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Review

Leveraging Microalgae to Achieve Zero Hunger: Enhancing Livestock Feed for Nutritional Security

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Abstract: Achieving "Zero Hunger" (SDG 2) requires overcoming complex challenges, especially in vulnerable communities in developing countries. Livestock plays a key role in food security, but limited resources threaten productivity, prompting interest in innovative solutions like microalgae supplementation in ruminant diets. Microalgae offer potential benefits by enhancing productivity and nutrition while addressing local protein deficiencies. However, barriers such as economic costs, processing requirements, and resistance to changing traditional feeding practices present challenges. This review examines the feasibility of microalgae-based livestock feed as a sustainable strategy to improve food security, particularly in arid, climate-affected regions. Biomass yield estimates suggest that small-scale cultivation can meet livestock nutritional needs; for example, a 22-goat herd would require approximately 88 g of microalgae per day to enrich meat with polyunsaturated fatty acids. Semi-continuous production systems could enable smallholders to cultivate adequate biomass, using local agricultural resources efficiently. This approach supports food security, improves meat quality, and strengthens community resilience. Collaboration among researchers, extension services, and local farmers is essential to ensure the effective adoption of microalgae feed systems, contributing to a sustainable future for livestock production in vulnerable regions.

Keywords: microalgae; food security; livestock feed

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1. Introduction

The global challenge of achieving "Zero Hunger" (SDG 2) involves overcoming a range of interconnected economic, environmental, social, and political obstacles that threaten food security. In developing countries, particularly in vulnerable communities, widespread poverty severely restricts access to nutritious food, resulting in chronic hunger and malnutrition. This issue is further compounded by inadequate infrastructure—such as poor roads, insufficient storage facilities, and limited market access—which increases post-harvest losses and hinders efficient food distribution. Moreover, farmers in these regions often lack access to critical agricultural inputs, including seeds, fertilizers, and irrigation systems, which impairs their ability to produce sufficient food and pursue sustainable farming practices. Climate change intensifies these challenges, as extreme weather events such as droughts and floods disrupt traditional farming patterns, lower crop yields, and worsen food insecurity. Meanwhile, developed countries face the paradox of overnutrition and food insecurity, with low-income populations struggling to access healthy food options. In these areas, food deserts and economic inequities leave marginalized groups reliant on calorie-dense, nutrient-poor foods, contributing to both malnutrition and rising diet-related diseases. Vulnerable populations such as children, the elderly, and minorities are disproportionately affected by this imbalance.

Ultimately, achieving SDG 2 requires innovative solutions tailored to the specific contexts of these diverse challenges. In the process of addressing global food security, efforts must focus on localized strategies that incorporate economic development, infrastructure improvements, climate adaptation, and equitable food access to ensure sustainable and inclusive progress in eradicating hunger.

Microalgae-based livestock feed is increasingly being explored as a strategy to improve animal health and product quality. However, its contribution to the SDG 2 goal remains understudied. A search in the Web of Knowledge database using the keywords "microalgae" and "animal feed" reveals 947 records spanning from 2000 to 2024. The data indicate a general upward trend in publication counts over this period, with a notable acceleration in recent years. Specifically, from 2020 to 2024, there has been a consistent increase in publication numbers, despite a slight decline in 2020 (83 publications, 8.76%). The year 2024, though not complete, already features 51 publications, reflecting ongoing interest and activity in this research area. This trend suggests that the study of microalgae in animal feed has gained prominence due to advancements in the field, technological progress, or increased funding. However, an analysis of the research records in relation to the Sustainable Development Goals (SDGs) reveals that only 28 records (representing 2.857% of the total) are associated with SDG 2, which focuses on ending hunger and ensuring food security. This suggests that, while the field is growing, its direct alignment with specific SDGs may still be limited. One reason why SDG Zero Hunger is often overlooked in articles discussing the use of microalgae in livestock feeding is that many studies tend to emphasize scientific findings in isolation. These research efforts frequently fail to connect their findings with the realities of livestock and water management in vulnerable communities. Instead, they often focus on intensive animal agriculture, which may not address the specific challenges faced by smallholder farmers in resource-limited settings. This lack of contextual understanding makes it difficult for various stakeholders, such as policymakers, practitioners, and local communities, to implement these innovative solutions effectively. By neglecting to consider the broader socio-economic context and the unique needs of these communities, the potential contributions of microalgae to achieving food security and sustainable agriculture are underexplored.

The aim of this paper is to investigate the real potential of microalgae-enhanced livestock feed as a solution to improve food security and nutritional well-being in vulnerable communities living in arid regions. Specifically, this study investigates the potential of microalgae-enhanced livestock feed, focusing on the integration of microalgae biomass into livestock diets. It evaluates the practicality of producing sufficient biomass at the community level and how these innovations can enhance animal productivity and improve the nutritional quality of animal products. The focus is on identifying sustainable strategies that can benefit small farmers and producers, particularly women, in regions disproportionately affected by climate change, water scarcity, and food insecurity, contributing to the global objective of achieving Zero Hunger.

2. Method

This study combines primary research (interviews and observations), secondary literature synthesis, and meta-analytical techniques to provide a comprehensive multidisciplinary understanding of the role of microalgae in livestock feed and sustainable agriculture.

The authors conducted an extensive review of the scientific literature in their respective areas of expertise, maintaining regular communication to align with the research objectives. The literature search was conducted using established academic databases (Web of Science and Scopus).

Shared digital platforms, such as reference managers (Mendeley Reference Manager Version 2.124.0) and Google Docs, facilitated collaborative writing and systematic compilation and annotation of relevant literature. Thematic analysis was conducted through online meetings via Google Meet and in-person meetings, where the research team regularly discussed findings, resolved differences in interpretation, and refined their collective understanding of the problem. ChatGPT (OpenAI, Generative Pre-trained Transformer 4) and the Ask AI tool from Writefull for Word were helpful tools for improving the cohesion of the draft and assessing clarity. The prompt used was "Improve cohesion of the following two paragraphs preserving the academic style". Clarity was validated by asking ChatGPT to provide summaries of the text to ensure alignment with the authors' objectives. Writefull for Word was used for automated writing and proofreading of the final manuscript.

In addition to the literature review, this study incorporated data from non-profit organizations (NPO). Reports from the NPOs and interviews with their staff provided essential context for understanding the socioeconomic challenges and opportunities related to rural and gender-focused development. Observations from the implementation of microalgae cultivation with a group of non-expert students offered additional insights into the feasibility of microalgae cultivation by nonscientific personnel. The interview with NPO personnel provided insight into the social and economic impacts of integrating microalgae into livestock feed, with a particular focus on gender perspectives.

3. Microalgae as Feed Livestock

Numerous studies [1–11] have confirmed that the incorporation of microalgae in livestock feed improves animal health and improves the quality of animal products (meat and milk). Table 1 provides a comparative analysis of various livestock species based on their adaptability to arid environments and economic viability.

Goats, with their low water intake (ranging from 3.8 to 11.4 L per day) and their ability to produce milk year-round, are especially advantageous for communities facing resource constraints. Their short gestation period and high turnover rate further enhance their economic resilience and reliability as a source of income. Sheep, while also adapted to arid environments, have seasonal milk production, which somewhat limits their potential compared to goats. Although they provide wool, which can generate additional income, the variability of market prices can affect their reliability as a sustainable resource. Although poultry is well adapted to arid conditions, this review will not focus on them, as they do not present significant challenges for growth in these regions. Poultry already constitutes a stable, low-cost, and quick-producing source of income for many communities. Instead, the focus will be on addressing specific resource constraints and nutritional challenges faced by ruminants such as goats and sheep through the integration of microalgae as a feed resource. This approach aims to enhance the quality of animal products while utilizing resources that do not compromise human food supplies, thus supporting the sustainability and resilience of livestock systems in arid regions.

Table 1. Comparative analysis of livestock animals based on adaptation and economic factors.

Animals	Well Adapted to Arid Environments?	Gestation Period (Incubation for Poultry), [Days]	Basic Animal Products (Other Than Meat)	Water Intake per Animal [L·Day^{-1}]	Suitability for Resilient Income
From		[12]		[13,14]	
MONOGASTRIC					
Swine	No	114	Milk is not consumed by humans	1–23	Moderate (often higher prices)
Poultry	Yes	21	Eggs	0.03–0.47	High (low cost, quick turnover)
RUMINANT					
Cattle	No	280	Milk all year round	24–155	Moderate (High investment)
Sheep	Yes	152	Milk only in certain months (spring–summer) Wool	4–10.5	Moderate (variable prices)
Goats	Yes	150	Milk all year round	3.8–11.4	High (low cost, quick turnover)

In a metanalysis carried out in 2024, the addition of microalgae to ruminants' feed proved to increase their weight gain and decrease their feed conversion ratio [5]. It has also been reported to increase food intake and rumen degradation of nutrients in sheep and camels [15]. Several studies discuss the double edge of microalgae supplementation, as it can negatively affect palatability [16,17]. Despite that, the data recorded in a meta-analysis of 2023 mention that, although lower dose supplementation with microalgae increased ruminant dry matter intake, the value remained unchanged with higher levels of microalgae supplementation in the diet compared to the traditional or non-supplemented diet [2].

