (though not considering nutritional and digestibility qualities that are considered in the GIANT LEAPS project as a whole). Data was gathered from published LCA studies and databases for each novel protein, and where multiple studies were sourced, different production methods or assumptions were considered. We also obtained some representative (though not comprehensive) GHG intensities for conventional proteins, such as beef, pork, poultry, dairy, and soy, to serve as benchmarks.

3. Results

Short of full assessment, below are the key insights of the climate change adaptation and mitigation potential assessment for each of the nine novel protein sources, covering their climate change vulnerabilities, adaptation capacities, and GHG mitigation potentials relative to conventional proteins.

Crickets (Insect Protein)

Vulnerability: low to moderate. Crickets are typically raised in climate-controlled enclosures, which buffers them against direct effects of weather extremes. The primary climate-related vulnerability lies in their feed supply; often grain-based feeds, which could be affected by droughts or crop failures.
Adaptive Capacity: high. Insect farming operations can be relocated or scaled modularly, and conditions (temperature, humidity) can be artificially maintained. Additionally, crickets can potentially be fed on a variety of organic side-streams or waste products, reducing dependence on conventional feeds and enhancing resilience (van Huis et al., 2013).
Mitigation Potential: high. Edible insects have a much smaller GHG footprint per kilogram of protein compared to livestock. Studies estimate cricket production can emit as little as 1–5 kg CO_2e per kg protein, depending on feed, which is an order of magnitude lower than beef (Oonincx et al., 2012). Land and water requirements for insects are also minimal.

Cultured Meat (Cell-Based Meat)

Vulnerability: moderate to low. Cultured meat production occurs in bioreactors within facilities, so it is insulated from direct climatic factors like temperature or rainfall. The main vulnerabilities are indirect: a heavy reliance on continuous energy supply (for bioreactor operation and maintaining sterile conditions) and inputs such as growth media (which currently are derived from agricultural products or fermentation). These dependencies mean that widescale cultured meat production could be impacted by climate-related disruptions to supply chains or energy infrastructure.
Adaptive Capacity: high. With adequate infrastructure, cultured meat production can be located almost anywhere (even in urban or climate-controlled environments) and could theoretically operate year-round independent of local climate. As renewable energy and smart grids are adopted, the reliability and sustainability of cultured meat systems might improve, enhancing their climate resilience. Adaptation measures include developing synthetic or plant-derived growth media that are less tied to crop agriculture, and on-site renewable energy generation or energy storage to buffer against grid instabilities.
Mitigation Potential: moderate (potentially high in the future). Early LCAs suggest cultured meat could greatly reduce land use (up to 90–99%) and GHG emissions (around 80% or more) relative to conventional beef production if production processes are optimized and powered by clean energy (Tuomisto & Teixeira de Mattos, 2011). However, current small-scale prototypes are energy-intensive, and if fossil fuels power the process, the GHG benefits shrink or could even reverse for certain meats (Lynch & Pierrehumbert,

2019). Assuming technological advances and decarbonized energy, cultured meat offers significant mitigation potential by reducing methane emissions associated with livestock. It is especially promising for mitigating climate impact of ruminant meat (beef, lamb) if it achieves cost and taste parity that would enable broad adoption.

Fava Beans (Vicia faba)

Vulnerability: high to moderate. Fava beans (broad beans) are a cool-season legume crop grown in parts of Europe; they are sensitive to high heat and drought, which are expected to become more frequent with climate change. Fava bean yields can be reduced substantially by heat stress during flowering and by water scarcity. Additionally, pests and diseases (such as aphids and fungal blights) may increase with warmer temperatures, posing further challenges (Stoddard et al., 2017).

Adaptive Capacity: moderate. As an annual crop, fava bean cultivation can adapt through measures like shifting planting dates, breeding or selecting heat- and drought- tolerant cultivars, and possibly expanding production into more northern regions with warming climates. Agronomic practices such as intercropping and integrated pest management can improve resilience. Fava beans have the advantage of nitrogen fixation, which improves soil fertility and reduces dependence on synthetic fertilizer – an adaptation benefit in rotations under climate stress. However, there are limits to how much the crop's biology can be adapted to extreme conditions, so significant climatic changes could constrain where fava beans are viable without irrigation.

