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Designer meat and cultured meat from broiler chickens

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Abstract

The world demand for poultry meats is growing more rapidly than that for any other type of animal protein, although the challenges posed by conventional broiler husbandry practices are growing exponentially at the same time. The following review seeks to highlight the potential of two innovative concepts for future chicken production: designer broiler meat – where improvements in nutritional profile are achieved through dietary, genetic and microbial manipulation of the living animal – and cultured chicken meat, derived from *in vitro* cultivation of avian myosatellite cells under bioreactor conditions. The two strategies will be analyzed along four axes: (1) the science and feasibility of the nutritional upgrading process, specifically the introduction of high levels of LCPUFA, CLA, selenium, vitamins D and E, carotenoids, and organic zinc into the meat; (2) the known effects of enhanced nutritional value on various biomarkers of health, such as CVD risk factors and inflammation; (3) carbon footprint, land use, water requirements and energy intensity of the production process relative to both conventional broiler production and alternative sources of protein; and (4) regulatory, market, technological and economic barriers to scaling up the technology. Another important aspect covered by the article in terms of critical evaluation is the myth that all chicken meat is nutritionally the same irrespective of the production method employed. Other aspects discussed include omega-3 oxidation and toxicity limits of selenium along with the open questions regarding safety data for cultured meat. One of the conclusions drawn from this review is the immediate ability of designer broiler meat to become a way to deliver targeted micronutrients with the current infrastructure intact. Cultured meat, on the other hand, can provide immense environmental benefits in the future but cannot currently overcome high energy requirements and scaling problems.

Keywords: cultured meat, designer broiler, omega-3 enrichment, carbon footprint, cell-based agriculture, sustainable poultry production, biofortification

1. Introduction

Chicken meat has become the most-consumed meat on the planet; it has surpassed pork as the most consumed meat at the global level for the first time in 2019, and there is no question about the direction: according to the FAO projections, poultry meat consumption will rise by an additional 40 percent by 2050, owing mainly to population growth, urbanization, increased income in developing nations, and a growing trend toward healthier diets that avoid red meat (FAO, 2023) ^[15]. Broilers make up the vast majority of this increase in demand, and the modern broiler chicken represents one of the wonders of selective breeding; whereas it took a full 84 days for a broiler to reach a weight of 1.5 kilograms at maturity in the 1950s, it takes only 35 days nowadays to reach a weight of 2.5 kilograms, all while having a feed conversion ratio of less than 1.7 kilograms feed per kilogram of weight gained (Havenstein *et al.*, 2023) ^[19].

The fatty acid composition of contemporary commercial broiler chicken breast and thigh meat is marked by an imbalance between n-6 (omega-6) and n-3 (omega-3) polyunsaturated fatty acids that is usually higher than 12:1 for breast muscle meat and 20:1 for skin-on thigh meat, due to the universal feeding of poultry with corn-soy diets containing excessive amounts of linoleic acid and negligible levels of alpha-linolenic acid and preformed docosahexaenoic acid (Simopoulos, 2020) ^[38]. In terms of micronutrients, their availability is also determined by the type of diet used. Selenium intake in broilers relies solely on the geographical provenance of feed ingredients, while vitamin E supply is marginal in standard diets, and fat-soluble vitamins

D and carotenoids are nutritionally insignificant without intentional fortification of feed. Two distinct, yet philosophically aligned approaches have developed in food technology with respect to nutritional improvement of poultry meats within this nutritional context. These approaches are designer broiler meat production and cultured chicken meat production.

But there are implications of this merger far beyond just improving nutrition for consumers. According to research, animal agriculture is responsible for about 14.5% of global anthropogenic GHGs, with cattle accounting for 65%, but the production of broilers also has its share of impacts on the environment: life cycle analyses show that conventional broiler production releases between 4.5 to 6.9 kg of CO₂ equivalent per kg of live weight, mostly because of crop cultivation and methane emissions from manure, in addition to the nitrous oxide generated from farm energy usage (Poore & Nemecek, 2018; Sandstrom *et al.*, 2022) ^[30, 34]. The claims by cultured meat supporters that cell-based products would resolve the problem of land usage, decrease GHGs, and eliminate animal welfare issues associated with the current system have been seriously challenged by recently conducted more robust LCA, especially in terms of climate equivalence of CO₂ versus CH₄ (Lynch & Pierrehumbert, 2019) ^[25].

This review critically analyzes the scientific fields of designer broiler meat and cultured chicken meat, placing them in the context of their common framework of nutrition performance, environmental effect, and feasibility of implementation. If the scientific evidence base lacks strength, is exaggerated, or has been contradicted by other studies, this is clearly stated in this review.

2. Nutritional Profile of Conventional Broiler Meat: Baseline and Limitations

Broiler meat is a good provider of high biological value

protein with DIAAS of around 1.08 for the cooked breast meat, which indicates abundant levels of all indispensable amino acids compared to the requirement by an adult, especially branched chain amino acids such as leucine, isoleucine, and valine, which play important roles in muscle protein synthesis (FAO, 2023; Van Vliet *et al.*, 2020) ^[15, 49]. This is a true fact with no argument whatsoever about the protein quality aspect. Shortcomings of the broiler meat are primarily found in the fat and micronutrients sections.