Microalgae have also emerged as a promising nutritional supplement to improve reproductive health in small ruminants, due to their rich content of polyunsaturated fatty acids (PUFAs) and antioxidants. These essential nutrients play a critical role in various reproductive processes, including hormone synthesis [18], semen quality [19], and embryo development [20]. The presence of omega-3 and omega-6 fatty acids in microalgae supports optimal ovarian function [21] and improves sperm quality [19]. Meanwhile, antioxidants help mitigate oxidative stress, thus safeguarding reproductive cells from damage and addressing the significant losses caused by free radical-induced oxidative stress in the livestock industry [22].

A study conducted in vitro demonstrated that embryos resulting from a short period of supplementation with a daily dosage of 20 g of *Chlorella* exhibited higher mitochondrial activity, a characteristic often associated with improved embryo viability and potential for successful implantation [20]. Another study from the same year proved that supplementing ewes with n-3 PUFA-rich fish oil increased the number of fetuses in comparison to non-supplemented ewes by 46% at day 45 of gestation, with a three times higher percentage of twinning [21].

These enhancements in reproductive outcomes are complemented by evidence that enriching the diet of male ruminants with polyunsaturated fatty acids (PUFAs) supports critical aspects of reproductive health, including testicular development, spermatogenesis, and the motility and viability of sperm [19]. Together, these findings underscore the potential of nutritional interventions in optimizing reproductive performance in both female and male ruminants.

Regarding meat quality, microalgae supplementation has been shown to increase omega-3 and omega-6 fatty acid levels in lamb meat, while also improving antioxidant content and thus protecting against lipid oxidation. Additionally, meat tenderness has been shown to improve, evidenced by increased water retention capacity and reduced Warner-Bratzler shear force values compared to lambs fed traditional diets [2]. In particular, supplementation of lamb feed with *Nannochloropsis oceanica* increased long-chain omega-3 polyunsaturated fatty acids, mainly eicosapentaenoic acid, followed by docosapentaenoic acid and docosahexaenoic acid, in lamb meat and subcutaneous fat while maintaining meat quality and productivity [8].

4. Source of Protein, PUFA and Antioxidants

Microalgae are rich in proteins, polyunsaturated fatty acids (PUFAs), and antioxidants, all beneficial for animal nutrition and health. Microalgae hold significant promise as a component in animal feed due to their rich nutritional profile and environmental benefits. Using microalgae as a resource can be sustainable when choosing the appropriate species for those culture conditions that make efficient use of local resources. The most common species of microalgae used to feed goats and sheep are generally chosen for their high nutritional content, including proteins, lipids, and essential fatty acids. Some of the most commonly used microalgae include:

Limnospira platensis (*Spirulina*) cyanobacteriae (*L platensis* (*maxima*), *L. platensis* (*fusiformi*), etc. . . . formerly classified under *Arthrospira*) can achieve a value of around 70% proteins [23] in biomass dry weight, up to 3% of ω-6 Gamma-Linolenic acid (GLA) [24], vitamins such as B12 (~1.64 µg·per 100 g) [25] and A [26], and minerals such as calcium (~15 µg·100 g), iron (~0.9 µg·100 g), and potassium (~14 µg·100 g) [27]. Spirulina is one of the most widely used microalgae in animal feed and one of the few species approved for human consumption in the European Union. This cyanobacteria can grow at very high pH [28], optimally around 9, which other organisms cannot tolerate so well, and can also tolerate different salinity levels (from 0 to 12.8 g L^{-1}) [29]. It is also capable of growing heterotrophically and mixotrophically [30].

Chlorella vulgaris can achieve up to 52% proteins [31] in terms of biomass, and approximately 12% polyunsaturated fatty acids such as linoleic acid and α-linolenic acid [32,33], along with antioxidants [33]. *Chlorella* is another popular microalgae used in livestock feed and is approved for human consumption. It supports heterotrophic and mixotrophic growth [34] and has also been used in wastewater treatment [35].

The small species of the genus *Nannochloropsis* (*Nannochloropsis oceanica* and *N. oculata*) are known for their high content of omega-3 fatty acids (around 5%), particularly eicosapentaenoic acid (EPA), alongside their antioxidant activity [33] and high protein content (55%) [36]. *Nannochloropsis* is increasingly being used in animal nutrition and can grow in wastewater with high levels of salinity [37].

Schizochytrium is a microalgae notable for its high content (up to 35% on a dry weight basis) of docosahexaenoic acid (DHA), an essential omega-3 fatty acid, which can improve the health and growth of livestock. The highest levels are reached when using organic carbon sources, and it tolerates very high salinities [38,39]. The oil extracted from this microalgae has been recently approved as a novel food in the European Union.

Dunaliella salina is rich in beta-carotene and other carotenoids, exhibiting great antioxidant activity [40]. *Dunaliella* is sometimes used as a supplement to improve antioxidant levels in animal diets. Although the total content is not comparable to other microalgae, it has a good proportion of EPA in its fatty acid profile [40]. Additionally, it can grow in high-saline environments [40].

Phaeodactylum tricornutum is made up of biomass that is rich in EPA (up to 3.2%). It also contains some DHA [41,42] and exhibits antioxidant properties, thanks to its fucoxanthin content, among other factors [43].

The biomass of *Porphyridium* (*cruentum*) *purpureum* microalgae can offer up to 40% proteins and araquidonic acid (1.72%), as well as eicosapentaenoic acid (1.63%) [44]. In addition, this microalgae can produce phycobiliproteins, with up to 3.42% phycoerythrin [44].

Global microalgae production is dominated by Asia, which accounts for over 97% of global output. In 2019, the total biomass of microalgae produced globally was approximately 56,456 tons [45]. *Spirulina* production led with 56,208 tons, primarily cultivated in China (97% of global production), using open-pond systems for applications in dietary supplements and food additives [45]. *Chlorella vulgaris* is widely produced in Japan and Korea, where closed photobioreactor systems are employed to meet demand for health foods and cosmetics [45]. *Nannochloropsis*, essential for aquaculture feed due to its high omega-3 fatty acid content, is cultivated across Asia and Europe using both open and closed systems [45]. In Europe, Germany, Spain, and Italy are the top three countries for microalgae production, while *Spirulina* producers are predominantly located in France, Italy, Germany, and Spain [46]. Photobioreactors are the main production method (71% of the production), while for *Spirulina*, open ponds prevail (83%) [46]. The most cultivated species in Europe in terms of the number of companies are *Nannochloropsis* spp., *Chlorella* spp., and *Haematococcus pluvialis* (the last two account for more than 80% of the total microalgae produced) together with *Spirulina* [46]. The European scale shows an approximate production of 182 tons dry weight (DW) of microalgae and 142 tons DW of spirulina. *Phaeodactylum tricornutum*, cultivated for its eicosapentaenoic acid (EPA) content, and *Porphyridium purpureum*, known for its polysaccharides and pigments, are grown in smaller volumes in specialized bioreactors, with a focus on nutraceutical and biotechnological applications [46]. In Latin America, Chile is the major producer of microalgae (903 tons per year), while in Africa, the main producers are Tunisia and Burkina Faso (140 tons per year each), followed by the Central African Republic (50 tons per year) and Chad (20 tons per year) [45]. These production systems reflect regional adaptations to environmental and market demands, emphasizing the diverse roles of microalgae in global sustainability efforts.

When comparing the protein content of ingredients traditionally used in animal feed to that of microalgae, microalgae have a similar protein percentage by dry weight (30 to 70%, with most species having values closer to 40%) [3] to that of soybean (30 to 40%), and higher than that of corn, barley, sorghum (9–10%), wheat, oats, or treacle (around 12%) [47].

In terms of polyunsaturated fatty acids (PUFAs), common sources in ruminant diets include oilseeds and their by-products. For instance, soybeans contain up to 9.1% PUFAs, predominantly linoleic acid, while canola contains up to 28.4% PUFAs, and sunflower seeds boast as much as 62.3% PUFAs [48]. Forages also contribute valuable amounts of PUFAs, with fresh grass providing up to 3.9% PUFAs [49]. Excessive PUFAs in ruminant diets can induce oxidative stress and disrupt mammary gland homeostasis, but plant-derived bioactive compounds may help alleviate these effects [10]. Therefore, the antioxidant properties of microalgae bioactives, such as carotenoids and phycocyanin, can help alleviate oxidative stress caused by dietary factors like high PUFA intake, allowing the animal to still benefit from the positive effects of PUFA.

Studies in sheep have demonstrated that adding 18:3 n-3 sources to their diet, despite ruminal biohydrogenation, effectively raises n-3 PUFA levels in the meat [1], ultimately benefiting consumers' health. Different PUFAs have varying impacts on meat quality and acceptability. A study showed that enriching goat meat with n-3 PUFAs did not negatively affect drip loss, cooking loss, shear force, or color, and meat with higher n-3 PUFA levels exhibited better tenderness, juiciness, and overall acceptability without exceeding oxidation thresholds that cause off flavors [1].

5. Microalgae Cultivation Systems for Sustainable Agriculture and Animal Feed

Microalgae cultivation systems present a transformative opportunity for sustainable agriculture and animal feed production. The ability of microalgae to thrive in challenging environmental conditions makes them ideal candidates for enhancing livestock production while minimizing resource inputs.