Mitigation Potential: high (indirect). As a plant protein source, fava beans have a low GHG emission intensity – typically a few kilograms CO_2e per kg of protein, largely from farming operations and soil N_2O emissions, which are much lower than emissions from producing the same amount of animal protein (Poore & Nemecek, 2018). Moreover, by fixing nitrogen biologically, fava cultivation can reduce fertilizer-related emissions. Replacing some animal feed or human food protein with fava beans (e.g. using fava in plant-based meat alternatives or as animal feed to displace soy imports) can mitigate emissions from land use change and transportation as well (Multari et al., 2015). The crop also offers co-benefits such as improved soil health and farm biodiversity when used in crop rotations.

Lentils (Lens culinaris)

Vulnerability: moderate to high. Lentils are another pulse crop that thrives in semi-arid climates (commonly grown in parts of Canada, Middle East, etc.) and can be cultivated in European regions such as the Mediterranean and Central Europe. They are somewhat drought-tolerant compared to other legumes but are still vulnerable to extreme heat and changes in rainfall timing. Climate change may alter the suitable growing zones for lentils, potentially pushing production northward or to higher elevations to maintain yields (Mamakhai & Zagoruiko 2022).

Adaptive Capacity: moderate. Many adaptation strategies for other legumes apply to lentils: breeding for shorter growth cycles or heat tolerance, adjusting planting times to avoid peak summer heat, and employing water-saving farming techniques. Lentils are often grown in rotation (e.g. with cereals), which can help maintain soil moisture and fertility. As with other legumes, lentils improve soil nitrogen content and can be a component of climate-resilient cropping systems (Gupta et al., 2019). Expanding lentil cultivation in Europe could diversify farmers' crop options, although market and agronomic support would be needed.

Mitigation Potential: high. Lentils have a very low carbon footprint per unit of protein. According to global analyses (Poore & Nemecek, 2018), pulses like lentils can produce <2 kg CO_2e per kg of protein (excluding any post-farm processing), which is drastically lower than most animal proteins. Increasing human consumption of lentils (in soups, pastes, or as ingredients in plant-based foods) in place of meat can significantly reduce diet-related emissions. Lentils store well and have high protein content, making them an attractive alternative from a sustainability perspective. Encouraging dietary shifts towards pulses like lentils aligns with both mitigation and nutrition goals (McDermott & Wyatt).

Microalgae

Vulnerability: low to moderate. Microalgae (such as spirulina, chlorella, and others) can be cultivated in various systems: open ponds, closed photo-bioreactors, or fermenters (heterotrophic algae). The vulnerability of microalgae production to climate depends on the method. Open pond cultivation is weather-dependent: extreme temperatures, evaporation, or contamination events (e.g. due to heavy rains or invasive species) can affect yields, so climate change could introduce volatility. In controlled bioreactors, microalgae production is largely shielded from external climate factors, aside from the need to maintain temperature and light (which can be done with artificial systems).

Adaptive Capacity: high. Microalgae cultivation is rather flexible: production can be located in climate-controlled facilities or in regions with favorable climates (e.g. using waste CO_2 and warm conditions in southern Europe). For outdoor systems, selecting robust algal strains that tolerate a range of conditions or can outcompete contaminants is an active area of research. In an adaptation context, microalgae offer the unique benefit of being able to utilize non-arable land (deserts, coastal areas) and saline or wastewater for growth, thereby reducing competition with traditional agriculture and providing a buffer against terrestrial crop failures (Yu et al., 2024). If one region becomes less suitable due to climate shifts, production can potentially be moved to another.