Despite being quite low, with an average of 1.0 to 1.5 g per 100 g in the skinless breast and 8 to 12 g per 100 g with skin in the thigh, the composition of fatty acids is rather poor. For example, the balance between omega-6 and omega-3 fatty acids is usually poor (it varies from 12:1 to 20:1) as a result of the predominance of linoleic fatty acids, which occur in corn and soybean oil. The omega-6 to omega-3 ratio in commercially produced broilers is not as good as in wild game birds (3:1-5:1) or pasture-reared broilers eating forages and insects (6:1-9:1) (Simopoulos, 2020) ^[38], indicating that the present system has managed to degrade a better ratio existing before industrialization. Finally, the concentration of selenium in commercially produced broiler meat is 15 to 22 µg per 100 g in North America but can be only 5 to 12 µg per 100 g in Europe and South Asia due to the poorer selenium content in the soil of those areas (Surai & Fisinin, 2021) ^[42]. The vitamin E levels are universally low at 0.3–0.5 mg per 100 g in commercially available poultry, which is inadequate to prevent oxidation of the polyunsaturated fatty acids in the meat, not to mention meeting the adequate daily intake level of 15 mg for an adult (Surai, 2020) ^[41]. Summary of key compositional differences between conventional broiler meat, designer broiler meat and current-generation cultured chicken meat, provided in the comparative framework in table 1 follow.

Table 1: Comparative nutritional and environmental profile of conventional broiler, designer broiler and cultured chicken meat. Values represent approximate ranges from published literature

Parameter	Conventional Broiler	Designer Broiler	Cultured Chicken Meat
Omega-6:Omega-3 ratio	12:1 to 20:1	4:1 to 8:1	Tunable (1:1 to 5:1)
DHA (mg/100 g)	~25-60	150-400	100-600 (designed)
Saturated fat (g/100 g)	3.0-3.6	2.0-2.8	0.5-2.5 (designed)
Selenium (µg/100 g)	15-22	40-90	Variable
Vitamin E (mg/100 g)	0.3-0.5	2.0-8.0	Not inherent
CLA (mg/100 g)	10-30	60-180	Not inherent
Antibiotic residues	Present (risk)	Reduced/none	Absent
Zoonotic pathogen risk	High	Reduced	Eliminated
GHG (kg CO ₂ eq/kg meat)	4.5-6.9	~5.0	4.0-25.0 (system-dep.)
Land use (m ² /kg)	7.3-9.8	Similar	0.1-0.5
Water use (L/kg)	4,300-5,400	Similar	~370-840

3. Designer Broiler Meat: Nutritional Engineering Strategies

3.1 Concept and Rationale

Designing broiler meat, as referred to throughout this paper, entails designing the meat obtained from live broilers in which there is purposeful alteration of the nutrient composition achieved by using one or all of the following approaches: diet fortification with nutrients aimed at the broiler, selective breeding or genetic engineering with regard

to metabolisms of the animal, manipulation of the intestinal microflora using probiotics or prebiotics, as well as changes in husbandry aimed at affecting feeding behavior. The rationale behind designer meat in the broiler is based on the fact that there is considerable flexibility of the muscle composition in terms of the genetic background of the broiler, and nutrients such as lipids, fat-soluble vitamins and minerals that are part of the diet are deposited to muscle and fat tissue predictably (Cherian, 2022) ^[7].

Table 3: Key dietary enrichment strategies for designer broiler meat production: target nutrient, dietary vehicle, inclusion rate, fold-change in meat concentration and representative reference

Target Nutrient	Dietary Strategy	Dose / Inclusion	Fold Change in Meat	Key Reference
Omega-3 (DHA+EPA)	Microalgae (<i>Schizochytrium</i> sp.)	0.5-1.5% diet	3-8x DHA increase	Bou <i>et al.</i> , 2022 ^[3]
Omega-3 (ALA)	Flaxseed / Chia seed	8-15% diet	2-4x ALA increase	Peiretti <i>et al.</i> , 2022 ^[28]
CLA	Rumen-protected CLA supplement	0.5-2.0 g/kg diet	3-6x CLA increase	Trigueros <i>et al.</i> , 2020 ^[45]
Selenium (organic)	Se-yeast / Selenomethionine	0.3-0.5 mg/kg diet	2-4x Se increase	Surai & Fisinin, 2021 ^[42]
Vitamin E	dl-alpha-tocopherol acetate	150-300 mg/kg diet	5-10x increase	Lopez-Bote <i>et al.</i> , 2019 ^[24]
Vitamin D3	Cholecalciferol supplement	2000-4000 IU/kg diet	4-8x increase	Browning & Cowieson, 2020 ^[4]
Carotenoids	Marigold extract (<i>Tagetes</i>)	1-3 g/kg diet	3-7x increase	Kljak <i>et al.</i> , 2021 ^[23]
Zinc (organic)	Zinc methionine chelate	50-80 mg/kg diet	1.5-2x increase	Swiatkiewicz <i>et al.</i> , 2021 ^[43]

3.2 Omega-3 Fatty Acid Enrichment

Enrichment with Omega-3 PUFA is the most commercially advanced and medically supported facet of the designer broiler meat field. This particular biochemical pathway bears a strong resemblance to the one employed in designer eggs, in which the concentration of phospholipids in the skeletal muscles of a broiler bird depends on the availability of fatty acids in the bird's intestines. This dependence allows for quantitative prediction of dietary DHA and EPA content in terms of their incorporation into the sn-2 position of phosphatidylcholine and phosphatidylethanolamine in a broiler's membranes (Bou *et al.*, 2022) ^[3]. DHA enrichment by microalgae addition (0.5–1.5%) in broiler feed is a superior strategy to avoid the taste and smell problems arising from the use of more than 2% fish oil in the broiler diet, increasing breast meat DHA content from 25 to 60 mg per 100 g up to 150–400 mg per 100 g (Xiao *et al.*, 2021) ^[51]. One should note that consuming only 150 grams of such enriched meat could result in an intake of 225 to 600 mg DHA, thus surpassing the 250–500 mg recommendation from EFSA (2023).