5.1. Sustainable Resource Utilization

Microalgae are highly efficient in converting sunlight, carbon dioxide, and nutrients into biomass, yielding a protein-rich feed source with a minimal ecological footprint. The recovery of wastewater for microalgae cultivation has significant implications for biomass production in water-scarce areas. In such areas, wastewater is frequently used as a water source due to the unavailability of safer (cleaner) alternatives [50]. In other regions, non-conventional water (NCW) is becoming the primary source for agriculture, as traditional high-quality water sources decrease or are allocated to different purposes [50]. While NCW can be a valuable resource, its use necessitates careful management to ensure food safety. The WHO-FAO-UNEP guidelines [51] provide a robust framework for managing water quality risks, emphasizing a multiple-barrier approach, effective treatment, rigorous monitoring, and consideration of vulnerable populations. By applying these principles, the potential benefits of NCW for microalgae cultivation can be realized while safeguarding public health. Microalgae can efficiently recycle trace elements, such as nitrogen and phosphorus, often abundant in wastewater, facilitating growth and biomass accumulation. The impressive removal rates of chemical oxygen demand (COD), ammoniacal nitrogen, and phosphorus—84%, 95%, and 97%, respectively—demonstrate the dual benefits of treating wastewater while generating valuable algal biomass [35].

This bioremediation approach reduces hazardous solid sludge and enhances local water resource management, alleviating seasonal water shortages. In addition, they can grow using organic carbon sources such as straw extracts, as well as by-products of the food processing industry, such as citrus peels and date palm waste [52]. Animal manure can also be treated to improve the nutrient content [53], while sugarcane molasses serves as an inexpensive carbon source [54]. Collectively, these glucose-rich materials, along with domestic wastewater, not only enhance microalgae production but also contribute to a circular economy by recycling waste, promoting sustainability, and improving food security [34]. However, the use of wastewater must adhere to strict safety guidelines outlined by the WHO-FAO-UNEP to mitigate potential health risks and ensure the safety of the final product [50,51]. Cultivating microalgae in non-arable land and low-quality water not only alleviates pressure on freshwater resources but also enables the valorisation of marginal lands for productive use.

5.1.1. Efficient Biomass Production Process

The process of obtaining microalgae biomass involves several key steps.

- Culturing: Microalgae are grown under optimal conditions in PBRs, where factors such as light intensity, temperature, and pH are carefully monitored and adjusted;
- Harvesting: After the desired biomass density is reached, microalgae are harvested using techniques such as centrifugation, filtration, or flocculation, which efficiently separate the biomass from the culture medium. Fresh biomass can be fed to animals, preferably after breaking cells with mechanical media for improved digestibility;

- Processing: The harvested biomass can be further processed into various forms, including dried powder, pellets, or liquid extracts, making it suitable for incorporation into animal feed or other applications.

  Cultivation technologies, such as photobioreactors (PBRs), have greatly enhanced the efficiency and scalability of microalgae production. PBRs provide a highly controlled environment that optimize critical growth factors such as light exposure, temperature, and nutrient supply, resulting in higher biomass yields compared to traditional open-pond systems [55]. The closed design of PBRs minimizes contamination risks and water loss, ensuring a more consistent and higher-quality biomass, especially for high-value products like nutraceuticals and pharmaceuticals [55]. Among PBRs, bubble columns stand out for their simplicity, offering controlled conditions for light and gas exchange and nutrient delivery, while being easier to clean compared to more complex systems such as tubular reactors. These reactors are ideal for producing microalgae with specific biochemical properties, such as a high omega-3 content or antioxidant activity [56]. Conversely, open bioreactors such as raceway ponds are shallow systems where water and nutrients are circulated. Although more cost-effective and simpler to operate, open systems are more vulnerable to contamination, evaporation, and environmental variability, making them more suitable for large-scale, low-cost applications like biofertilizer and animal feed production where water is not highly appreciated (i.e., wastewater treatment).

  Regardless of the PBR selected, first, the bioreactor is cleaned (and usually disinfected/sterilized), and the appropriate growth medium is added. Bioreactor inoculation involves introducing a controlled amount of prepared cells into the bioreactor to initiate the biological process. After inoculation, critical parameters such as temperature, pH, and oxygen levels are monitored and adjusted to optimize growth and ensure that the bioprocess runs efficiently. Once the culture reaches the desired biomass concentration, harvesting begins. This can be performed in a continuous or semi-continuous mode, where part of the culture is harvested regularly and replaced with fresh medium (Figure 1b), or as a batch process when the entire culture is harvested at the end of the cycle (Figure 1a). To maximize light availability, which is usually a limiting factor for biomass productivity, most microalgae cultivation systems operate in semi-continuous or continuous modes [57–59]. These methods involve regular or continuous addition of fresh medium while simultaneously harvesting culture, ensuring optimal growth conditions and preventing light limitation in dense cultures (Figure 1b).

  The opposite operation mode is called batch, where cells and nutrients are incorporated at the beginning of the culture and left to grow for a determined period of time before harvest (Figure 1a). Cells grow at different speed rates according to the local environmental conditions (such as light, physiological state, and nutrient availability) (Figure 1c). Harvesting is usually performed when cells are growing slowly, mainly due to the biomass concentration being high, and light being strongly attenuated. The operation mode will determine the velocity of biomass production and the volume of water that must be handled.

  Microalgae biomass harvesting methods are crucial to optimizing the efficiency and economic viability of microalgae production systems. Several techniques are commonly employed, each with their advantages and limitations:
- Filtration is one of the most straightforward methods, which involves the separation of microalgae from water using various types of filters. This method is often effective for large-scale operations, but it can be energy-intensive and can cause cell damage if not performed with care [60].

- Centrifugation is another widely used technique that utilizes centrifugal force to separate microalgae from the culture medium on the basis of density differences. Although this method is highly efficient and capable of producing high concentrations of biomass, it also requires significant energy input and specialized equipment.
- Flocculation is an increasingly popular method, in which chemical agents or natural polymers are added to promote the aggregation of microalgae cells into larger flocs, which can then be easily removed by sedimentation or filtration. This technique is often less energy-intensive and can be cost-effective, particularly for large-scale operations [61].
- Air flotation involves the introduction of air bubbles into the microalgae culture, causing the cells to rise to the surface, where they can be skimmed off. This method has shown promise related to its lower operating costs and reduced energy consumption [62].
- Forward osmosis (FO) is a promising energy-efficient technology for microalgae dewatering, leveraging osmotic pressure to enhance algae cell recovery while minimizing energy consumption. In FO, water molecules are driven across a semipermeable membrane by an osmotic gradient, concentrating microalgae cells on the feed side until an osmotic balance is achieved. The feed solution, comprising microalgae and associated salts, is placed on one side of the osmotic membrane, while the draw solution is applied on the opposite side. The osmotic pressure gradient between the two solutions drives the movement of water from the feed to the draw solution, allowing an effective concentration of microalgae [63].

  In general, the choice of the harvesting method depends on various factors, including the specific microalgae species, the scale of production, and the intended application of the biomass.

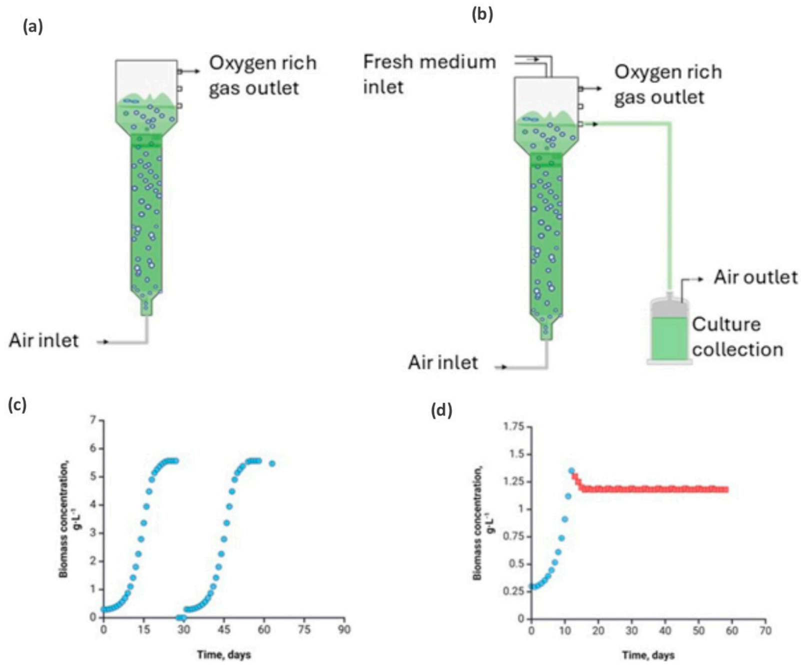

Figure 1. Differences between batch (**left**) and continuous (**right**) operation modes for a bubble column to produce microalgae. On top: schematic representation of the column operation; (**a**) working in batch between the operations of inoculation and the final harvesting, and (**b**) working in continuous after inoculation. Bottom: feasible (ideal) evolution of biomass concentration during the same time (**c**) after the first cycle of inoculation and up to the harvesting of the second cycle (total time = 57 days) (**d**) after the first inoculation on day 0 and during the 57 days of continuous culture. Continuous culture is established at day 13.

5.1.2. Economic and Feasibility Issues

- Producing microalgae biomass is often considered expensive because it requires specialized equipment, significant energy inputs, and careful management of cultivation systems, whether in open ponds or closed photobioreactors. Producing microalgae also requires technical training to manage critical factors such as water quality, nutrient supply, and aeration. Another challenge is the variability in the composition of microalgae, which can change significantly based on culture conditions, such as climate, light availability, nutrient concentrations, and CO_2 levels. These factors influence the levels of proteins, lipids, and other valuable compounds in biomass, complicating consistent production and requiring customized strategies for each cultivation environment.