Mitigation Potential: moderate to high. Microalgae are very productive per unit area – they can yield more protein per hectare than conventional crops or livestock. They also can capture CO_2 during growth (Vale et al., 2020). However, the total GHG footprint depends on inputs, such as energy for mixing, pumping, and drying, as well as nutrient supply. With renewable energy and nutrient recycling, microalgae protein can have a low GHG footprint, potentially comparable to other plant proteins (Ali et al., 2025). If produced at scale suing low-carbon circular systems, microalgae-based foods or feeds could displace some high-impact protein sources. They do not require soil or pesticides and can be part of a circular bioeconomy (e.g. using power plant flue gas CO_2 and waste heat). Several European startups are already producing microalgal protein for human food supplements or animal feed, indicating growing feasibility.

Oats (Avena sativa)

Vulnerability: moderate. Oats are a temperate climate cereal grain, well-suited to cooler and wetter parts of Europe (such as Scandinavia, the UK, and parts of Central Europe). Climate change impacts on oats include the risk of higher temperatures and drought in some regions reducing yields, while in northern zones a longer growing season might improve production if water is sufficient. Oats are somewhat hardy, but prolonged heat above ~30°C or water stress during grain filling can harm yield (Barnabás et al., 2008). Changes in disease and weed pressure with warmer winters could also affect oat cultivation.

Adaptive Capacity: moderate. Oat breeders are developing varieties with improved heat and drought tolerance, which has a potential to aid adaptation (Sandras et al., 2017). Agronomic adaptation includes shifting cultivation to more suitable regions as climates change, e.g., extend northward and employing practices to retain soil moisture (Singh et al., 2024). Oats are often grown in rotation and can benefit from preceding legumes to improve nitrogen availability (Barsila, 2018). As a relatively resilient crop, oats could remain a staple in European agriculture under moderate climate change, but extreme scenarios of warming could restrict their range to north Europe or high elevations (Elsgaard et al., 2012).

Mitigation Potential: moderate. Oats have garnered attention not just as animal feed but as a human protein source, particularly with the rise of products like oat milk and oat-based meat analogues. The GHG emissions from oat production are low (on the order of 1–2 kg CO_2e per kg of oats and ~5–10 kg CO_2e per kg protein since oats are less protein-dense than legumes) (Poore & Nemecek, 2018). When oats replace dairy or meat products (e.g. oat milk vs. cow's milk), significant emission savings occur. Oats also typically require less fertilizer than more intensive crops like wheat or maize, especially if grown in rotation, further reducing emissions (Singh et al., 2024). The mitigation contribution of oats in a protein transition is moderate because while they are sustainable, their protein content is lower (Kumar et al., 2021). However, as part of a diversified strategy (such as using oats as a base for plant protein foods), they support emissions reduction and resource-efficient food production.

Quinoa (Chenopodium quinoa)

Vulnerability: moderate. Quinoa is a pseudo-cereal originally from the Andean region, known for its high nutritional value and ability to grow in poor soils and dry conditions. It has been introduced to parts of Europe (e.g. Spain, Italy, France, UK) on a small scale. Quinoa varieties are quite adaptable; some are tolerant to salinity and drought (Hinojosa et al., 2018). However, quinoa's optimal growing conditions are generally cool daytime temperatures with cold nights (as in high altitudes), making it ill-adapted to very high temperatures during flowering and seed set (ibid.). In a warming climate, lowland cultivation of quinoa in Europe might face challenges unless heat-tolerant varieties are used (Jacobsen, 2017).

Adaptive Capacity: moderate. The adaptive capacity of quinoa lies in its genetic diversity; plant breeders are working on developing quinoa strains suited to different climates, including European latitudes (ibid.). Quinoa's tolerance to water scarcity and saline soils is a strength; it could be grown on marginal lands that are less useful for other crops, providing an adaptation strategy for farmers in drought-prone areas (Aly et al., 2018). There is potential to incorporate quinoa into crop rotations to diversify production and spread climate risk (Bazile et al., 2022). However, expanding quinoa production will require knowledge transfer and possibly policy support, as it is still a novel crop for European farmers.