Inclusion of flaxseed at 8 to 15% results in substantial ALA content in the broiler breast meat (2 to 4 times the control levels), while the DHA content remains very low due to the low liver delta-6 desaturase activity of the broiler bird, preventing elongation and further desaturation of ALA to DHA (Peiretti *et al.*, 2022) ^[28]. Inclusion of chia seeds (*Salvia hispanica*) at 8 to 12% provides the same amount of ALA content with improved palatability due to its better taste profile, without the presence of anti-nutritional factors such as cyanogenic glycosides and viscous mucilage which may cause malabsorption in large amounts. Alpha-tocopherol supplementation between 150 to 300 mg per kg feed along with the omega-3 fatty acids provides adequate protection from rancidity, reducing TBARS formation below threshold organoleptic levels for up to 10 to 14 days of chilled storage (Lopez-Bote *et al.*, 2019) ^[24].

While there are relatively fewer randomized controlled trials conducted on humans that have been specifically designed to examine the effects of omega-3 enriched broilers on human health, those which are present have shown encouraging results. In one parallel-group randomized control trial conducted for 12 weeks, it was shown that consumption of 150 grams of omega-3 enriched chickens (providing around 350 mg of DHA daily) increased erythrocyte membrane DHA content and reduced fasting serum triglyceride levels by 11% as opposed to regular chickens in healthy adult subjects with elevated triglycerides (Dawczynski *et al.*, 2018) ^[10].

3.3 Conjugated Linoleic Acid Enrichment

Conjugated linoleic acids (CLA) are a set of positional and structural isomers of linoleic acid that are generated mainly

through microbial biohydrogenation in ruminants' guts, and to a minor extent in non-ruminants due to delta-9 desaturase activity on trans-vaccenic acid. Endogenous CLA formation is low in monogastric poultry such as broilers; therefore, the dietary intake of CLA is critical for determining meat CLA levels. Dietary supplementation with rumen-protected CLA at a dose of 0.5 to 2.0 g/kg of diet increases the CLA content of breast and thigh meats 3 to 6 times compared to control (Trigueros *et al.*, 2020) ^[45]. Cis-9, trans-11 isomer (rumenic acid), the dominant form of ruminant-derived CLA and the one with the most convincing evidence for its anti-carcinogenic and anti-atherogenic effects in animal models, contributes between 80% to 90% of the total CLA deposition in the muscle of broilers supplemented with CLA. Clinical studies of CLA taken in meat products are based on the results of CLA supplements in capsule forms; there are only mild effects of reducing body fat mass and minor anti-inflammatory effects at doses of 3 to 6 g/day, which is far higher than food-intake doses of CLA.

3.4 Mineral Enrichment: Selenium, Zinc and Iron

Similar to selenium deposition in eggs, selenomethionine (selenium enriched yeast) deposition in skeletal muscle protein occurs about two times more efficiently compared to inorganic selenium (sodium selenite) and results in highly bioavailable selenium (85-90% absorption efficiency) in the form of meat proteins containing selenomethionine which effectively increases plasma selenoprotein P concentrations and erythrocyte glutathione peroxidase activities (the major functional biomarkers of optimal selenoprotein concentrations in tissues) (Surai & Fisinin, 2021) ^[42]. Organic selenium supplementation in broiler diets within 0.3-0.5 mg/kg feed results in deposition of 40-90 ug of selenium per 100 g of breast meat which allows a 150 g portion of this meat to contain 60-135 ug of selenium thus providing sufficient amounts (or even exceeding them) of the daily recommended intake in adults (55 ug/day) by only consuming one protein portion of food (Skrivan *et al.*, 2020) ^[39]. Moreover, antioxidant effect of high selenium content in meat itself is significant as muscle tissue selenoproteins inhibit lipid peroxidation and therefore improve the color retention of meat during storage (Surai, 2020) ^[41].

The enrichment of zinc by organic zinc chelates (zinc methionine, 50-80 mg per kg feed) increases zinc content in breast muscle meat from 1.5 to 2.0 mg/100 g to 2.5 to 3.5 mg/100 g, which is important due to the high bioavailability of zinc in meat compared to vegetable sources (Swiatkiewicz *et al.*, 2021) ^[43]. The issue is highly relevant for the countries of Asia and Africa where the problem of zinc deficiency and malnutrition persists among growing economies where the use of chicken products is increasing. Iron content in the breast meat of broilers is low as compared to red meats such

as beef (about 0.7 to 1.0 mg heme iron per 100 g as against 2.5 to 3.5 mg in beef) and the same cannot be increased using iron supplementation in broilers' diets (Pisarski *et al.*, 2020) [29].

3.5 Vitamin Enrichment

The enhancement of vitamin E is one of the most thoroughly studied designer broiler applications because of its dual function, which consists in increasing consumers' vitamin E consumption and protecting the PUFA content of the meat itself against oxidation in storage and cooking. The addition of dl-alpha-tocopherol acetate at a rate of 150 to 300 mg/kg diet five to ten times higher than the NRC minimum requirements raises the alpha-tocopherol content of the breast muscles from a baseline concentration of 0.3 to 0.5 mg/100 g to 2.0 to 8.0 mg/100 g (Surai, 2020) [41]. Thus, one hundred grams of meat that is highly fortified in terms of vitamin E will provide 3.0 to 12.0 mg vitamin E, or 20 to 80% of the recommended adult intake of 15 mg/day. The oxidative stability of meat has been extensively studied. Meat that contains vitamin E has a TBARS value of less than 0.5 mg malondialdehyde/kg throughout chilled storage for 10 to 14 days, while normal meat exceeds this limit in 5 to 7 days (Lopez-Bote *et al.*, 2019) [24].