Producing wet microalgae biomass (containing 10% to 20% solids by weight) in open ponds on a scale of 200 to 300 tons per year is estimated to cost approximately 3.2 to 4.5 EUR per kilogram of dry weight [64]. Estimating the cost of microalgae production involves considering various factors that contribute to overall expenses, such as capital and operating costs, energy consumption, and cultivation resources. Capital expenditures for large-scale microalgae cultivation include significant investments in large open ponds or advanced photobioreactor (PBR) systems designed for higher productivity and better control of cultivation conditions. Additionally, large tracts of land (non-arable), specifically allocated for microalgae cultivation, are typically chosen based on water availability and sunlight. Advanced systems for managing water and air/CO_2 supply, often utilizing CO_2 captured from industrial plants, automated and energy-efficient mixers, aerators, and in some cases, artificial lighting for indoor PBR systems, can increase investment costs. Lastly, high-efficiency harvesting and processing equipment, including centrifuges, filtration systems, and potentially spray dryers or freeze dryers for biomass processing, also contribute significantly to overall capital expenditures. Operational expenditures for the cultivation of large-scale microalgae can be significant due to the various inputs required. Nutrients, such as nitrogen, phosphorus, and micronutrients, are often purchased in bulk, sometimes sourced from industrial waste streams, to support large-scale production. The energy costs are also substantial, driven by the need for mixing, aeration, artificial lighting (if used), and energy-intensive harvesting processes. Integrating renewable energy sources can help reduce these expenses. Water use is another major factor, especially when water treatment and recycling systems are required, particularly in closed-loop photobioreactors. In particular, costs for water, nutrients (fertilizers), and carbon dioxide account for nearly 8% of the total production cost, indicating that efficient management of these inputs is critical to maintaining economic viability. Labour costs include hiring a professional workforce of managers, technicians, and labourers. Harvesting and processing also require high-end equipment such as centrifuges and drying systems to refine microalgae into specific products such as biofuels or food supplements. However, costs differ significantly depending on the scale of the operation, whether on a family scale (100 L–500 L per month), community level (volumes usually around 1000 L–1500 L), or large-scale/commercial operation (usually over 10,000 L). For family-scale microalgae cultivation, basic cultivation systems such as low-tech open ponds or small, homemade photobioreactors (PBRs), typically constructed from inexpensive materials like plastic containers, small tanks, or PVC pipes, are suitable. Land or space is often a minimal expense, as it usually involves using a small backyard or family farm. Additionally, basic equipment, such as manual aeration tools or home-made mixing devices, can be employed to further reduce costs. Moderate investment in basic filtration, small centrifuges, or flocculation systems is required. However, operational expenditures for microalgae cultivation on a family scale are relatively low, making it a feasible option for small producers. Nutrients, often sourced from fertilizers or organic waste such as manure, are essential but affordable. Energy costs remain minimal, as manual labour or simple, low-tech systems, such as solar or gravity-based setups, can be used, stirring can be performed intermittently by hand, and aeration can be conducted through basic methods. Water requirements are modest, typically drawn from local sources or collected via rainwater harvesting. Labour costs are usually not a concern, as family members often manage the system themselves. Harvesting and processing rely on simple, labour-intensive techniques like cloth filtration or gravity settling, keeping expenses low but requiring more manual effort. To test its feasibility, in our family-scale experiment, we engaged secondary school students from Canjayar, Almeria, Spain, in a hands-on microalgae cultivation project using *Arthrospira platensis* (Figure 2). We provided the group with 500 mL of this microalgae and, with the collaboration of their teachers and online tutoring, they designed various bioreactors using readily available materials (Figure 2a–d) and custom harvesting techniques (Figure 2e,f). Although they started using chemical salts to produce the microalgae, they gradually changed culture media to be able to produce it at home. Over the course of more than 12 months, the students maintained the growth of the cultures, actively learning about the cultivation process and monitoring growth conditions. Their efforts yielded impressive results, achieving concentrations of approximately 2 to 3 g per litre. This practical experience not only demonstrated the feasibility of small-scale microalgae cultivation, but also highlighted the potential for educational initiatives to foster interest in sustainable agriculture among young students.

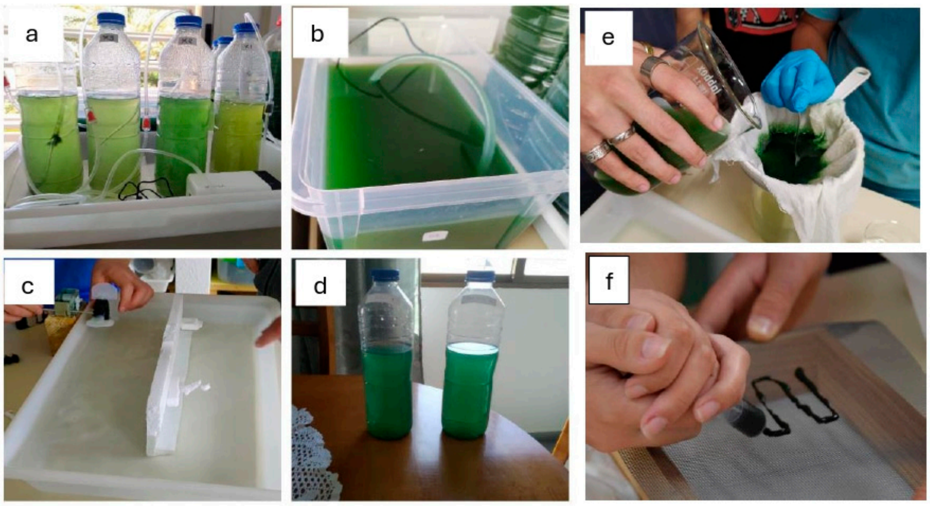

Figure 2. Experience in cultivating microalgae on a family scale with secondary school students. Reprinted with permission of IQ-boletin. Figures (**a**–**d**) are home-made bioreactors for culturing *Spirulina*; Figure (**e**) shows the harvesting systems designed by secondary school students and (**f**) shows the drying system selected by the students.

At the community level, capital expenditures for microalgae cultivation include medium-sized open ponds or photobioreactors, with higher infrastructure costs due to the need for larger systems and higher quality materials. Land costs may be reduced if community or shared spaces are used. Water and air/CO_2 management systems, including storage, plumbing, and air/CO_2 input, might be included. Simple mechanical mixers or aeration equipment, such as pumps and blowers, are needed for nutrient and Air/CO_2 distribution. In addition, harvesting equipment such as basic filtration systems, centrifuges, or flocculation setups can be required. Operational expenditures for microalgae cultivation vary depending on the scale of the operation and the resources involved. Nutrient costs increase with production, as more fertilizers or organic inputs are required to sustain growth. Energy expenses also increase due to the need for pumps, aerators, and mechanical systems to ensure proper mixing and lighting for optimal cultivation. Water use becomes more significant, often sourced from local systems, rainwater harvesting, or recycled water solutions. Labour costs depend on whether the operation is volunteer-based or requires paid workers to manage the system. Harvesting and processing costs, although generally low, involve the use of simple equipment such as centrifuges or filtration methods to handle the biomass.

When comparing microalgae cultivation on different scales, there are significant differences in capital and operational expenditures, as well as in technology and labor requirements. In essence, the family and community scales are more accessible, focusing on low-cost, small-batch production, while large-scale operations benefit from economies of scale, leading to greater productivity and efficiency, but at a much higher investment.

The use of microalgae in animal feed is defined by economic and feasibility issues, as well as the specific nutritional requirements of livestock. Later in this article, we will discuss the scale of production needed to meet the nutritional and economic needs of animal feed, while addressing environmental sustainability and potential social benefits, including the empowerment of women in microalgae-based enterprises.

5.2. Focus on Semi-Arid Regions

Globally, rangelands cover approximately 79 million km^2, with 43% classified as arid or semi-arid. These rangelands are essential for many pastoral communities, particularly in arid and semi-arid regions, which account for 46% of global livestock production. In fact, arid rangelands represent two-thirds of national rangelands and provide between 20% and 60% of livestock feed requirements [65].

Agriculture is the main economic activity in semi-arid regions, where water shortages are prevalent. Smallholder farming systems in these areas typically focus on livestock production, especially ruminants, due to their ability to thrive on unsuitable forage for human consumption. In South Africa's Limpopo province, an estimated 369,460 households were engaged in farming activities as of 2016. Most of these households practiced only livestock farming (43%), while others focused on only cropping (38%) or mixed farming systems (18%). This reliance on livestock highlights its critical role in the agricultural landscape of the region and food security [66]. The Caatinga region in Brazil illustrates the dependence of approximately 26 million predominantly poor residents on natural resources for their livelihoods. It provides sustenance through fuelwood harvesting, subsistence agriculture, and the grazing of domestic herbivores, particularly goats. With around 9 million goats, representing 96% of Brazil's goatherds, raised extensively and freely here, they play a crucial role in providing protein and income to local communities [67].

Collectively, these studies illustrate the significant role of livestock production in various agricultural systems, particularly in regions characterized by aridity and resource constraints. As these communities face environmental challenges, livestock farming remains a critical component of their livelihoods and food security.