Mitigation Potential: moderate. Quinoa, when produced without excessive processing or transport, has a relatively low environmental footprint similar to other grains or pulses. Its GHG emissions per kg of protein are low, although precise values depend on yields and inputs (Degieter et al., 2025). By offering a high-protein, gluten-free grain alternative, quinoa can substitute for some animal protein in diets and add to the variety of sustainable plant-based foods. The current scale of quinoa production in Europe is small, so near-term mitigation impact is limited, but has a potential to grow. Additionally, encouraging quinoa consumption has a potential to lessen reliance on imports of other protein-rich grains and animal protein, indirectly contributing to emission reductions (Glatzel et al., 2025).

Rapeseed (Brassica napus)

Vulnerability: high. Rapeseed (canola) is widely grown in Europe for vegetable oil, with the residual protein-rich meal typically used for animal feed. Climate change poses several threats to rapeseed: it is sensitive to heat and drought during flowering and seed development, and milder winters can exacerbate pest problems (such as cabbage stem flea beetle, already a major issue in parts of Europe) (Ortega-Ramos et al., 2022; Zheng et al., 2020). Recent years have seen rapeseed yields drop in some regions due to summer droughts and pest pressures (Pullens et al., 2019).

Adaptive Capacity: moderate. Adaptation options for rapeseed include breeding for drought and heat tolerance, improving pest and disease resistance, and adjusting sowing dates (many rapeseed varieties are sown in autumn in Europe, so climate shifts in winter/spring timing matter). Literature points to exploration of mixed cropping techniques to shield young rapeseed plants from stress (Lizarazo et al., 2020). As a deep-rooted crop, rapeseed can access soil moisture better than shallow-rooted plants, which provides some resilience to moderate drought. However, severe climate stress could significantly affect its viability in traditional growing areas; farmers might shift more production to northern Europe under warming scenarios (Pullens et al., 2019).

Mitigation Potential: high (with full utilization). Rapeseed's significance for mitigation in this context comes from better utilizing its protein byproduct. Currently, the rapeseed meal after oil extraction is mostly fed to livestock. If processed and upgraded for direct human consumption (as a flour or isolate), rapeseed protein could supply a substantial amount of plant protein with very little additional land use, since the crop is primarily grown for oil. This is essentially a waste-to-food valorization: using an existing resource more fully. The GHG emissions attributed to rapeseed protein would be low because the main emissions are allocated to the oil product; in a system expansion view, rapeseed protein for food has potential to complement or replace other protein sources (like imported soy or animal products) at a minimal incremental footprint. Thus, integrating rapeseed protein into the human food supply could yield notable emission savings and reduce reliance on more GHG-intensive (Du et al., 2025). One caveat is that rapeseed cultivation itself must remain viable under climate change to harness this potential, which circles back to the need for adaptation in how and where rapeseed is grown.

Single-Cell Protein (Microbial Fermentation)

Vulnerability: low. Single-cell protein refers to edible microbial biomass produced via fermentation, such as yeast, fungal mycoprotein or bacterial protein. These production systems are typically entirely indoors in bioreactors, unaffected by weather or seasonal climate variation and can operate in controlled conditions year-round. The main external dependencies are energy and feedstock inputs (e.g. sugars and organic waste) (Martínez-Ibáñez et al., 2025). Climate change impacts on those inputs (for instance, availability of feedstock if it's agricultural or reliability of electricity) are the indirect vulnerabilities. Overall, the direct vulnerability of single-cell protein production to climate is very low compared to traditional agriculture (Bogdahn, 2015).

Adaptive Capacity: high. These systems are highly controllable and can be located strategically (even in urban/industrial areas). They can also switch feedstocks if designed flexibly: for example, if sugar prices rise due to crop failures, a facility might use another carbon source like ethanol or certain wastes, given that the microbes can metabolize it. Some advanced concepts use emissions themselves as inputs (e.g. bacteria that consume CO_2 or methane), with a potential to turn a climate problem into a feedstock supply. If there is sufficient infrastructure and energy available, single-cell protein production can be scaled up to meet demand when other protein sources falter, making it a potential tool for food security and climate adaptation (Li et al., 2024).