The use of vitamin D₃ fortification in broiler chickens has gained popularity as a potential alternative for vitamin D intake via eggs. Vitamin D₃ dietary supplementation of 2,000 to 4,000 IU cholecalciferol/kg in diet results in meat that has 8 to 20 µg vitamin D₃ per 100 g compared with 0.1 to 0.4 µg found in regular broilers (Browning & Cowieson, 2020) [4]. Vitamin D₃ metabolite, 25-hydroxyvitamin D₃ [25(OH)D₃], accumulates much more effectively into muscle tissues and is available commercially in feed additives, resulting in meat that contains 15 to 40 µg 25(OH)D₃ per 100 g. Just one portion of such meat would be enough to fulfill an adult daily requirement of 15 µg of vitamin D₃ (Grundmann *et al.*, 2021) [18]. This vitamin D₃ enrichment strategy becomes even more valuable due to almost all meat consumers' practice of cooking their food prior to eating. Meat from broilers enriched with vitamin D₃ retains its vitamin content during cooking at temperatures of 75 to 85 degrees Celsius, which is the range used in household cooking, in the amounts ranging from 80 to 95% (Browning & Cowieson, 2020) [4].

3.6 Carotenoid and Pigment Enrichment

The carotenoid fortification of broiler meat is mainly motivated by market demands for yellow to golden colored skin and fat, which is associated with diets rich in carotenoids; however, additional nutritional advantages are achieved as a consequence of this process. The addition of marigold petal extract (*Tagetes erecta*), canthaxanthin or algae-based astaxanthin in the diet at 1-3 g/kg results in the deposition of xanthophylls into subcutaneous fat, muscle fat, and to a lesser degree lean muscle tissue at levels relevant to antioxidant activity (Kljak *et al.*, 2021) [23]. The deposition of lutein and zeaxanthin into broiler meat and fat contributes to the total intake of carotenoids in the diet of consumers, although the levels found in muscle tissue are significantly lower than those found in egg yolks and would not exceed the levels used in studies to increase macular pigment unless consumed in large amounts.

A daily dosage of 40-80 mg/kg of astaxanthin in broiler diets results in muscle tissue astaxanthin content of 0.5-2.0 mg/100g and increases the oxidative stability during storage while simultaneously exhibiting anti-inflammatory and post-

exercise recovery properties for the consumer although evidence through randomized controlled trials using broiler meat enriched with astaxanthin as an intervention tool is lacking (Kamath *et al.*, 2020) [21].

3.7 The Role of the Gut Microbiome

A new aspect in designer broiler meat research is the targeted modification of the broiler's gastro-intestinal microbiome for maximizing the availability of nutrients and their metabolism. Broiler's gut microbes include *Lactobacillus*, *Clostridium*, *Bifidobacterium*, and *Ruminococcus* in the ileum and cecae and contribute significantly to the mineral absorption, such as selenium, zinc, and calcium, as well as the biohydrogenation of polyunsaturated fatty acids (PUFA) and the production of short-chain fatty acids which influence the lipid metabolism of the liver and, thus, the muscle fatty acid profile (Ding *et al.*, 2020) [11]. Probiotics like multi-strain *Lactobacillus* and spore-forming *Bacillus subtilis* strains have demonstrated an improved omega-3 fatty acid transfer rate from feed to meat, a reduced pro-inflammatory arachidonic acid (AA; 20:4n-6) level in meat, and improved selenium uptake from inorganic feed sources by 15 to 30% relative to non-supplemented groups (Ding *et al.*, 2020) [11]. Prebiotics like fructooligosaccharides and inulin increase the proliferation of *Bifidobacterium*, which increases enterocyte performance, improving the absorption of fat-soluble vitamins. The microbiome is an untapped resource in the development of designer broiler meat and could be a promising factor in nutrient enrichment.

4. Science, Technology and Current Status of Cultured Chicken Meat

4.1 Foundational Biology

Cultured meat, otherwise known as cell-based meat, cultivated meat, or *in vitro* meat, refers to meat that is derived from isolating muscle stem cells (also referred to as myosatellite cells) from an intact organism through a biopsy, cultivating these cells using a nutrient-enriched growth medium and inducing their differentiation into myotubes, which will eventually develop into a tissue resembling regular meat in structure and composition (Post *et al.*, 2020) [31]. When it comes to broiler chickens specifically, the type of cells that are primarily used in cultured meat production include the avian myosatellite cells, which have the ability to maintain a high level of self-renewal and differentiation capacity while being cultured under the proper conditions; therefore, chicken has been deemed one of the easiest animals to produce cultured meat from (Datar & Betti, 2021) [9]. The first cultured chicken product was developed by Memphis Meats, now UPSIDE Foods, in 2017, after which GOOD Meat received the regulatory approval for its own cultured chicken in Singapore in 2020 the first cultured meat product authorized for public consumption in any country (Choudhury *et al.*, 2020) [8].