Livestock not only provides direct food sources, but also improves food and nutrition security by offering traction, manure, and income to purchase staples while creating jobs in local communities. Increasing livestock productivity could improve food security, although some scholars argue that significant contributions depend on favorable natural resources for crop production [68]. Furthermore, microalgae could serve as a valuable supplement for ruminant diets in these regions, where traditional feed may be scarce. Consuming small amounts of ruminant products can help address nutrient deficiencies in human diets, as they provide animal proteins, which are generally more digestible and efficiently metabolized than plant proteins, and are also important sources of vitamins, minerals, antioxidants, and essential nutrients like polyunsaturated fatty acids (PUFAs) [69].

5.2.1. Challenges in Producing Microalgae Supplementation in Semiarid Zones

The integration of microalgae into animal feed will face several challenges, particularly in regions where feeding practices rely on locally available crops for grazing and the use of crop residues [65–67].

The production, processing, and distribution of microalgae-based ruminant feed in arid areas can be prohibitive for small farmers who may already be operating on thin margins. Additionally, the potential processing of microalgae into a usable feed format would require specialized equipment and expertise, further increasing costs. Together, these factors would create economic barriers that must be addressed to facilitate the adoption of microalgae-based feed and enhance livestock productivity in arid regions.

To further evaluate the costs and demand for microalgae, we work with a model herd size. A study in 2021 carried out in Brazil described small goat herds as those formed by 2–100 goats per household, with a mean of 22 goats per household [67].

Goats have specific nutritional requirements that vary according to their physiological states and environmental conditions. On average, they consume approximately 1.8% to 2.0% of their body weight in dry matter daily. For maintenance, it is essential that goats consume forage with a crude protein concentration of 7% to 9% and a total digestible nutrient (TDN) value of 50%. However, these requirements increase significantly during periods of heightened physiological demand, such as late gestation, lactation, and growth. During these stages, does and kids require a crude protein concentration of up to 16% and a TDN of approximately 70% [70]. Additionally, the nutritional needs of goats raised in hot environments differ from those of goats raised in temperate climates. Research indicates that goats in hot conditions experience a decrease in energy utilization efficiency, necessitating higher metabolizable energy requirements. These variations underscore the importance of tailoring nutritional models to meet the unique challenges and physiological adaptations faced by goats in hot climates, ensuring optimal health and productivity [71].

A family holding 22 ruminants with an average weight of 40 kg per animal would require around 1.5 kg to 2.8 kg of protein per day, which would represent around 2.5–4 kg per day of microalgae biomass. This is completely unrealistic to be obtained on a family or community scale, making microalgae unreliable as a sole source of protein in these animals' diets.

However, the production of polyunsaturated fatty acids (PUFAs) and antioxidants remains a key goal, as these valuable compounds can improve animal health and improve the quality of animal products. Data from different works show that approximately 15% of dietary polyunsaturated fatty acids (PUFAs) escape ruminal biohydrogenation (BH) in ruminants [72]. To increase the n-3 content in ruminant tissues and products, more PUFA must be fed due to the significant losses incurred during digestion (about 85% of PUFAs are hydrogenated), especially if the PUFA sources have relatively low digestibility. Therefore, the diet of the ruminant must contain a higher amount of PUFA to ensure that a sufficient level reaches the duodenum and contributes to tissue deposition and enrichment of the product. It is clear that only PUFAs from sources unsuitable for human consumption should be used in ruminant feed. In semi-arid regions facing challenges such as water scarcity, climate change, and poverty, the incorporation of microalgae grown in low-quality water emerges as a promising alternative, providing essential PUFAs without competing with human food resources. A recent study on lamb diets supplemented with fresh microalgae (*Chlorella vulgaris*) found that adding 0.5% dry matter (DM) increased beneficial omega-3 fatty acids such as alpha-linolenic acid (ALA) in the meat without affecting growth or carcass traits. Higher doses (1% DM) did not improve omega-3 levels further. Thus, 0.5% DM microalgae appears to be optimal for enhancing meat quality without compromising lamb performance.

The proposed herd model, based on an average weight of 40 kg per animal and a dry matter intake of 2 kg per 100 kg body weight, would require the production of 88 g of microalgae per day, an achievable target. A hypothetical case of a 100 L bubble column bioreactor operating in batch up to 4.5 $g \cdot L^{-1}$ or semi-continuous mode at an average biomass concentration of 1 $g \cdot L^{-1}$ yields the results shown in Table 2. Batch operation achieves a higher biomass concentration compared to semi-continuous mode. However, batch mode produces only 75% of the total biomass compared to semi-continuous operation over the same 57-day period, as cell growth occurs below the maximum rate for most of the time. In arid regions, where water scarcity is a concern, comparing the water volumes required for both modes is essential. As shown in Table 2, batch operation requires approximately six times less water than semi-continuous mode, making batch cultivation more water efficient in resource-limited environments.

Table 2. Estimate of biomass produced and volume of aqueous media required to operate a 100 L bubble column to produce microalgae. It is assumed that the reactors operate at 90% of the concentrations indicated in Figure 1 for each of the cases.

	Batch	**Semicontinuous**
Concentration when harvesting [$g \cdot L^{-1}$]	4.5	1.0
Days of Harvesting [days]	27, 57	13, 14...57
Volume harvested each time from a 100 L bioreactor [L]	100	25
Biomass obtained from a 100 L bioreactor [g] after 57 days	900	1200 (considering harvesting the bioreactor)
Volume of water handled for culturing [L]	200	1200

To meet the target production of 88 $g \cdot day^{-1}$ (5.02 kg over 57 days), six 100 L bubble columns operating in batch mode or five 100 L columns in semi-continuous mode would suffice. The total water volume required for these 57 days would be 1200 L for batch and 6000 L for semi-continuous mode. The choice between these operating modes will depend on factors such as water recovery potential, water availability, and the technology at hand. However, this case study demonstrates that the production of microalgae biomass for the proposed purpose is entirely feasible.

Concentrating microalgae cultures into a paste is essential for incorporation of microalgae into the solid animal diet. Among the different methods, gravity settling and flocculation are cost-effective. Minimal equipment is required, although it can be time consuming, especially for very dilute cultures. Adding natural flocculants to the culture can help aggregate microalgae cells, increasing their size and weight, thus accelerating the settling process and leading to higher biomass recovery rates. Natural flocculants that can be sourced from arid zones include several plants and biopolymers that can help in the aggregation of microalgae for concentration, such as mucilage from certain species of cactus, guar gam from the seeds of the guar plant, and in regions where almonds and olives are grown, the by-products of these industries can serve as natural flocculants [73–75].

Another possible approach is the use of forward osmosis to concentrate microalgae. For this approach, semipermeable membranes and osmotic fluids must be easily available. In this sense, the intestines of ruminants, such as cows and sheep, show natural water permeability and resistance to fouling, which positions them as promising candidates for FO applications. Regarding osmotic fluids, high-osmotic pressure fluids in arid zones could include saline groundwater, desalination brine, concentrated solutions in evaporative ponds, and nutrient-laden agricultural runoff. These fluids present opportunities for innovative water management and resource recovery strategies in these challenging environments and in conjunction with the utilization of the intestinal tract in this manner could not only improve the efficiency of concentrating microalgae cultures after harvesting, but also align with sustainable practices.

5.2.2. Challenges in Adopting Microalgae Supplementation in Semi-Arid Zones

Another significant barrier is the need to adjust existing feeding protocols. Farmers used to traditional practices may be resistant to adopting new methods, viewing changes as unnecessary or risky. This resistance can stem from a lack of familiarity with microalgae benefits, concerns about cost-effectiveness, and uncertainty regarding the impact on livestock health and productivity. Furthermore, integrating microalgae requires establishing production facilities in areas where they can be cultivated sustainably, which may not always align with existing agricultural infrastructures. Farmers may also need guidance on effective supplementation strategies, including appropriate inclusion rates in animal diets and the timing of microalgae application.

To address these challenges, it is essential to engage farmers through education and outreach programs that highlight the nutritional benefits of microalgae and demonstrate successful case studies. Providing technical support for transitioning to microalgae-based diets can help alleviate concerns and facilitate smoother adoption. Collaborative efforts between researchers, agricultural extension services, and local farming communities can pave the way for the integration of microalgae, ultimately improving the sustainability and resilience of livestock production systems.

5.2.3. Empowering Women Through Microalgae Cultivation

The role of women in the livestock sector in semi-arid regions is crucial, multifaceted, and often underappreciated. Women are primarily responsible for the daily care of livestock, including feeding, watering, cleaning, and caring for sick animals. They often manage smaller livestock such as goats, sheep, poultry, and sometimes cattle, depending on local cultural norms. In many of these regions, women are also tasked with fetching water for household consumption, livestock, and small-scale agriculture. This often involves traveling long distances to access water, especially during the dry season when water is scarce.

In widely spread areas, such as the Mtubatuba community of KwaZulu-Natal (East Africa), in informal settlements in the north and northeast of Brazil (South America), and in south Asia and India (Rajasthan and Gujarat), as well as in West Africa, such as Cinzana in Mali, water shortages severely hinder subsistence farming, disproportionately impacting women [76–79], who bear the responsibility for water management and food production, but remain marginalized in rural development efforts. Despite their exclusion from formal decision-making structures, women often exert an informal influence in their communities. They organize themselves into water user groups, sharing information, pooling resources, and advocating for better access to water. In some cases, these groups lead initiatives to improve water access through small-scale projects, such as digging wells, installing hand pumps, or constructing rainwater harvesting systems, often with the support of local NGOs or development organizations. For example, the Sister Watersheds project (2002–2008) aimed to address water issues and empower women in low-income communities in Brazil and Canada by increasing their participation in water management and policy [77]. The project linked universities and NGOs to develop educational materials and training programs focused on water-related challenges, with a strong emphasis on gender equity. It provided workshops for over 1450 participants, two-thirds of whom were women, teaching them about water management, health, and environmental policy.