Mitigation Potential: high. Fermentation-derived proteins can be extremely resource-efficient at a large scale. For example, mycoprotein products have been shown to generate far lower GHG emissions per kilogram than beef or pork, with potential for even greater improvements if renewable energy is used (Finnigan et al., 2010). Bacterial single-cell proteins grown on waste gases can be nearly carbon-neutral or even carbon-negative if they capture emissions that would otherwise occur (Zhuang et al., 2024). Additionally, land use is negligible for these systems, relieving pressure to clear forests for agriculture. If European consumers and feed industries embrace single-cell proteins (for example, incorporating microbial protein in animal feed to displace soy, or as direct food ingredients), there is significant potential to cut GHG emissions associated with both domestic production and imported feed commodities. The scalability and year-round production capability also mean it could quickly contribute to emissions reduction if supported by policy and investment (Nath, 2025).

Cross-cutting Findings

Across these nine sources, a general pattern emerges: novel proteins produced in controlled environments (cultured meat, insects, microalgae in bioreactors, single-cell fermentation) tend to have lower direct vulnerability to climate change and higher adaptive capacity, due to lower degree of direct exposure to climatic fluctuations. Their successful adaptation mainly hinges on securing stable energy and input supplies, which can be managed with proper planning and infrastructure (e.g. backup systems, diverse supply chains, renewable energy integration). In contrast, field-grown protein crops (fava, lentil, oat, quinoa, rapeseed) are more sensitive to direct climate stressors, also observed in other agricultural crops, e.g., maize (Webber et al., 2018). They will require significant adaptation efforts in agronomy and breeding to maintain yields under future conditions. However, these plant-based sources are already part of existing food systems and can often be expanded or encouraged with relatively low-tech solutions and policy incentives to farmers, making them accessible and cost-effective in the near term.

In terms of mitigation potential, all nine novel protein sources show substantially lower GHG emissions per unit of protein than ruminant animal proteins (beef and lamb), and most are lower than pork and dairy as well. Plant- and fermentation-derived proteins generally have the lowest GHG intensities, while insects and cultured meat can have footprints comparable to or slightly above those of plant proteins depending on rearing and energy inputs. Land use requirements for all alternatives are dramatically lower than for livestock; for instance, producing 1 kg of protein from legumes or microbial sources might use only a few square meters of land versus hundreds of square meters for 1 kg of beef protein (Poore & Nemecek, 2018; Alexander et al., 2017). This indicates significant potential for land sparing and associated carbon sequestration or biodiversity benefits if these alternatives replace a portion of animal agriculture. From a water use perspective, pulses and microbial proteins also generally use less water than livestock production, though careful management is needed for water in algae cultivation.

Table 1. *Summary of climate vulnerabilities and mitigation potentials of nine novel protein sources in Europe under climate change scenarios.*