4.2 Cell Line Development and Proliferation

Cell line stability and scalability present the main technical obstacles in the production process of cultured chicken meat. Primary chicken myosatellite cells that are obtained from either chicken embryos or chicken muscle biopsy samples after hatching have limited replicative ability, with only 20 to 40 rounds of doubling prior to replicative senescence. Consequently, regular harvesting of biopsy samples or cell immortalization are required (Genovese *et al.*, 2022) [17]. Some of the current strategies being studied for cell

immortalization involve the use of TERT genes, overexpression of Myc family members, and utilization of CRISPR-Cas9 gene editing technology to inhibit the functions of aging-related regulators, such as p16/INK4a genes (Genovese *et al.*, 2022) [17]. The regulatory concerns related to cell immortalization are considerable and yet unresolved, and since the immortalized cells exhibit enhanced proliferation, a detailed evaluation is needed that differs from food safety assessments. As of now, guidelines and regulatory requirements in relation to cultured meat are lacking in regards to characterizing cell lines used in the production process (Bryant *et al.*, 2023) [5].

The second key technical and economic hurdle concerns the ingredients used in growth medium. Fetal bovine serum (FBS) served as the first source of the cocktail of growth factors (including insulin-like growth factor-1, fibroblast growth factors, epidermal growth factor, and others) necessary for the proliferation of myosatellite cells in the early studies of cultured meat. Such reliance poses three sets of issues – ethical (since it requires the collection of embryonic calf blood), safety (the possibility of infection from prions and xenogeneic diseases) and costliness (FBS costs around USD 800 to 1,500 per liter). Serum-free and animal-component-free (ACF) growth media, hence, are necessary steps towards commercial production and ethical acceptability of the technology (Humbird, 2021) [20]. The replacement of animal components with either plant-derived or recombinant growth factors appears possible, although not entirely so – several studies show the successful proliferation of avian myosatellite cells using growth factor cocktails combined with hydrolyzed plant material, though not at levels comparable to those obtained through the use of FBS (Post *et al.*, 2020) [31].

4.3 Scaffolding and Texture Engineering

An unstructured version of cultured meat in which myotubes are separated rather than organized as they are in conventional meats would not have the texture expected from a chicken breast or thigh (Rubio *et al.*, 2019) [32]. In order to produce an analog with the macroscopic structure of a chicken breast, a scaffold material must be used to give shape to the three-dimensional arrangement of aligned muscle fibers, allowing muscle to develop in such a way that the scaffold degrades into muscle after cultivation or remains intact as edible structural support in the final product (Rubio *et al.*, 2019) [32]. Edible scaffolding material options being actively explored include cellulose nanofibers derived from plants, mycoprotein (Quorn-type fungus mycelia), gels of soy protein isolate, pea protein scaffolds, and electrospun zein fibers each of which can support growth and development of muscle cells from chickens in the lab (Enrione *et al.*, 2022) [12]. Producing whole muscle cuts of any species on a scale suitable for cooking has not yet been accomplished, though minced and ground versions of cultured chicken meat have been successfully produced at a small scale in Singapore and the US.

4.4 Bioreactor Scale-Up

Moving from bench-scale culture flasks to bioreactors with sufficient capacity to produce meat in volumes which can compete economically in price points poses an enormous technical challenge. Given the limited cell density possible in suspension bioreactors constrained by oxygen diffusion to the cells, shear resistance to the cells, and waste accumulation very large volume reactors hundreds of thousands of liters of working volume per year for producing 1,000 tonnes per year

would be necessary given current cell density and conversion efficiencies (Humbird, 2021) [20]. In a highly critical techno-economic assessment carried out by Humbird (2021) [20], it was found that given realistic engineering assumptions including raw material costs, bioreactor costs, cleaning-in-place costs, and cold chain considerations the cost of goods of cultured chicken meat in a mature, optimized plant would be more than USD 25 per kg, while even the most optimistic estimate would put the bottom limit at USD 17 per kg as opposed to USD 1.5 to 3 per kg farmgate price for conventional broiler meat. The cost differential is not one that can be addressed merely through process optimization.

4.5 Nutritional Profile of Cultured Chicken Meat

The primary concern that remains constant in the debate about cultured meat is that the nutrient content of cultured chicken does not necessarily match that of conventional chicken meat and in many aspects can be entirely different if not explicitly tailored. *In vitro* cultured muscle tissue lacks the fat, connective tissue, and blood vessel cell lines that provide for the nutritional composition of the fat, collagen, and micro-nutrients found in whole muscle conventional meat, indicating that the cultured breast muscle will likely be less complex tissue than conventional muscle (Van Vliet *et al.*, 2020) [49]. The amino acid content of the myotubes in terms of their protein composition will be similar to the nutrient content of conventional chicken skeletal muscles, as both myosins, actins, and tropomyosins remain the same irrespective of the manufacturing process. However, the intramuscular fat component, which in the conventional chicken provides omega-3 fatty acids such as docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), conjugated linoleic acid (CLA), fat-soluble vitamins, and carotenoids, is lacking in cultured muscle unless supplemented through lipid emulsions in the growth media or co-cultivated with adipogenic cells (Datar & Betti, 2021) [9]. The crucial factor about the iron concentration of cultured meat is that it comes mostly from the heme iron bound in myoglobin just like in conventional meat while micronutrients like selenium, zinc, and vitamin D could be absent unless consciously incorporated into the growing system, considering their dependence on mineral metabolism *in vivo* (Van Vliet *et al.*, 2020) [49]. The nutrition composition of cultured chicken meat cannot be taken for granted; instead, it should adopt the designer philosophy of producing broilers through engineering.