By building women's capacity to participate in watershed governance, the project helped amplify their voices in decision-making processes related to water access and sustainability.

Women collectives and cooperatives also play a vital role in pooling resources, sharing knowledge, and increasing access to markets. As an example, the Barefoot College exemplifies how effective water management stakeholder engagement can be significantly enhanced by empowering women, particularly in rural communities [80]. By training older women as solar engineers—referred to as "Solar Mamas"—the organization addresses not only the pressing need for sustainable energy solutions but also challenges restrictive gender roles that often limit women's participation in vital sectors like water management [80]. Evidence from the college's innovative educational methods, which include non-normative strategies such as color coding and sign language, shows that these women gain the practical skills necessary to implement solar electrification projects that directly impact their communities. This empowerment fosters a sense of ownership and leadership among women, allowing them to contribute meaningfully to local water management initiatives and ensuring that their unique needs and perspectives are incorporated into stakeholder discussions.

Teaching women in vulnerable, arid communities to grow microalgae in brackish water can have profound impacts on their livelihoods. Microalgae cultivation can reduce livestock feed costs at the family level and, at the community level, surplus algae can be sold for animal feed, biofertilizers, or even human consumption, providing a new income stream. These skills and knowledge empower women to take on leadership roles in community-based enterprises, creating employment opportunities and supporting economic stability.

By mastering sustainable practices such as microalgae cultivation, women can help their communities adapt to challenges such as climate change, droughts, and water scarcity, increasing their resilience to environmental shocks.

Women can form cooperatives around microalgae production, strengthening community bonds and fostering collaboration. These networks can improve women's social capital and collective bargaining power, helping them access better markets and resources.

With better access to food, income, and water, women can provide more stable and secure living conditions for their families, ultimately raising the overall standard of living in their communities.

In summary, teaching women in vulnerable, arid regions to cultivate microalgae has the potential to transform their economic opportunities, improve food security, improve environmental sustainability, and empower them socially and politically. This multifaceted solution not only addresses immediate problems such as water and food scarcity, but also fosters long-term resilience and development in these communities.

6. Conclusions

In conclusion, this article explores the potential of integrating microalgae into livestock production systems as a strategy to improve food security and sustainability in semi-arid regions. Given the challenges posed by water scarcity, climate change, and resource limitations, the incorporation of microalgae into ruminant diets emerges as a promising avenue to improve livestock productivity.

The evidence presented highlights the significant role of livestock in various agricultural systems, particularly in regions where pastoral communities depend heavily on ruminants for their livelihoods. While utilizing the nutritional advantages of microalgae can enhance the fatty acid profile of animal products, which is crucial for human health, it should be viewed as a supplement rather than a complete replacement for existing protein sources. By strategically incorporating microalgae biomass into ruminant diets, we can improve not only the quality of animal feed but also the nutritional quality of livestock products, providing consumers with healthier options rich in essential fatty acids.

Furthermore, this article emphasizes the crucial role of women in livestock management within semi-arid regions. Empowering women through training in microalgae cultivation not only enhances their economic opportunities, but also fosters community resilience. By equipping women with the necessary skills to produce high-quality animal feed, we can improve their families' livelihoods while contributing to a broader community development.

Ultimately, this paper advocates for a comprehensive approach that recognizes the interconnectedness of livestock production, food security, and the innovative use of microalgae. By addressing the economic, social, and technical challenges associated with microalgae integration, we can pave the way for a more sustainable and resilient agricultural future in semi-arid regions. Collaborative efforts among researchers, farmers, and policy makers are essential to realize the full potential of microalgae to improve food security and sustainability, while acknowledging its limitations in replacing traditional protein sources in livestock diets.

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References

1. Abuelfatah, K.; Zuki, A.B.Z.; Goh, Y.M.; Sazili, A.Q. Effects of Enriching Goat Meat with n − 3 Polyunsaturated Fatty Acids on Meat Quality and Stability. *Small Rumin. Res.* **2016**, *136*, 36–42. [CrossRef]
2. Orzuna-Orzuna, J.F.; Hernández-García, P.A.; Chay-Canul, A.J.; Díaz Galván, C.; Razo Ortíz, P.B. Microalgae as a Dietary Additive for Lambs: A Meta-Analysis on Growth Performance, Meat Quality, and Meat Fatty Acid Profile. *Small Rumin. Res.* **2023**, *227*, 107072. [CrossRef]
3. Espinosa-Ramírez, J.; Mondragón-Portocarrero, A.C.; Rodríguez, J.A.; Lorenzo, J.M.; Santos, E.M. Algae as a Potential Source of Protein Meat Alternatives. *Front. Nutr.* **2023**, *10*, 1254300. [CrossRef] [PubMed]
4. Kholif, A.E.; Morsy, T.A.; Matloup, O.H.; Anele, U.Y.; Mohamed, A.G.; El-Sayed, A.B. Dietary *Chlorella vulgaris* Microalgae Improves Feed Utilization, Milk Production and Concentrations of Conjugated Linoleic Acids in the Milk of Damascus Goats. *J. Agric. Sci.* **2017**, *155*, 508–518. [CrossRef]

5. Harahap, M.A.; Widodo, S.; Handayani, U.F.; Altandjung, R.I.; Wulandari; Sakti, A.A.; Atmoko, B.A.; Negara, W.; Dewi, Y.L.; Julendra, H.; et al. Examining Performance, Milk, and Meat in Ruminants Fed with Macroalgae and Microalgae: A Meta-Analysis Perspective. *Trop. Anim. Health Prod.* **2024**, *56*, 243. [CrossRef]
6. Mavrommatis, A.; Skliros, D.; Sotirakoglou, K.; Flemetakis, E.; Tsiplakou, E. The Effect of Forage-to-concentrate Ratio on *Schizochytrium* spp.-supplemented Goats: Modifying Rumen Microbiota. *Animals* **2021**, *11*, 2746. [CrossRef]
7. Tsiplakou, E.; Abdullah, M.A.M.; Mavrommatis, A.; Chatzikonstantinou, M.; Skliros, D.; Sotirakoglou, K.; Flemetakis, E.; Labrou, N.E.; Zervas, G. The Effect of Dietary *Chlorella vulgaris* Inclusion on Goat's Milk Chemical Composition, Fatty Acids Profile and Enzymes Activities Related to Oxidation. *J. Anim. Physiol. Anim. Nutr.* **2018**, *102*, 142–151. [CrossRef]
8. Vítor, A.C.M.; Godinho, M.; Francisco, A.E.; Silva, J.; Almeida, J.; Fialho, L.; Soldado, D.; Jerónimo, E.; Scollan, N.D.; Huws, S.A.; et al. *Nannochloropsis oceanica* Microalga Feeding Increases Long-Chain Omega-3 Polyunsaturated Fatty Acids in Lamb Meat. *Meat Sci.* **2023**, *197*, 109053. [CrossRef]
9. Valença, R.d.L.; Silva Sobrinho, A.G.D.; Borghi, T.H.; Meza, D.A.R.; Andrade, N.D.; Silva, L.G.; Bezerra, L.R. Performance, Carcass Traits, Physicochemical Properties and Fatty Acids Composition of Lamb's Meat Fed Diets with Marine Microalgae Meal (*Schizochytrium* sp.). *Livest. Sci.* **2021**, *243*, 104387. [CrossRef]
10. Kyriakaki, P.; Zisis, F.; Pappas, A.C.; Mavrommatis, A.; Tsiplakou, E. Effects of PUFA-Rich Dietary Strategies on Ruminants' Mammary Gland Gene Network: A Nutrigenomics Review. *Metabolites* **2023**, *13*, 44. [CrossRef]
11. Wodajo, H.D.; Gemeda, B.A.; Kinati, W.; Mulem, A.A.; van Eerdewijk, A.; Wieland, B. Contribution of Small Ruminants to Food Security for Ethiopian Smallholder Farmers. *Small Rumin Res.* **2020**, *184*, 106064. [CrossRef]
12. Benes, A.; Reiling, B. Animal reproduction Field Day. In *Animals Inside & Out. Lessons for Reproduction, Byproducts, Animals Close Up*; University of Nebraska: Lincoln, NE, USA, 2015.
13. Water Advice for Livestock Farmers. Available online: https://www.daera-ni.gov.uk/articles/water-advice-livestock-farmers (accessed on 1 October 2024).
14. Peischel, A. Browsing Academy Nutrition of the Goat. 1999. Available online: https://ucanr.edu/sites/placernevadasmallfarms/files/197793.pdf (accessed on 1 October 2024).
15. Rabee, A.E.; Younan, B.R.; Kewan, K.Z.; Sabra, E.A.; Lamara, M. Modulation of Rumen Bacterial Community and Feed Utilization in Camel and Sheep Using Combined Supplementation of Live Yeast and Microalgae. *Sci. Rep.* **2022**, *12*, 12990. [CrossRef]
16. Hintz, H.F.; Heitman, H., Jr.; Weir, W.C.; Torell, D.T.; Meyer, J.H. Nutritive Value of Algae Grown on Sewage2. *J. Anim. Sci.* **1966**, *25*, 675–681. [CrossRef]
17. Van Demmon, M.L.; Loy, D.D.; Hansen, S.L. Determining the Preference, in Vitro Digestibility, in Situ Disappearance, and Grower Period Performance of Steers Fed a Novel Algae Meal from Heterotrophic Microalgae. *J. Anim. Sci.* **2015**, *93*, 3121–3129. [CrossRef] [PubMed]
18. Mattos, R. Effects of Dietary Fatty Acids on Reproduction in Ruminants. *Rev. Reprod.* **2000**, *5*, 38–45. [CrossRef]
19. Van Tran, L.; Malla, B.A.; Kumar, S.; Tyagi, A.K. Polyunsaturated Fatty Acids in Male Ruminant Reproduction—A Review. *Asian-Australas. J. Anim. Sci.* **2016**, *30*, 622–637. [CrossRef]
20. Silva, M.R.L.; Alves, J.P.M.; Fernandes, C.C.L.; Cavalcanti, C.M.; Conde, A.J.H.; Bezerra, A.F.; Soares, A.C.S.; Tetaping, G.M.; de Sá, N.A.R.; Teixeira, D.Í.A.; et al. Use of Green Microalgae *Chlorella* as a Nutritional Supplement to Support Oocyte and Embryo Production in Goats. *Anim. Reprod. Sci.* **2023**, *256*, 107296. [CrossRef]
21. Mahla, A.S.; Bunkar, S.K.; Kumawat, B.L.; Kumar Saxena, V.; Selvaraju, S.; Bhatt, R.S.; Singh, R.; Kumar, A. Dietary N-3 PUFA Augments Pre-Ovulatory Follicle Turnover and Prolificacy in Well-Fed Ewes. *Anim. Reprod. Sci.* **2023**, *252*, 107231. [CrossRef]
22. Zhong, R.; Zhou, D. Oxidative Stress and Role of Natural Plant Derived Antioxidants in Animal Reproduction. *J. Integr. Agric.* **2013**, *12*, 1826–1838. [CrossRef]
23. Villaró, S.; Acién, G.; Alarcón, J.; Ruiz, Á.; Rodríguez-Chikri, L.; Viviano, E.; Lafarga, T. A Zero-Waste Approach for the Production and Use of *Arthrospira platensis* as a Protein Source in Foods and as a Plant Biostimulant in Agriculture. *J. Appl. Phycol.* **2023**, *35*, 2619–2630. [CrossRef]
24. Mofeed, J. Stimulating Gamma-Linolenic Acid Productivity by *Arthrospira platensis* (*Spirulina platensis*) Under Different Culture Conditions (Temperatures, Light Regime, and H_2O_2 Stress). *Egypt. Acad. J. Biol. Sci. G Microbiol. EAJBSG* **2019**, *11*, 89–99. [CrossRef]
25. Tzachor, A.; van den Oever, S.P.; Mayer, H.K.; Asfur, M.; Smidt-Jensen, A.; Geirsdóttir, M.; Jensen, S.; Smárason, B.O. Photonic Management of Spirulina (*Arthrospira platensis*) in Scalable Photobioreactors to Achieve Biologically Active Unopposed Vitamin B12. *Discov. Food* **2024**, *4*, 69. [CrossRef]
26. Annapurna, V.V.; Deosthale, Y.G.; Bamji, M.S. *Spirulina* as a Source of Vitamin A. *Plant Foods Hum. Nutr.* **1991**, *41*, 125–134. [CrossRef]
27. Moreira, M. *Spirulina platensis* Biomass Cultivated in Southern Brazil as a Source of Essential Minerals and Other Nutrients. *Afr. J. Food Sci. AJFS* **2013**, *7*, 451–455. [CrossRef]