Protein Source	Key Climate Risks & Opportunities	Adaptive Capacity	Climate Vulnerability
Crickets	**Risks:** Climate-linked feed crop failures; extreme heat events could overwhelm indoor cooling. **Opportunities:** Indoor farming buffers weather; can use alternative feed inputs (e.g., food waste) to reduce external dependency.	**High:** technologically and biologically flexible	**Low-moderate:** well-insulated from direct climate impacts; manageable indirect risks.
Cultured Meat	**Risks:** High energy demand makes it vulnerable to power outages or high energy costs; reliant on stable supply of growth media inputs (which could be disrupted). **Opportunities:** Not land-dependent; could relocate facilities as needed, and improvements may cut resource needs.	**Moderate:** high long-term potential, but current processes are rigid	**Moderate-low:** exposure to gradual climate change, but some vulnerability to infrastructure failures.
Fava Beans	**Risks:** Heat waves and spring drought reducing yields; expanded pest/disease range with warming. **Opportunities:** Nitrogen-fixing trait useful under climate stress; potential expansion into cooler areas as they warm.	**Moderate:** traditional breeding and farming practices can partly adapt	**High-moderate:** yield losses likely in warmer/drier parts, but tolerant in cooler climates; moderate overall resilience.
Lentils	**Risks:** Increased drought frequency in semi-arid zones; heat stress during flowering in hotter climates. **Opportunities:** Highly drought-tolerant crop; new regions at higher latitudes suitable with warmer temps.	**Moderate:** some genetic diversity and agronomic flexibility	**Moderate-high:** Generally resilient to dry conditions, though extreme heat can impact; one of the more climate-hardy crops.
Microalgae	**Risks:** Open-pond systems vulnerable to temperature extremes, evaporation, and contamination; water scarcity in drought regions. **Opportunities:** Can be cultivated in closed systems insulated from climate; may utilize waste CO_2 and non-arable land, offering carbon capture synergies.	**High:** many species/strains to choose, and systems engineered for control	**Low**: production can be relocated or shifted to closed systems; inherently adaptable, albeit with some cost implications.
Oats	**Risks:** More frequent drought and heat in growing season harming yields; possible uptick in diseases (rusts) with warmer, humid conditions. **Opportunities:** Longer growing seasons in northern Europe; could shift to winter oat varieties if milder winters, improving yields.	**Moderate**: extensive breeding programs and agronomic know-how	**Moderate**: some yield decline expected under climate stress, but oats can be adjusted to new conditions; moderate vulnerability overall.

Quinoa	**Risks:** Susceptible to high heat during flowering; humidity and rainfall can trigger downy mildew disease and reduce seed quality. **Opportunities:** Warmer climates open new suitable areas (north Europe); extremely drought- and salt-tolerant varieties could thrive where other crops fail.	**Moderate**: broad genetic diversity but limited current cultivation experience	**Moderate**: mixed outcomes: could flourish in some new regions but struggle in others; moderate adaptive potential through breeding.
Rapeseed	**Risks:** Spring heat waves and dry spells during flowering severely cutting yields; increased pest survival and disease pressure with milder winters and warmer seasons. **Opportunities:** Expansion into currently cooler zones (if winters warm enough for cultivation); CO_2 fertilization offering slight yield buffering.	**Moderate**: significant breeding and agronomic efforts, though constraints in extreme scenarios	**High:** yields are very climate-sensitive; without major adaptation, production may decline in many areas under climate change.
Single-Cell protein	**Risks:** Dependent on continuous energy and feedstock supply (power outages or feed disruptions could halt production). **Opportunities:** Not weather-dependent; can use various feedstocks (sugars, gases) including waste emissions, offering flexible, year-round production.	**High:** industrial process can be engineered and scaled; strain and feedstock can be changed as needed	**Low**: highly controllable environment and flexible siting make it resilient to climate variability; minimal direct exposure.

4. Discussion

The results underscore the dual role that alternative protein sources can play in climate change mitigation and adaptation within Europe's food systems. By significantly lowering GHGs emissions associated with protein production, these novel sources offer a pathway to mitigate climate change. At the same time, many of them provide opportunities to adapt the protein supply chain to be more resilient against climate-related disruptions. This aligns with the core idea that a sustainable food transition can deliver co-benefits for both reducing climate change and coping with its impacts.

One of the clearest findings is that no single protein source is a panacea; each has its own strengths and challenges. For instance, plant-based proteins like fava beans and lentils are immediately available, cost-effective, and culturally familiar in various European cuisines, making them prime candidates for scaling up in diets to achieve rapid emission reductions. Their mitigation potential is unquestionable given their low emissions profile. However, their production remains tied to the climate in farmers' fields, meaning that without adaptation measures (such as improved varieties and climate-smart farming), their yields and reliability may be compromised by more extreme weather patterns. This suggests that policies to promote legumes and other plant proteins should be coupled with robust agricultural adaptation strategies and research, such as breeding programs for drought-resistant pulses or incentives for water-efficient irrigation infrastructure.