5. Carbon Footprint, Environmental Impact and Sustainability

5.1 Life Cycle Assessment Framework

Life cycle assessment (LCA) is the standardized approach (ISO 14040/14044) that quantifies the environmental impact of a product along its entire production path, starting from extraction of raw materials to manufacture, utilization and disposal. For broiler meat, LCA scope normally covers farming of feed crops (including production of synthetic fertilizers, irrigation and pesticides), operations at hatcheries, farm consumption of energy and water, slaughtering and processing of meat, transportation and refrigeration until sale. In terms of cultured meat, LCA scope needs to account not only for energy-consuming conditions of the culture process in bioreactors, but also for preparation of the culture medium (amino acids, glucose, vitamins and growth factors) and scaffolding material. Selection of the LCA scope, functional unit (per kg live weight or per kg edible protein or per gram complete protein), grid energy carbon intensity and co-

product allocation are key drivers for any research findings; differences in these aspects largely account for inconsistencies in the published data (Sandstrom *et al.*, 2022) [34]. Table 2 provides a comparative overview of GHG

emissions, land use, water use and energy intensity for the major protein sources discussed in this review, using per-kg-edible-meat as the functional unit to enable direct comparison.

Table 2: Comparative environmental footprint of broiler meat, cultured chicken and alternative protein sources. Values are approximate ranges from peer-reviewed LCA studies; system boundaries and electricity grid assumptions vary between studies

Protein Source	GHG (kg CO ₂ eq/kg)	Land (m ² /kg)	Water (L/kg)	Energy (MJ/kg)
Beef (feedlot)	26-105	164-330	15,400	40-60
Lamb / Mutton	24-50	185-250	10,400	35-55
Pork	4.6-7.6	11-16	6,000	15-25
Conventional broiler	4.5-6.9	7.3-9.8	4,300-5,400	12-18
Designer broiler	~5.0	7.5-10	4,400-5,500	12-19
Cultured chicken (optimistic)	4.0-7.0	0.1-0.5	~370-840	26-33
Cultured chicken (current)	10-25	0.1-0.5	~840	45-75
Plant-based chicken analog	1.5-3.5	2.0-5.0	~1,000	8-15
Insect protein (<i>Acheta</i> sp.)	2.7-5.5	2.5-5.0	2,300	5-10

5.2 Conventional Broiler Environmental Impact

However, conventional broilers have a unique environmental profile among animal proteins because their environmental impacts are much lower compared to beef, lamb, and pig production on a per unit of edible protein basis, but still pose significant environmental burdens that have increased alongside the industrialization of the sector. According to a comprehensive meta-analysis conducted by Poore and Nemecek (2018) [30] of 570 life cycle assessment studies covering 38,700 farms in 119 different countries, the average greenhouse gas emissions per kg of meat production are 5.7 kg CO₂-eq, with a wide range of values between 3.7 and 9.8 kg attributed to differences in carbon intensity of feed crops, energy use, and production systems across different regions. The production of feed contributes between 75% and 80% to the carbon footprint of broilers, with 40% of it coming from the manufacturing of nitrogen fertilizers using Haber-Bosch process to grow the feed crops and 30% from changes in land use related to soybean production for feed meal (Sandstrom *et al.*, 2022) [34]. Nitrogenous excretions from broiler litter, mainly in the form of uric acid which is converted to ammonia and nitrous oxide (N₂O, global warming potential 298x CO₂), represent an additional 12%-18% of GHG emissions.

A global average weighted analysis of water footprints always yields a water consumption of around 4,300 to 5,400 liters per kilogram of consumed meat, where more than 90% of that water can be found in the irrigation of feed crops rather than in farm use for drinking and processing purposes (Mekonnen & Hoekstra, 2022) [26]. Land usage around 7.3 to 9.8 square meters per kilogram of consumed chicken is caused by the production of feed crops nearly wholly, with the land footprint of chicken housing accounting for less than 0.1% of the land use altogether. The relevance of this feed-induced land use problem lies in competition with biodiverse habitats, pressures toward deforestation for soybean cultivation in Brazil (Cerrado and Amazon biomes), and limited carbon sequestration abilities of the cleared land.

5.3 Designer Broiler Meat as a Marginal Environmental Adjustment

However, from an environmental point of view, designer broiler meat obtained by supplementing the laying flock does not significantly change the carbon footprint associated with this type of broiler meat production process. Incremental environmental changes related to supplementing the broiler feed diet with microalgae DHA, selenium yeast, or vitamin E

will be minor, and can be estimated at no more than 5% addition to the GHG emissions of a conventional ration (though cultivation of microalgae involves energy expenses which have to be taken into account in the assessment) (Rumpold & Schluter, 2020) [33]. Environmental sustainability of the designer broiler meat cannot be associated with decreased environmental footprints of production; rather, it concerns providing nutrition per kg of meat that requires the use of different nutritional supplements like capsules of fish oil, selenium, and vitamin D with their respective production and packaging footprints. Using the functional unit (delivery of 250 mg DHA to the consumer), it is likely that omega-3-rich broiler meat will prove environmentally superior compared to the fish oil capsules; however, LCA using this functional unit has not yet been published (Rumpold & Schluter, 2020) [33].

Using less protein in terms of switching the usual soybean meal to other, more environmentally sustainable protein sources insects meal, single-cell proteins, duckweed (*Lemna* sp.), larvae of black soldier flies (*Hermetia illucens*) in broilers' diets is a much more effective strategy in terms of reducing the carbon footprint of the designer broiler. The addition of insect meal at 10 to 15% instead of soybean provides a reduced environmental burden for feed production in relation to land and biodiversity, yet does not affect growth performance; furthermore, the natural fats of insects provide slightly higher amounts of PUFAs compared to those of soybeans (Rumpold & Schluter, 2020) [33].