28. Ismaiel, M.M.S.; El-Ayouty, Y.M.; Piercey-Normore, M. Role of PH on Antioxidants Production by *Spirulina* (*Arthrospira) platensis*. *Braz. J. Microbiol.* **2016**, *47*, 298–304. [CrossRef] [PubMed]
29. Tambiev, A.K.; Vasilieva, S.G.; Lukyanov, A.A. Manifestation of Salt Tolerance of *Spirulina platensis* and *Spirulina Maxima* Cyanobacteria of the Genus *Arthrospira* (*Spirulina*). *Mosc. Univ. Biol. Sci. Bull.* **2011**, *66*, 133–137. [CrossRef]
30. Marquez, F.J.; Sasaki, K.; Kakizono, T.; Nishio, N.; And, I.; Nagap, S. Growth Characteristics of *Spirulina platensis* in Mixotrophic and Heterotrophic Conditions. *J. Ferment. Bioeng.* **1993**, *76*, 408–410. [CrossRef]
31. Sharma, R.; Gajendra, P.S.; Vijendra, K.S. Effects of Culture Conditions on Growth and Biochemical Profile of *Chlorella vulgaris*. *J. Plant Pathol. Microbiol.* **2012**, *3*, 5. [CrossRef]
32. Freitas, H.R. *Chlorella vulgaris* as a Source of Essential Fatty Acids and Micronutrients: A Brief Commentary. *Open J. Plant Sci.* **2017**, *10*, 92–99. [CrossRef]
33. Conde, T.A.; Neves, B.F.; Couto, D.; Melo, T.; Neves, B.; Costa, M.; Silva, J.; Domingues, P.; Domingues, M.R. Microalgae as Sustainable Bio-Factories of Healthy Lipids: Evaluating Fatty Acid Content and Antioxidant Activity. *Mar. Drugs* **2021**, *19*, 357. [CrossRef]
34. Yun, H.S.; Kim, Y.S.; Yoon, H.S. Effect of Different Cultivation Modes (Photoautotrophic, Mixotrophic, and Heterotrophic) on the Growth of *Chlorella* sp. and Biocompositions. *Front. Bioeng. Biotechnol.* **2021**, *9*, 774143. [CrossRef]
35. Alazaiza, M.Y.D.; He, S.; Su, D.; Abu Amr, S.S.; Toh, P.Y.; Bashir, M.J.K. Sewage Water Treatment Using *Chlorella vulgaris* Microalgae for Simultaneous Nutrient Separation and Biomass Production. *Separations* **2023**, *10*, 229. [CrossRef]
36. Hulatt, C.J.; Wijffels, R.H.; Bolla, S.; Kiron, V. Production of Fatty Acids and Protein by *Nannochloropsis* in Flat-Plate Photobioreactors. *PLoS ONE* **2017**, *12*, e0170440. [CrossRef]
37. Parsy, A.; Sambusiti, C.; Baldoni-Andrey, P.; Elan, T.; Périé, F. Cultivation of *Nannochloropsis oculata* in Saline Oil & Gas Wastewater Supplemented with Anaerobic Digestion Effluent as Nutrient Source. *Algal Res.* **2020**, *50*, 101966. [CrossRef]
38. Yaguchi, T.; Tanaka, S.; Yokochi, T.; Nakahara, T.; Higashihara, T. Production of High Yields of Docosahexaenoic Acid by *Schizochytrium* sp. Strain SR21. *Appl. Microbiol. Biotechnol.* **1998**, *74*, 1431–1434. [CrossRef]
39. Yokochi, T.; Honda, D.; Higashihara, T.; Nakahara, T. Optimization of Docosahexaenoic Acid Production by *Schizochytrium Limacinum* SR21. *Appl. Microbiol. Biotechnol.* **1998**, *49*, 72–76. [CrossRef]
40. Araj-Shirvani, M.; Honarvar, M.; Jahadi, M.; Mizani, M. Biochemical Profile of Dunaliella Isolates from Different Regions of Iran with a Focus on Pharmaceutical and Nutraceutical Potential Applications. *Food Sci. Nutr.* **2024**, *12*, 4914–4926. [CrossRef] [PubMed]
41. Qiao, H.; Cong, C.; Sun, C.; Li, B.; Wang, J.; Zhang, L. Effect of Culture Conditions on Growth, Fatty Acid Composition and DHA/EPA Ratio of *Phaeodactylum tricornutum*. *Aquaculture* **2016**, *452*, 311–317. [CrossRef]
42. Fernández, F.G.A.; Pérez, J.A.S.; Sevilla, J.M.F.; Camacho, F.G.; Grima, E.M. Modeling of Eicosapentaenoic Acid (EPA) Production from *Phaeodactylum tricornutum* Cultures in Tubular Photobioreactors. Effects of Dilution Rate, Tube Diameter, and Solar Irradiance. *Biotechnol. Bioeng.* **2000**, *68*, 173–183. [CrossRef]
43. Pocha, C.K.R.; Chia, W.Y.; Chew, K.W.; Munawaroh, H.S.H.; Show, P.L. Current Advances in Recovery and Biorefinery of Fucoxanthin from *Phaeodactylum tricornutum*. *Algal Res.* **2022**, *65*, 102735. [CrossRef]
44. Fuentes, M.M.R.; Acien, N.; Fernandez, G.G.; Sanchez Perez, J.A.; Guil Guerrero, J.L. Biomass Nutrient Profiles of the Microalga *Porphyridium cruentum*. *Food Chem.* **2000**, *70*, 345–353. [CrossRef]
45. FAO. *Fishery and Aquaculture Statistics—Yearbook 2021*; FAO: Rome, Italy, 2024.
46. Araújo, R.; Vázquez Calderón, F.; Sánchez López, J.; Azevedo, I.C.; Bruhn, A.; Fluch, S.; Garcia Tasende, M.; Ghaderiardakani, F.; Ilmjärv, T.; Laurans, M.; et al. Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy. *Front. Mar. Sci.* **2021**, *7*, 626389. [CrossRef]
47. Leng, R.; Nunn, M.; Dhendup, T.; Qi, G.-H.; IB, F.; Yong Jiu, C.; Balakrishnan, V.; Manget Ram, G.; Talakesh, S.F.; Kamalzadeh, A.; et al. Protein sources for the animal feed industry. In *FAO Animal Production and Health*; FAO: Rome, Italy, 2004.
48. Valero Gaspar, T.; Molinero Hernando, F. *La Alimentación Española: Características Nutricionales de Principales Alimentos de Nuestra Dieta*; Gobierno de España, Ministerio de Agricultura Pesca y Alimentación: Madrid, Spain, 2018.
49. The Nutritional Value of Grass Guide (Guides). Available online: https://germinal.ie/knowledge-hub/grass-nutritional-value/ (accessed on 20 September 2024).
50. UNICEF; WHO. *Joint Monitoring Programme for Water Supply, Sanitation and Hygiene*; WHO: Geneva, Switzerland; UNICEF: New York, NY, USA, 2023. Available online: https://washdata.org (accessed on 12 December 2024).
51. World Health Organization. *Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture*; WHO: Geneva, Switzerland, 1989.
52. Khan, S.; Das, P.; Thaher, M.I.; AbdulQuadir, M.; Mahata, C.; Al Jabri, H. Utilization of Nitrogen-Rich Agricultural Waste Streams by Microalgae for the Production of Protein and Value-Added Compounds. *Curr. Opin. Green Sustain. Chem.* **2023**, *41*, 100797. [CrossRef]