On the other hand, high-tech alternatives like cultured meat and single-cell protein promise a more fundamental decoupling of protein production from natural climate variability. If powered by renewable energy and sustainable inputs, these technologies could provide large quantities of protein with minimal land use and potentially year-round consistency. From an adaptation perspective, they could allow food production to expand into controlled, urban, or otherwise climate-sheltered environments, thereby reducing vulnerability to climate extremes that devastate farms. The trade-off, however, is that these systems depend on complex technological infrastructure and steady energy supplies. Extreme events like power grid failures, supply chain breakdowns, or other systemic shocks could interrupt production. Policymakers should recognize that resilience is multi-faceted: moving food production indoors solves some vulnerabilities but creates others (notably reliance on technology and energy). Thus, diversification across different alternative proteins is key, and protein portfolio approach can hedge against the limitations of any single solution.

Another important discussion point is the role of policy and public acceptance. The European Green Deal and Farm to Fork Strategy provide a high-level mandate to support alternative proteins but translating that into tangible outcomes requires addressing regulatory hurdles and consumer perceptions. For example, insects and cultured meat are novel to many consumers and must overcome psychological and cultural barriers (Hartmann & Siegrist, 2017). The EU's novel food regulations also necessitate rigorous safety and nutritional assessments before such products can be widely marketed. The GIANT LEAPS project and similar research efforts are critical in building the evidence base to ensure these novel foods are safe, nutritious, and acceptable, alongside being climate friendly. Policy incentives might be needed to encourage early adoption – such as supporting pilot production facilities, subsidizing farmers to grow high-protein crops like legumes or quinoa or including sustainable protein criteria in public procurement (e.g. for school or hospital meals). Additionally, putting a price on carbon or implementing true-cost accounting in food could indirectly favor low-emission protein sources by making high-emission foods relatively more expensive, thereby nudging both producers and consumers toward alternatives (Searchinger et al., 2019).

The discussion of mitigation potential also raises the issue of scale and displacement. The climate benefit of alternative proteins will only be realized if they actually displace a significant portion of conventional animal protein production and consumption, rather than simply adding to an ever-growing food supply. In a worst-case scenario, one could imagine alternative proteins becoming an added market segment (for niche consumers) while traditional meat and dairy consumption remains high or even grows, leading to continued high emissions. To avoid this, climate and food policies should aim for a genuine substitution effect, for example, through dietary guidelines that emphasize plant proteins, campaigns to reduce meat intake, and possibly supply-side measures to manage livestock production levels in line with climate goals. Encouragingly, some European countries are already incorporating sustainability into dietary recommendations and exploring measures like meat taxes or subsidies for plant-based foods (Springmann et al., 2018). Our results bolster the argument that such measures could have substantial payoffs, given the magnitude of emission reductions possible and the added resilience benefits.

From an adaptation and food security standpoint, incorporating novel proteins could buffer Europe against both local and global food shocks. Climate change is projected to impact major protein sources globally: for example, heat and disease stress on livestock, or declining yields in soybean-producing regions. By developing alternative protein industries domestically (be it insect farms, algae cultivation, or fermentation facilities), Europe can reduce dependence on imported feed and food, which is a strategic advantage in an uncertain climate future (European Commission, 2020). Several of the novel proteins discussed (e.g., single-cell protein from bacteria consuming waste gases, or microalgae grown using recirculated wastewater) have the intriguing benefits of using resources that are by-products or waste from other processes, in this way increasing circularity of food production (van Zanten et al., 2023). This circular approach enhances overall system resilience and sustainability. It also highlights an often-under-appreciated facet of climate adaptation: innovation can create new ways to produce food that are inherently more resilient, not just adapting existing methods.

Despite the positive prospects, there are limitations and uncertainties to consider. The LCA data for some novel proteins (especially cultured meat at scale, or certain fermentation methods) are still preliminary and oftentimes contested. As technologies improve, footprints can decrease, but unforeseen challenges could also arise (for example, large bioreactors may have diminishing efficiencies or new waste streams to manage). Additionally, our qualitative assessments of vulnerability and adaptive capacity, while grounded in expert knowledge, would benefit from more quantitative research. For instance, more studies are needed on how precisely different climate scenarios will affect yields of specific protein crops like oats or quinoa in Europe, or how an insect farm might cope with a 5-day power outage during a heatwave. Similarly, social factors (will consumers readily eat insect-based foods or cultured meat?) will influence the real-world impact of these protein sources on both mitigation and adaptation outcomes. If certain alternatives face public resistance, their contribution will be limited, no matter what their technical merits might be.