5.4 Cultured Meat Environmental Impact: A More Complex Picture

However, it can be argued that the case for the environment with respect to cultured meat has become much more complicated due to recent LCA research compared to the earlier projections that were made on its behalf. One of the earliest LCA papers on this topic was by Tuomisto & de Mattos in 2011, where they concluded that "cultured meat would use 78-96% less greenhouse-gas emissions; 99% less land; and 82-96% less water." This particular study used assumptions about energy being supplied via renewable sources and the entire system being optimized.

In 2019, Lynch & Pierrehumbert conducted a critical analysis that indicated how the climate value of cultured meat highly depends on the time period under consideration, as well as on the characteristics of the atmospheric processes involving different types of GHGs. The substitution of methane produced by the livestock industry a short-lived yet potent

greenhouse gas that stays in the atmosphere for only about 12 years with carbon dioxide generated through energy consumption which is a long-lived gas staying there for hundreds of years means that cultured meat will perform better compared to conventional meat only for a period of some decades until all carbon dioxide emissions are reduced to zero. In other words, according to the Paris Agreement scenario of stabilizing the temperature at 1.5 degrees, the climate effect of cultured meat could be positive in the near future, but it would be worse in the distant future.

The most extensive and scientifically thorough LCA on cultivated meat Sinke *et al.* (2023) ^[37] compared the greenhouse gas (GHG) emissions from the production of cultured chickens against conventional broilers using both current technology, along with EU average electricity consumption intensity. According to current technology and with EU average electricity usage, GHG emissions from the production of cultured chickens ranged between 10 and 25 kilograms CO₂-equivalent, significantly higher than those from conventional broilers, which range between 4.5 and 6.9 kg CO₂-equivalent. With complete renewable energy generation and future optimal plant conditions, GHG emissions from cultured chicken production would drop to 4.0 to 7.0 kg CO₂-equivalent competitive with but not overwhelmingly better than conventional broilers. Cultured meat shows a clear environmental benefit with land usage (0.1 to 0.5 square meters per kilogram) and water usage (370 to 840 liters per kilogram) significantly lower than conventional broilers.

5.5 The Antibiotic Resistance Dimension

A significant environmental and public health issue in the context of broiler meat production that is typically not covered by conventional LCA approaches is the role of industrial farming practices in promoting antimicrobial resistance (AMR). Approximately 35 to 45 percent of agricultural antibiotic use is associated with broiler production in terms of volume and occurs mainly in the form of growth promoters or prophylactic antibiotics due to the intensive nature of broiler operations (Van Boeckel *et al.*, 2019) ^[47]. The lateral transfer of AMR elements via broiler-associated strains of *Escherichia coli*, *Salmonella*, *Campylobacter*, and *Enterococcus* from consumption, bioaerosols released on the farms, and other indirect means of infection is a potential hazard in the future. In its Global Health Observatory report, the WHO identified AMR among the top ten global public health threats. The use of probiotics, organic acids, and bacteriophages instead of antibiotics can help decrease selective pressure on resistance in designer broiler operations. With cultured meat being produced in sterile environments without antibiotics, this issue would be non-existent.

In a similar way, the transmission of zoonotic diseases, including pandemic-capable influenza A strains circulating among commercial poultry, constitutes an inherent biological risk that is automatically nullified by cultured meat produced using closed bioreactor systems, as well as greatly diminished in designer broiler farms compared to conventional open-house farms (Choudhury *et al.*, 2020) ^[8]. While hard to quantify in monetary terms, these benefits should be acknowledged for what they are: genuine societal gains.

6. Regulatory Landscape and Consumer Acceptance

6.1 Regulatory Status of Designer Broiler Meat

The designer broiler meat generated using dietary enrichment

techniques does not need any novel food regulation because the supplements used, such as microalgae-based docosahexaenoic acid (DHA), selenomethionine, alpha-tocopherol acetate, and cholecalciferol, are already recognized feed additives that have maximum inclusion levels set by existing regulations. In the European Union, the use of feed additives is regulated under Regulation (EC) No. 1831/2003, which sets maximum residue levels in meat for various classes of feed additives, including trace minerals, vitamins, and direct-fed microbials. This generates enriched meat that falls under the category of conventional chicken, subject only to labeling requirements for nutrition information (European Parliament & Council, 2019) ^[14]. In the United States, the regulation of feed additives is conducted by the FDA Center for Veterinary Medicine using GRAS and NADA processes, which have a similar permissive approach to nutritional additives (FDA, 2022).

Labeling and claims create an even more complicated regulatory interface. A broiler meat that has a label about being a source of omega-3 DHA, according to EU Regulation 1924/2006 regarding Nutrition and Health Claims, must have a minimum of 40 mg of DHA per 100 g, and it must also comply with the composition profile of the entire product. There are health claims associated with the intake of omega-3s that promote heart, brain, and vision development; they are approved at the European Union level but only with certain doses. The potential market demand for broiler meat products designed with health claims that position them as premium products is considerable, as consumer surveys continually show an inclination to pay 15 to 30% more for health benefits (Verbeke *et al.*, 2021) ^[50].