53. Chang, Y.C.; Pan, Y.J.; Huang, T.H.; Hsiao, T.H.; Wei, L.Y.; Hsu, T.H. Cultivation of Brackish Water Microalgae for Pig Manure Liquid Digestate Recycling. *Sustainability* **2023**, *15*, 16278. [CrossRef]
54. Rahman, M.H.; Khan, A.N.M.A.I.; Bin Habib, M.A.; Hossain, M.S. Evaluation of Sugar Mill By-Product Molasses as a Low Cost Culture Media for Microalgae. *Aquac. Stud.* **2022**, *22*, AQUAST776. [CrossRef]
55. Fernández, F.G.A.; Fernández-Sevilla, J.M.; Moya, B.L.; Grima, E.M. Chapter 6—Microalgae production systems. In *Handbook of Microalgae-Based Processes and Products*; Jacob-Lopes, E., Maroneze, M.M., Queiroz, M.I., Zepka, L.Q., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 127–163. [CrossRef]
56. Sánchez Mirón, A.; Contreras Gómez, A.; Camacho, F.G.; Molina Grima, E.; Chisti, Y. Comparative evaluation of compact photobioreactors for large-scale monoculture of microalgae. *J. Biotechol.* **1999**, *70*, 249–270. [CrossRef]
57. Acién Fernández, F.G.; García Camacho, F.; Chisti, Y. Photobioreactors: Light regime, mass transfer, and scaleup. In *Progress in Industrial Microbiology*; Osinga, R., Tramper, J., Burgess, J.G., Wijffels, R.H., Eds.; Elsevier: Amsterdam, The Netherlands, 1999; Volume 35, pp. 231–247. [CrossRef]
58. Mazzuca Sobczuk, T.; Chisti, Y. Potential fuel oils from the microalga *Choricystis minor*. *J. Chem. Technol. Biotechnol. JCTB* **2010**, *85*, 100–108. [CrossRef]
59. Sobczuk, T.M.; Camacho, F.G.; Grima, E.M.; Chisti, Y. Effects of agitation on the microalgae *Phaeodactylum tricornutum* and *Porphyridium cruentum*. *Bioprocess Biosyst. Eng.* **2006**, *28*, 243–250. [CrossRef]
60. Mata, T.M.; Martins, A.A.; Caetano, N.S. Microalgae for Biodiesel Production and Other Applications: A Review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 217–232. [CrossRef]
61. Chatsungnoen, T.; Chisti, Y. Harvesting Microalgae by Flocculation-Sedimentation. *Algal Res.* **2016**, *13*, 271–283. [CrossRef]
62. Zhao, F.; Li, Z.; Han, X.; Shao, Z.; Li, Z. Optimization of Air Flotation and the Combination of Air Flotation and Membrane Filtration in Microalgae Harvesting. *Processes* **2022**, *10*, 1594. [CrossRef]
63. Yazdanabad, S.K.; Samimi, A.; Shokrollahzadeh, S.; Kalhori, D.M.; Moazami, N.; Ibáñez González, M.J.; Mazzuca Sobczuk, T.; Molina Grima, E. Microalgae Biomass Dewatering by Forward Osmosis: Review and Critical Challenges. *Algal Res.* **2021**, *56*, 102323. [CrossRef]
64. Acién Fernández, F.G.; Fernández Sevilla, J.M.; Molina Grima, E. Chapter 21—Costs Analysis of Microalgae Production. In *Biofuels from Algae*, 2nd ed.; Pandey, A., Chang, J.-S., Soccol, C.R., Lee, D.-J., Chisti, Y., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 551–566. ISBN 978-0-444-64192-2.
65. Rjili, H.; Muñoz-Ulecia, E.; Bernués, A.; Jaouad, M.; Martin-Collado, D. Evolution of Pastoral Livestock Farming on Arid Rangelands in the Last 15 Years. *Animal* **2023**, *17*, 100748. [CrossRef]
66. Lamega, S.A.; Komainda, M.; Hoffmann, M.P.; Ayisi, K.K.; Odhiambo, J.J.O.; Isselstein, J. It Depends on the Rain: Smallholder Farmers' Perceptions on the Seasonality of Feed Gaps and How It Affects Livestock in Semi-Arid and Arid Regions in Southern Africa. *Clim. Risk Manag.* **2021**, *34*, 100362. [CrossRef]
67. Jamelli, D.; Bernard, E.; Melo, F.P.L. Habitat Use and Feeding Behavior of Domestic Free-Ranging Goats in a Seasonal Tropical Dry Forest. *J. Arid Environ.* **2021**, *190*, 104532. [CrossRef]
68. Murali, R.; Ikhagvajav, P.; Amankul, V.; Jumabay, K.; Sharma, K.; Bhatnagar, Y.V.; Suryawanshi, K.; Mishra, C. Ecosystem service dependence in livestock and crop-based production systems in Asia's high mountains. *J. Arid Environ.* **2020**, *180*, 104204. [CrossRef]
69. Mlambo, V.; Mapiye, C. Towards Household Food and Nutrition Security in Semi-Arid Areas: What Role for Condensed Tannin-Rich Ruminant Feedstuffs? *Food Res. Int.* **2015**, *76*, 953–961. [CrossRef]
70. Balch, S.G. MSD Veterinary Manual. Available online: https://www.msdvetmanual.com (accessed on 5 September 2024).
71. Teixeira, I.A.M.A.; Härter, C.J.; Vargas, J.A.C.; Souza, A.P.; Fernandes, M.H.M.R. Review: Update of Nutritional Requirements of Goats for Growth and Pregnancy in Hot Environments. *Animal* **2024**, *18*, 101219. [CrossRef] [PubMed]
72. Palmquist, D.L. Omega-3 Fatty Acids in Metabolism, Health, and Nutrition and for Modified Animal Product Foods. *Prof. Anim. Sci.* **2009**, *25*, 207–249. [CrossRef]
73. Bouaouine, O.; Bourven, I.; Khalil, F.; Baudu, M. Reuse of Olive Mill Wastewater as a Bioflocculant for Water Treatment Processes. *J. Clean. Prod.* **2020**, *246*, 119031. [CrossRef]
74. Gomes, A.; Jorge, N.; Teixeira, A.; Peres, J.A.; Lucas, M.S. Cattle Wastewater Treatment Using Almond Hull and Cherry Pit as Coagulants–Flocculants. *Eng. Proc.* **2023**, *56*, 222. [CrossRef]
75. Rachdi, R.; Srarfi, F.; Shimi, N.S. Cactus Opuntia as Natural Flocculant for Urban Wastewater Treatment. *Water Sci. Technol.* **2017**, *76*, 1875–1883. [CrossRef] [PubMed]
76. Bakre, O.; Dorasamy, N. Rural Redress through Investment in Water Resource Management for Subsistence Farming. *Environ. Econ.* **2015**, *6*, 151–166.
77. Figueiredo, P.; Perkins, P.E. Women and Water Management in Times of Climate Change:Participatory and Inclusive Processes. *J. Clean. Prod.* **2013**, *60*, 188–194. [CrossRef]

78. Segnon, A.C.; Magassa, M.; Obossou, E.A.R.; Partey, S.T.; Houessionon, P.; Zougmoré, R.B. Gender Vulnerability Assessment to Inform Gender-Sensitive Adaptation Action: A Case Study in Semi-Arid Areas of Mali. *Front. Clim.* **2024**, *6*, 1418015. [CrossRef]
79. Yadav, S.S.; Lal, R. Vulnerability of Women to Climate Change in Arid and Semi-Arid Regions: The Case of India and South Asia. *J. Arid Environ.* **2018**, *149*, 4–17. [CrossRef]
80. Shaikh, N.P. Feminism in Practice: Learning from the Barefoot "Solar Mamas". *J. Int. Women's Stud.* **2024**, *26*, 1–14.