Our findings suggest some priorities for future research and policy. Breeding programs for climate-resilient high-protein crops (e.g. heat-tolerant lentils or disease-resistant fava beans) emerge as a clear need, combining the adaptation and mitigation agenda. In the technology realm, investments to improve the efficiency of cultured meat and fermentation processes (for example, developing strains that yield more protein with less energy, or bioreactors that can utilize variable renewable power effectively) will directly enhance their climate benefits. Additionally, interdisciplinary research that examines the integration of these novel proteins into existing agricultural and food systems can reveal synergies or unintended consequences. For example, if many Europeans shift to oat milk from dairy, what are the implications for land use (e.g., less pasture) and how can freed-up grasslands be repurposed (perhaps for biodiversity or carbon sinks)? Or, if insect farming scales up using agricultural by-products, could that compete with livestock feed or composting uses, and what would be the net effect on emissions? When considering these multifaceted effects, a systems perspective is essential.

Ultimately, this discussion highlights that alternative protein sources should be viewed as complementary pieces of a larger transformation toward a sustainable and climate-resilient food system. They each contribute differently: some cut emissions drastically, some provide a safety net against climate shocks, and some do both. The most robust strategy for Europe will involve pursuing a diverse array of these alternatives in parallel. In doing so, Europe can reduce its agricultural emissions (helping to meet climate mitigation commitments under the Paris Agreement) and build a food supply that can endure the stresses of a changing climate, all while providing healthy locally based nutrition to its population.

5. Conclusions

This study presented an initial assessment of climate adaptation and mitigation potential of nine novel protein sources in Europe, evaluating each for its potential to mitigate climate change and its capacity to adapt to or withstand climate impacts. Our findings confirm that alternative proteins can play a pivotal role in a climate-friendly food transition. All nine sources investigated – spanning plant, microbial, and novel animal-origin proteins – have substantially lower greenhouse gas footprints than traditional animal proteins, indicating significant mitigation potential if they are incorporated into diets at scale. Additionally, many of these sources (especially those produced in controlled environments like insects, cultured meat, and fermentation-based protein) offer promising adaptation advantages, as they are less directly vulnerable to climate stresses and can enhance the resilience of the food system. The six-step methodology developed for assessing climate adaptation and mitigation potential provides a useful framework to systematically compare different protein options. Through an application of the framework, it was demonstrated that each of the nine novel protein sources examined has a unique profile of climate vulnerability and adaptive capacity that should be considered alongside its climate mitigation potential. For instance, field-grown protein crops will require parallel investments in agricultural adaptation to realize their benefits under climate change, whereas technologically driven solutions will require investments in infrastructure and energy sustainability to be truly climate-proof.

Diversification and investment in alternative proteins is crucial and instead of relying on a single solution. This can be done by creating enabling conditions for multiple sustainable protein industries to grow, which includes supporting research and development (such as the GIANT LEAPS and other Horizon4Protein projects) to close knowledge gaps and updating regulatory frameworks to safely integrate new protein products into the market while aligning economic incentives with climate-smart dietary shifts. Encouraging dietary change through education and awareness campaigns is also the key, so that consumers are informed about both the health and climate benefits of embracing alternative proteins. Aligning protein production and consumption with climate mitigation and adaptation goals will require coordinated efforts across science, industry, policy, and society. The insights from this initial assessment support a strategic pathway where alternative proteins are integrated into climate policy as both mitigation actions (reducing emissions from food production) and adaptation measures (building a flexible, robust food system). By acting on the evidence and recommendations, we can move closer to food systems that are sustainable, secure, and aligned with our climate objectives.

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