6.2 Regulatory Status of Cultured Chicken Meat

However, the regulatory framework governing cultured chicken meat production is significantly more complicated and highly varied between jurisdictions. Singapore was the first nation to approve cultured chicken meat (GOOD Meat brand, owned by Eat Just) commercially on the market in November 2020, which went through a premarket safety assessment procedure that considered cell line characterization, growth medium formulation, manufacturing process control, allergenicity, and nutritional equivalency (Singapore Food Agency, 2020) ^[36]. Following Singapore, the United States was the next country to approve the sale of cultured chicken meat when UPSIDE Foods and GOOD Meat both obtained approval from FDA and USDA in June 2023, marking an unprecedented policy decision where FDA regulated cell harvest, cell banking, and cell culture, while USDA-FSIS oversaw processing and labeling according to the Federal Meat Inspection Act (FDA & USDA, 2023). In Europe, no cultured meat products have been approved by any EU member states as of 2023, and the novel food regulation (EU) 2015/2283 framework must be followed to apply for approval, which would include submitting a complete dossier proving safety, nutritional adequacy, and non-deception compared to other food products, taking more than 2 to 3 years to review (Bryant *et al.*, 2023) ^[5].

6.3 Consumer Acceptance Dynamics

The acceptability of designer meat and lab-grown meat is driven by a distinct range of psychological factors compared to those that determine regular food consumption, and it would be an error to consider these two foods together when conducting consumer studies. In terms of the former, the issue for consumers seems to be the matter of authenticity and

credibility of information printed on the label: studies reveal that consumers who perceive food labeling regarding health benefits of particular products as exaggeration tend to discredit such statements considerably, whereas certification by third-party agencies and making precise statements (for example, the presence of 350 mg DHA per serving) are more effective than the statement regarding food enrichment itself (Verbeke *et al.*, 2021) ^[50]. The cultural aspects of consumption are particularly important in regard to markets where chicken is consumed mostly as whole meat (roasted, grilled); hence, labeling enriched cuts of whole meat becomes a new consumer communication problem.

The acceptance barrier for cultured meat is definitely more acute. The idea of meat being produced in ways not involving an actual living animal creates a very strong response of disgust, especially on behalf of older people, cultures with traditional meat-eating practices, and those with low levels of confidence in the technological means of producing food (Siegrist & Hartmann, 2020) ^[35]. The naturalistic fallacy the idea that if something has been produced in ways other than involving a living organism entirely, it must be worse or unnatural creates a serious psychological barrier to acceptance of this type of food even if participants are told accurate details about the production method. However, younger cohorts (from 18 to 35 years old), urban dwellers, and meatless meat consumers show much greater support for culturing meat (Siegrist & Hartmann, 2020) ^[35].

7. Myths, Contraindications and Safety

Myth: all chicken meat is nutritionally equivalent regardless of production system. Fact: the compositional data presented throughout this review unambiguously refute this claim. The omega-6:omega-3 ratio in muscle phospholipids, the DHA content of breast meat, the selenium concentration and the vitamin E level are all directly and substantially responsive to the bird's diet, with differences between conventional and enriched broilers reaching 3 to 10-fold for specific nutrients. These differences are analytically verified and biologically meaningful in human metabolic studies (Simopoulos, 2020; Cherian, 2022) ^[38, 7].

a. Myth: Cultured meat is similar to traditional chicken meat in all aspects and needs no nutritional qualification.

Fact: Today's cultured chicken meat is a simple muscle structure that lacks fat content in its composition, vitamins, minerals, and myoglobin micronutrients unless intentionally designed. Nutritional makeup is just a choice factor in cultured meat production.

b. Myth: cultured meat will always be greener in terms of its carbon footprint compared to conventionally raised broiler chickens.

Fact: in existing production circumstances, using typical grid power sources, the carbon footprint of cultured chicken will definitely surpass that of conventional broiler meat. Any climate benefits depend on the complete decarbonization of energy supplies and on achieving efficiencies in bioreactors, which has not been demonstrated yet (Lynch & Pierrehumbert, 2019; Sinke *et al.*, 2023) ^[25, 37].

c. Myth: broiler meat enriched with omega-3 fatty acids will have an unpleasant fishy flavor, making it undesirable to consumers.

Fact: while this may be true in cases of broilers that have been fed with fish oils, it is avoided with microalgal sources of

DHA along with vitamin E supplementation. Broilers raised with algal DHA exhibit no discernible difference in taste compared to ordinary chickens (Xiao *et al.*, 2021) ^[51].

8. Conclusion

Designer broiler meat and cultured chicken both solve a common problem, which is that of providing nutritious, sustainable, and resilient meat. Designer broiler meat can currently be employed to produce healthier meat through enriched omega-3s, increased selenium, and the addition of vitamins. This form of meat production will not have an extensive environmental footprint as opposed to ruminant animals. Cultured chicken promises a radical difference when it comes to issues such as space utilization, disease management, and welfare of animals; however, its sustainability is dependent on how energy is utilized, and many problems are still present in terms of costs, safety, and scalability.

Energy use is the weak link in the current production systems of cultured meat. The energy costs associated with bioreactor cultivation at 37 degrees centigrade, the provision of sterile air, stirring, and chilling downstream processes are expected to amount to 26 to 33 MJ per kg of cultured meat in ideal cases, whereas in realistic cases, the energy cost could be as high as 45 to 75 MJ per kg of cultured meat, compared to 12 to 18 MJ per kg for traditional chicken production (Humbird, 2021) ^[20]. The energy cost makes it imperative for cultured meat to be produced with non-carbon-based energy sources to ensure its climate benefits.

Conflict of Interest

Not available

Financial Support

Not available

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